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Air DTH Hammer Drilling Equipment and Its Application Status in China's Geothermal Industry

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ABSTRACT

Air DTH underbalance drilling technique has high efficiency in hard rock. The application of this technology in geothermal wells can not only greatly improve the rate of penetration, but also protect the reservoir, maximize the productivity of geothermal wells, increase the benefits of geothermal project exploitation, and promote the rapid development of geothermal industry. However, there are still many bottleneck technologies to be broken through in the application and popularization of DTH. After nearly 10 years of continuous research and innovation by the cooperating teams, China's air DTH drilling technology and application has achieved a series of achievements that attract worldwide attention, i.e. economic drilling depth, the highest drilling rate, single bit life, high pressure pneumatic DTH hammmer, large tonnage drill for air DTH hammer. The cost of the whole series of supporting equipment greatly reduced. This paper will comprehensively introduce the research, development and application of air DTH drilling technology and equipment in China's geothermal industry, as well as the research and development goals of key technologies and major equipment in the next step, and advocate large-scale promotion of air DTH drilling technology in the geothermal industry.

1. INTRODUCTION

Air DTH hammer drilling technology is a branch of air drilling technology. It is an impact rotary method that uses compressed air as both flushing medium and rock crushing energy. At present, it is one of the most effective methods to improve the drilling efficiency of hard rock. This underbalanced drilling technology has the advantages of no damage to the reservoir, high drilling efficiency, no environmental pollution, low cost, etc., Su. et al (2017). Water well drilling in China has a history of at least 40-50 years. In recent years, more and more air DTH hammer drilling equipment has been used in the drilling of bedrock fracture geothermal wells, Zhao H. et al (2016).The site construction drawing is shown in figure 1. For the bedrock fissure geothermal well with a good depth of less than 1500m, the air DTH hammer drilling equipment is relatively mature; The drilling equipment with a drilling depth of more than 2500m or even more than 3000m is in the stage of research and development, It is described in detail below.

Figure. 1 Construction drawing of a site for air DTH hammer drilling in China

2. AIR DTH DRILLING EQUIPMENT

The air DTH hammer drilling process is that the air compressor and booster pressurize the air and then enter the downhole equipment impactor through the drill to do impact work on the drill bit. The process flow diagram is shown in figure 2. The drill bit performs impact rotary rock fragmentation under the combined action of the drill's torque and the impact force of the impactor; air as the flushing medium brings rock cuttings out of the formation, Zhang X. et al (2019). Its leading equipment includes a DTH hammer rig, air compressor, booster, foam pump, pneumatic impactor, DTH hammer bit, etc. The application status of this equipment in China will be introduced below.

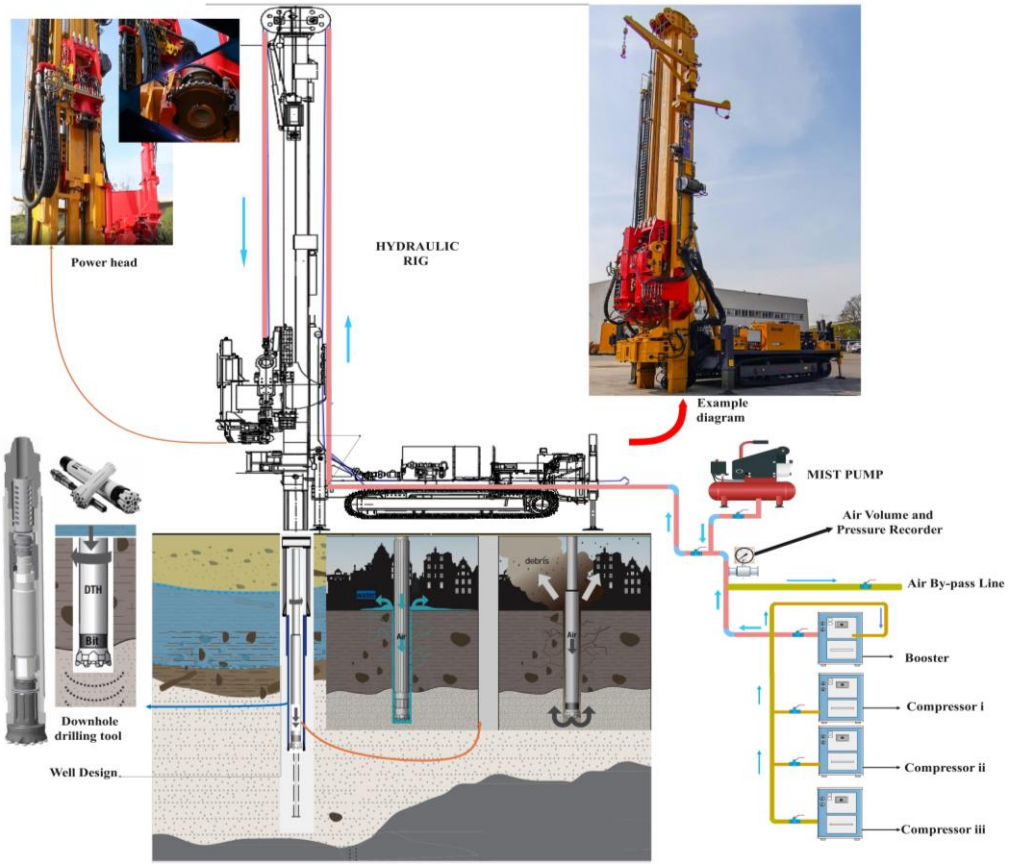

Figure. 2 Drilling process flow chart of air DTH hammer

2.1 Full Hydraulic Top Drive Rig

Among geothermal drilling wells, various types of air DTH hammer rigs can be used for deep hole 1500-3000m geothermal drilling construction, including traditional oil rotary table rigs, water source rigs, full hydraulic top drive rigs, etc. In recent years, the full hydraulic top drive rig has gradually occupied the market due to its unique advantages, which will be introduced below.

The full hydraulic top drive rig has many advantages, such as small volume, lightweight, convenient transition, safe operation, fast connection speed, etc,Liu X. et al (2013). It is a drilling rig with a high matching degree with the air DTH hammer drilling technology, Shi Y. et al (2022). Compared with an oil drilling rig or water source drilling rig, a full hydraulic top drive rig has the following advantages:

- All rigs are driven by top drive, improving the ability to deal with complex situations.
- The second-floor operation platform is cancelled, and all operators are working on the ground, improving safety.
- Equipped with an automatic/semi-automatic shackle device, the connection speed is fast, and the labour intensity of workers is reduced.
- The drilling parameter instruments are fully equipped, which greatly improves drilling safety.
- Small size and lightweight, low transportation cost and wide application range.

The basic performance parameters of some domestic and foreign deep well full hydraulic top drive rigs are shown in table 1, Yu J (2022).Examples are shown in figures 3 to 6.

Table 1 Comparison of basic performance parameters of domestic and foreign deep hole full hydraulic rigs

Model of drilling rig	Germany BAUER RB-T100	Drillmec 102, IHHtaly	Drilling Division SS-200K	American Shim T200XD	China Tianhe Zhongbang CMD100T	XCMG XSL20/1000
Maximum lifting force (kN)	980	1000	892	889	980	1000
Maximum downforce (kN)	196	200	133	142	196	Unknown
Drilling capacity (m)	2000-2500	2000	2600	2000-2500	2000-2500	2000

Maximum opening diameter (mm)	Unknown	Unknown	673	768	810	610
Power head torque(N • m)	36000	35300	16000	24000	28000	31500
Power head stroke (m)	16.4	16	15	15.2	15.2	15.0
Whether the power head can be tilted	Sure	Sure	May not	May not	Sure	Sure
Type of shipping	Trailer type	Trailer type	Vehicle mounted	Vehicle mounted	Trailer type	Walking disc type
Hydraulic system power（kw）	708	447.5	410	560	560	405

Figure. 3 HH102 rig

Figure. 4 RB-T100 rig

Figure. 5 T200XD rig

Figure. 6 CMD100T rig

With the increasing market demand for full hydraulic top drive rigs, Chinese drilling rig manufacturers have established full hydraulic top drive rig product lines with lifting capacities of 60t, 68t, 100t, 120t and 150t, which can meet the drilling demand of 1500-4000m well depth. Its basic parameters are shown in table 2.

Table 2 Main technical parameters of chinese hydraulic rigs

Model Of Drilling Rig	Lifting Force(kN)	Torque(N • m)	Maximum Drift Diameter（mm）	Power(kW)	Tower Height(mm)	Drilling Depth(m)
XSL12/600	600	20000	Φ500	191	4500	1200

XSL15/680	680	24000	Φ500	268	19490	1500
XSL20/1000	1000	31500/21000	ϕ610	405	15330-22930	2000

In order to meet the drilling needs of various deep wells with deeper drilling depths, China has developed a series of modular rigs. It has produced two types of rigs, 180 tons and 230 tons. It will gradually improve the series of modular rigs with a more profound drilling capacity. The basic parameters of some new hydraulic modular rigs in China are shown in table 3.Examples are shown in figures 7 to 8.

Table 3 Main technical parameters of china's new hydraulic modular rigs

Model	Drilling Capacity(m)	Maximum Load(kN)	Downforce (kN)	Torque(kN •m)	Power Head Stroke(m)	Power (kW)	Transportation Form
XSM1800	4000	1800	320	41	15.2	400x2	Trailer (skid) type
XSM2300	5000	2300	400	49	22.5	570x2	Skid-mounted

Fig. 7 XSL20/1000 rig

Fig. 8 XSM1800 rig

In order to further improve the functions of the full hydraulic rig and make its advantages more prominent, the full hydraulic rig needs to make breakthroughs in the following aspects.

- Automation: Fully automatic drill pipe loading and unloading, automatic drilling control
- Multi-function: Drilling, coring and multi-process drilling
- Modularization: It has the omnidirectional movement of the wellhead
- Large scale: The trend of large lifting force and large diameter
- Electrification: Motor drive, oil power, new energy ·
- Intelligence: Internet of Things, AI remote, adaptive drilling

2.2 Air Compression Equipment

The air compression equipment is the core power equipment of the air DTH hammer drilling technology, accounting for more than 85% of the power of all air DTH hammer drilling technology equipment. The deeper the drilling depth is, the greater the power proportion is; At the same time, the use characteristics of the air DTH hammer drilling technology require that the air compressor must have high reliability and a low failure rate.

Air compression equipment is generally divided into air compressors and boosters. When the hole depth is shallow, only the air compressor can meet the drilling requirements; As the hole depth becomes more profound and the water inflow in the borehole becomes more prominent, the booster must be added to meet the requirements of drilling technology. The application status of the air compressor and booster is introduced as follows.

2.2.1 Air Compressor

The air DTH hammer drilling technology is adopted for drilling medium and deep geothermal wells. The working air volume is usually 90-120 m^3/min, and the working air pressure is generally 55-65 kg. Due to the large air volume and high air pressure, and to reduce the booster's use time, the air compressor with the highest air pressure greater than 34 kg and a maximum air volume more significant than 35 m3/min is usually selected. The large displacement high air pressure air compressor is mainly a screw machine, which is limited by the material and processing accuracy. Currently, the technology of large displacement and high air pressure screw air compressors in China is not up to standard. The large displacement and high air pressure screw air compressor used in the

market is mainly foreign brands, and the brands with extensive usage are Atlas and Sullair. The models of air compressors commonly used for drilling medium and deep geothermal wells are briefly shown in table 4 and table 5.

Table 4 Main technical parameters of Atlas air compressor

Model	Exhaust Volume(m^3/min)	Working Pressure(bar)	Engine Model	Power(kW)
X1300	38.8-35.3	13-30	QSZ13-C550-30	410
Y1300	36.5-32.3	15-35	QSZ13-C550-30	410
Y1200	38.6-32.3	15-35	CATC15ACERT Gll	403
Y1260	41.2-34.7	15-35	CATC18ACERT GIl	429

Table 5 Main technical parameters of sullair air compressor

Model	Exhaust Volume(m^3/min)	Working Pressure(bar)	Power(kW)	Oil Consumption （L/h）
XSK39SD	31.1-36.8	24.1-34.5	410	90
1250XHH-1525Xh	35.1-43.2	24.1-34.5		
1100XH/1300XH	31.1-36.8	20.7-34.5		Unknown

2.2.2 Booster

A booster is mainly in the form of a piston engine. China's low-displacement high-pressure superchargers and large-displacement low-pressure superchargers have mature products, but they still need to produce large-displacement high-pressure superchargers. Presently, the foreign brands of booster commonly used in the industry are Denver and Atlas, while the Chinese brands are XCMG and Enrico. The main booster models and technical parameters used in the air DTH hammer process of some medium and deep geothermal wells at home and abroad are shown in table 6.Examples are shown in figures 9 to 10.

Table 6 Comparison of main technical parameters of booster at home and abroad

Name	Model	Nominal volume flow（m^3/min）	Inspiratory pressure（MPa）	Rated discharge pressure （MPa）	Shaft power （kW）
Gardner Denver	JY500	3	3.0	12.0	Unknown
Atlas	B18TT-62/3000	Unknown	3.5	10	563
	B18-63/3000	Unknown	2.4	20.7	470
XCMG	DFW-2/(33-35)-70	2	3.3-3.5	7.0	160
Enric	SF-2.35/28-70	2.35	2.8	7.0	180
	SF-1.2/2.3-3.35-110	1.2	2.3-3.35	11	180

Figure 9 Atlas B18

Figure 10 Dengfu JY500

2.3 DTH Hammer

In geothermal air DTH hammer drilling, high air pressure, low gas consumption, high reliability and low-frequency slow impact hammers are often used for good deep drilling. Some Chinese manufacturers, such as Black King Kong, New King Kong, and Tianhe Company, have made some progress. For example, the New King Kong's standard DTH hammers parameters are shown in table 7.

Table 7 Main technical parameters of DTH hammer

Model	Using Hole Segments(m)	Borehole Diameter(mm)	External Diameter（mm）	Air Consumption	Working Air Pressure(Mpa)	Speed (r/min)
（ND1080）12in	0-500	Φ295-Φ400	Φ275	1.8Mpa:45.0m^3/min	1.5-3.3	30-55
（ND1080）10in	0-500	Φ254-Φ311	Φ225	2.4Mpa:62.0m^3/min	2.2-3.5	25-50
（ND882）8in	500-1500	Φ200-Φ254	Φ185	1.8Mpa:23.0m^3/min	1.7-3.0	25-50
（ND680）6in	1500-2500	Φ158-Φ203	Φ148	1.8Mpa:17.0m^3/min	1.5-2.6	25-55

2.4 Bit

The bits selected for the air DTH hammer drilling process must have an advanced heat treatment process, high matrix strength, and long service life of drilling teeth, Luo H. et al (2019). The main parameters of commonly used bits in China's geothermal exploitation market are shown in table 8.

Table 8 Main technical parameters of common bit in each well section

Use Well Section（m）	Bit Diameter And Grade Difference(mm)		Number Of Exhaust Holes（Number）	Side Tooth Specification（Quantity * Diameter）	Middle Gear Specification（Quantity * Diameter）
	Diameter	Gradational Difference			
0-500	315	2	4	12*Φ20	29*Φ18
500-1500	220-212	2	2	10*Φ20	14*Φ18
1500-2500	158-150	2	2	8*Φ20	7*Φ18

2.5 Hydraulic Foam Pump

During geothermal drilling with air down the hole hammer, a special foam pump must be equipped to ensure the ability to continuously inject foam fluid into the gas supply system during drilling; It can effectively assist in slag removal and drainage and reduce the back pressure of the impactor to obtain economic footage. Main parameters are shown in table 9.

Table 9 Main technical parameters of foam pump

Model	Speed（r/min)	Pump Pressure(Mpa)	Pump Volume(L/min)	Driving Form	Sports Form
GFP 210-40/25-G	1450-3400	16-25	20-40	Liquid drive	Screw

3. TECHNOLOGICAL ACHIEVEMENTS

3.1 Drilling Depth

Through the air DTH hammer drilling technique, there are multi-hole wells with a drilling depth of more than 2500 meters, and the Lianhua Mountain hot well in Panshi, Jilin, China, has a drilling depth of more than 3000 meters. Through technical research and development, it is estimated that the maximum drilling depth of the air DTH hammer drilling technology can exceed 5000m, Liu M et al (2019),Shi J. et al (2021). The typical geothermal well projects are shown in table 10.

Table 10 Cases of china geothermal well project

Well Name	Well Depth(m)	Outlet Water Temperature (°)	Water Yield (ton/day)

Geothermal well in Fanjing Mountain Scenic Area, Guizhou	2400	50	610
Geothermal well in Dong Township, Guizhou	2500	42	400
Shunhuangshan geothermal well, Yongzhou, Hunan	1820	42	400
Geothermal well in Jitang, Changdu, Tibet	1700	55	1500
Geothermal well in Kangping County, Liaoning Province	2250	34	203
Hunan Fenghuang Ancient City Geothermal Well	1820	50	500
Geothermal well in Xinquan Township, Jiangxi Province	1680	60	1000
Jilin Panshi geothermal well	3000	50	600

3.2 Capacity to Cope with Formation Water Yield.

At present, in the case of geothermal wells drilled with air DTH hammer in China. he formation water inflow of 150 tons/hour can be easily handled within the depth range of 311mm aperture from 0 to 500 meters; The depth range of 216mm aperture is 500-1500m, which can easily cope with the formation water inflow of 40tons/hour; Within the depth range of 1500-2500 meters of 152 mm aperture, it can cope with the formation water inflow of 25 tons/hour.The Well depth structure is shown in figure 11.

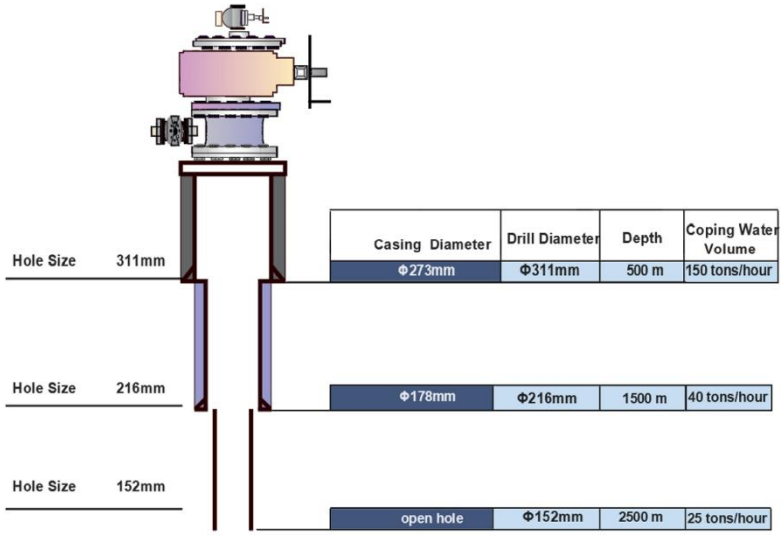

Figure 11 Well bore structure diagram

3.3 Drilling Efficiency

At present, for carbonate, shale, slate and other medium hard formations, the drilling efficiency of air DTH hammer can exceed 40m/h, that of general granite can exceed 18m/h, and that of extra hard granite can exceed 8m/h. The prominent successful construction cases of geothermal wells in China are shown in the table 11.

Table 11 Actual project cases

Well Name	Well Depth(m)	Main Lithology	Major Equipment			Drilling Speed (m/hour)
			Air Compressor	Booster	Rig	
Hunan Fenghuang Ancient City Geothermal Well	1820	Slate	3*39SD+1*Y1200	1*JY500	XSL12/600	15
Hot Spring Well in Heshun County, Shanxi Province	2700	Sandstone and Shale	4*39SD	2*JY500	ZJ30	13
Yichun geothermal well, Jiangxi	1500	Granite	3*Y1200+1*39SD	1*JY500+2*DFW70	XSL12/600	18
Jilin Panshi geothermal well	2800	Granite	4*39SD	1*JY500+1*DFW70	XSL20/1200	16

3.4 Economy

1. The cost of air DTH hammer drilling technology under unit production capacity has been superior to any traditional process.

2. On the premise that the geological conditions are relatively complete and there is no seriously broken stratum, the construction cost per unit production capacity can be lower than that of the traditional process.

4. CONCLUSIONS AND SUGGESTIONS

The air DTH hammer drilling technology has obvious advantages compared with other drilling technologies, which brings dawn for large-scale and efficient exploitation of geothermal energy in the future:

- No damage to the reservoir: It belongs to the underbalanced drilling technology. The drilling process always keeps the wellbore in a negative pressure state, which will not cause damage to the reservoir. It is equivalent to washing the well while drilling, maximising productivity.
- High drilling efficiency: The drilling efficiency of the air DTH hammer drilling process is generally 10-40m/h—the more significant the formation hardness, the more pronounced the drilling efficiency advantage.
- High drilling verticality and low wear of drilling tools: The air DTH hammer drilling technology has the characteristics of low drilling pressure and low rotating speed, so the drilling verticality is high, which effectively reduces the torque of drilling tools, which is conducive to reducing the wear of drill pipes, reducing the bending and breaking accidents of drilling tools, and improving the drilling capacity of the drill.
- Low cost

It is suggested to use the air DTH hammer drilling technology on a large scale in geothermal exploitation in the future, which can significantly reduce the drilling cost target. At the same time, there are still many bottleneck technologies to be broken through in the application and promotion of the air DTH hammer drilling technology, and the following points need to be achieved:

- Promote the intellectualization and popularization of drilling equipment,Randeberg. et al (2012).
- Continuously improve the technical level of the booster.
- Overcome the technical difficulties of a deep well and ultra-deep well DTH hammer.
- Continue to tackle the critical technologies of DTH hammer bits so that the footage life of a single bit in moderately complex formations exceeds 1000 meters and significantly reduces the application cost of air DTH hammer drilling technology.
- Continue to tackle foam drilling technology and improve geothermal deep well air drilling technology to deal with formation water inflow of more than 60 tons/hour.
- Continue to tackle the technical solutions of air DTH hammer drilling in complex formations and significantly improve the applicability of the geological conditions of the process.
- Research and development key technologies of air DTH hammer drilling technology so that the process can deal with formation water inflow of more than 100 tons/hour.
- The goal of significantly reduce the drilling cost through the air DTH hammer drilling technology.

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