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DRILLING TECHNOLOGIES FOR GEOTHERMAL WELLS IN CHINA

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ABSTRACT

China is rich in geothermal resources which include different kinds of geothermal energy with high, low-medium and low temperature. With the development of geothermal source heat pumps (GSHPs), the exploitation of shallow geothermal energy with low enthalpy buried underground within 200 meters has grown rapidly in China. This paper introduces in detail drilling technologies for geothermal wells in China, including high temperature wells in Yangbajing, low-medium and low temperature wells in Beijing and some oilfield wells., Some drilling methods for GSHPs are also briefly discussed, with which the development of geothermal energy can effectively and efficiently be guaranteed.

1. INTRODUCTION

China is rich in geothermal resources and has a long history of use. The High temperature (>150°C) resources, mainly concentrated in Tibet, Tengchong in Yunnan and Taiwan, have been developed for power generation; the low and medium temperatures (<90°C and 90-150°C) resources, distributed over almost the whole of China, are used for space heating, industrial processing, agriculture, aquaculture, bathing and spas (CGSB 2006).

With the development of GSHPs, shallow geothermal energy sources with low enthalpy, which at present are defined in China as resources with temperature lower than 25°C and stored within 200 m depth underground both in aquifers and formations, are playing a more important role in heating and cooling buildings owing to its energy-saving and environment-friendly competitive advantages.

Advanced drilling technologies guarantee the effective and efficient development of geothermal energy which is discussed in this paper.

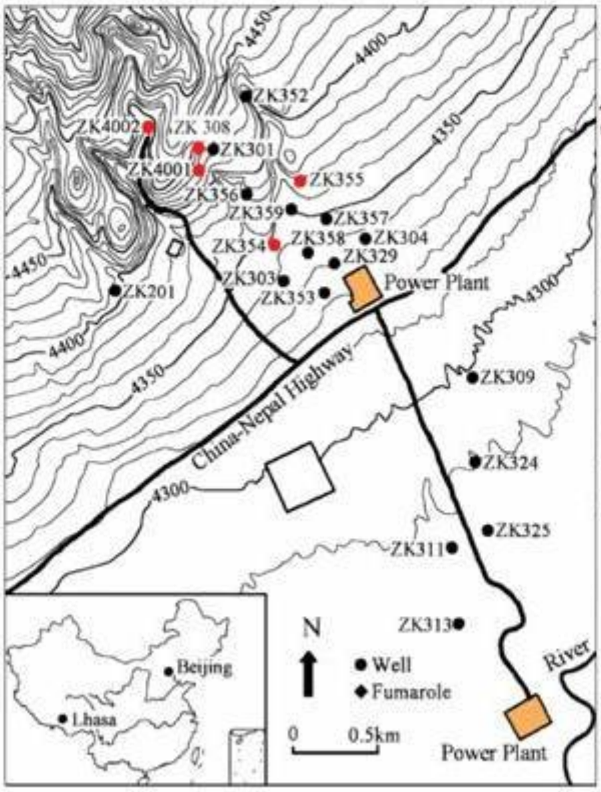


Fig. 1 The location and the topography of Yangbajing geothermal field and the distribution of some drill wells

2. DRILLING TECHNOLOGIES FOR HIGH TEMPERATURE GEOTHERMAL WELLS IN YANGBAJING, TIBET

2.1 The Geological Characteristics of Yangbajing Geothermal Field (Wolff et al. 2007)

The Yangbajing geothermal field is located about 90 km north of Lhasa in Tibet and is divided into a southern and a northern area by the China-Nepal Highway. Figure 1 shows its location and the topography,and the locations of some wells (Zhao et al. 2000).

The Yangbajing geothermal field consists of two reservoirs which are shown in Figure 2. The lithological profiles for some wells are shown in Figure 3 (Zhao et al. 2000).

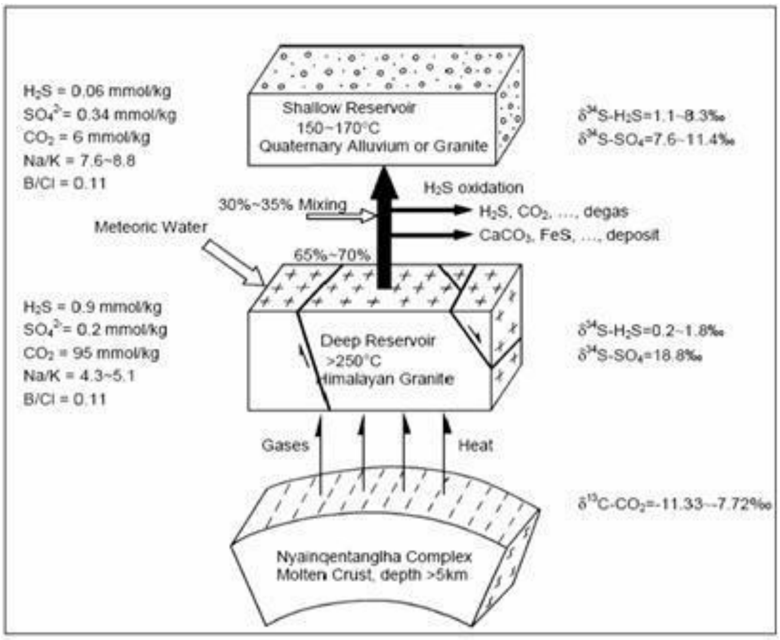


Fig. 2 The geothermal model of Yangbajing geothermal field

The upper geothermal reservoir, which is located in the southern area of this field lies near the surface, at a depth from 180 m to 280 m, and the first signs of the reservoir even can be detected at 30 and 50 meters depth. The lithological profile of this shallow reservoir is mainly composed of quaternary alluvium and granite. The temperature varies from 150°C to 160°C. The water is a mixture of deep geothermal water and shallow cold groundwater, which contains NaCl.

The deep reservoir is located in the northern area of the China-Nepal Highway. The temperature of this reservoir is 251°C at depths between 950 m and 1 350 m, and reaches 329°C at 1 850 m depth.

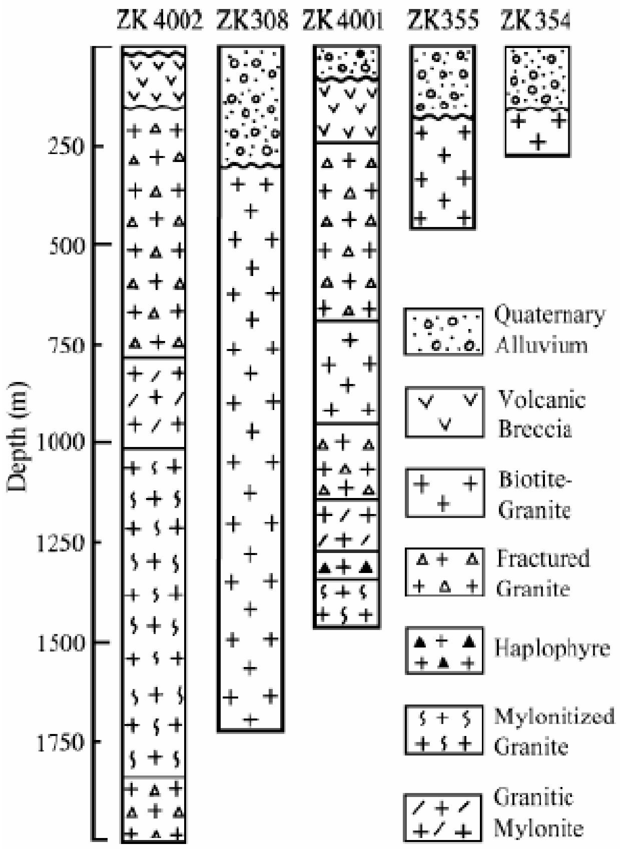


FIGURE 3: The lithological profiles of some wells of Yangbajing geothermal field

2.2 The Exploration of Yangbajing Geothermal Resources

In the 1970's China started exploitation of high temperature geothermal resources in Yangbajing. The first well was drilled in 1975, and until early 1997 four wells (Y-1, 2, 3 and 4) were drilled, all of which had to be abandoned before the designed depth was reached due to serious blowouts and subsequent ground cracks or wellhead explosions, which showed a potential for geothermal resources with high temperature and pressure in this area. In 1976 the first geothermal team of China was founded in Tibet to implement this particular exploration. In the latter half of 1977, the Exploration Technology Institute of Geological and Mineral Ministry was asked to cooperate with the Tibet Geothermal Team to solve the drilling problems. As a result of their common effort the first artesian high temperature wet vapour geothermal well in mainland China was successfully completed. Subsequently about 45 wells in succession were completed, and used to investigate the geophysical, hydrological and geothermal characteristics of an area about 14 km^2 In the 1980's 25 production wells and 13 injection wells were completed, showing that resources protection and sustainable development were getting attention.

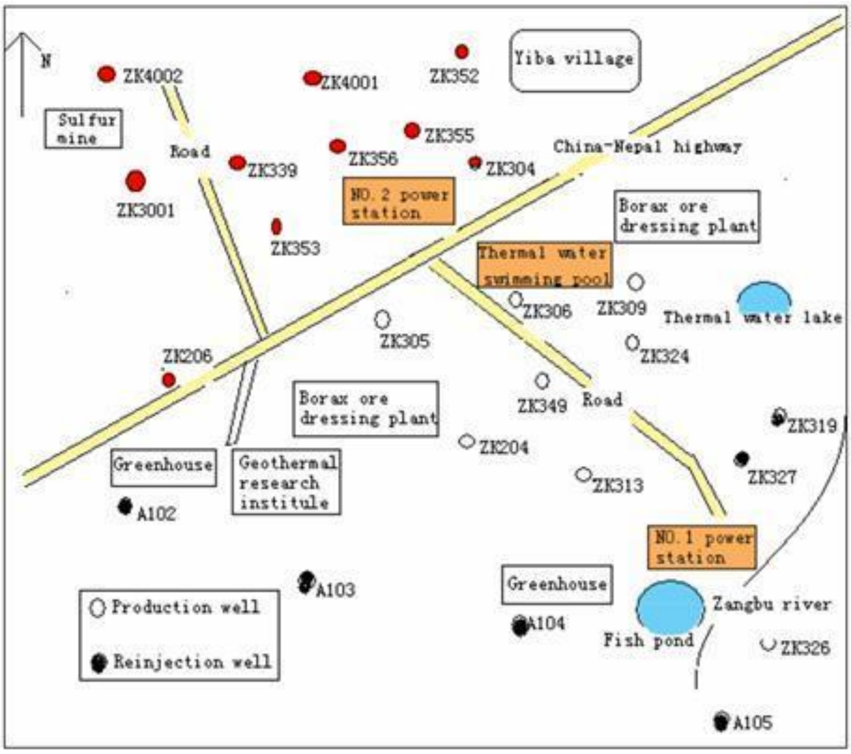


Fig. 4 The location Yangbajing geothermal power station and production wells and injections wells

At present there about 60 total geothermal wells in this geothermal field, of which only 14 are still in use. Figure 4 shows the locations of the Yangbajing geothermal power station and production wells and injection wells, the ten wells marked red provide the hot water consumed for this power station in the northern area. Table 1 shows the reservoir parameters.

Table 1 The reservoir parameters of some wells

well No.	depth (m)	WBT (°C)	WHT (°C)	WHP **(kPa)**	flowrate **(t/h)**	drilled
Zk311	82	157	147	446.8	164	July. 1980
Zk328	108		138	340.3	134.6	July. 1984
zk319	157	161	133	323.6	108	June. 1980
Zk324	90	160	147	431.9	163	Oct. 1982
Zk325	94.5		143	403	159	Aug.1984
Zk314	355	160	132	348	110	Nov. 1978
Zk327	118		116	255	91	June. 1984
Zk304	207	170	133	368.7	98	Sept.1978
Zk329			141	333.4	115.5	1988
Zk333	204	160	133	333.4	106	June 1985
Zk303	336	165	133	343.2	103	July 1979
Zk302	457	172	131	313.8	101	June 1979
Zk332	213	152	130	255	80	May 1985
Zk331	173	158	130	304	85	Sept. 1984
Zk346	258	169	134	304	94	1988
Zk330	213	150	132	264.8	95	Sept. 1984
Zk339	260	162	141.5	299.1	120.1	1988
Zk344	291	167	138	323.6	108.6	1988
a337	300	159	142	313.8	117.2	1988
Zk343	358.5	162	131	205	96	1988

In 2005 a well was drilled to 2 600 m depth and a geothermal resource with about 200°C and 1.2 MPa at a depth of 1800 m was tapped, which signifies the possibility of new and further geothermal exploitation in Tibet.

2.3 The Drilling Technologies used in Yangbajing

2.3.1 The Pressure Gradient in Yangbajing Geothermal Field

The pore pressure and its gradient are preconditions to design drilling parameters for wells, such as choice of a casing program, drilling fluid technology; pressure balanced drilling, prevention of blowout and well killing method and well completion. Figure 5 shows the relation of pore pressure to depth.

$$E_f = \overline{\rho_w} + \frac{\Delta H_0}{Z} \tag{1}$$

where, E_f is equivalent pore pressure; $\overline{\rho_w}$ s the average specific gravity of hot water; $\triangle H_0$ is a pressure constant, expressed as the height of water column, m; and *Z* is the depth to the calculated point, m (Liu. 1992).

TABLE 2: The classification and characteristics of drilling challenges

Classification	**Pressure gradient (MPa/m)**	**Drilling challenges**	**Drilling technologies**
High pressure	0.012-0.023	Readily flowing	Weighted mud, blowout preventer
Normal pressure	0.010-0.012	Readily flowing	Clear water or non- weighted mud, blowout preventer
Low pressure	0-0.010	Flowing air-lift induced	Foam of air; flow drilling with clear water
Low than zero	≦0	Permanent clog	Foam of air; flow drilling with clear water

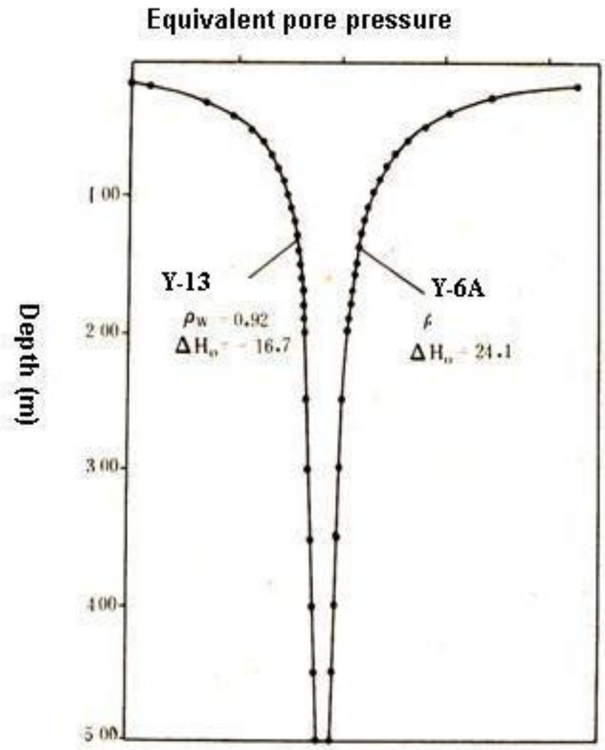


Fig. 5 The reservoir parameters of wells Y-13 and Y-6A

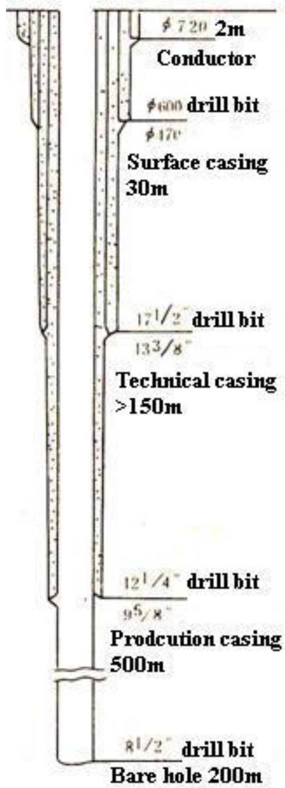


Fig.6. Casing programme for deep well in northern area

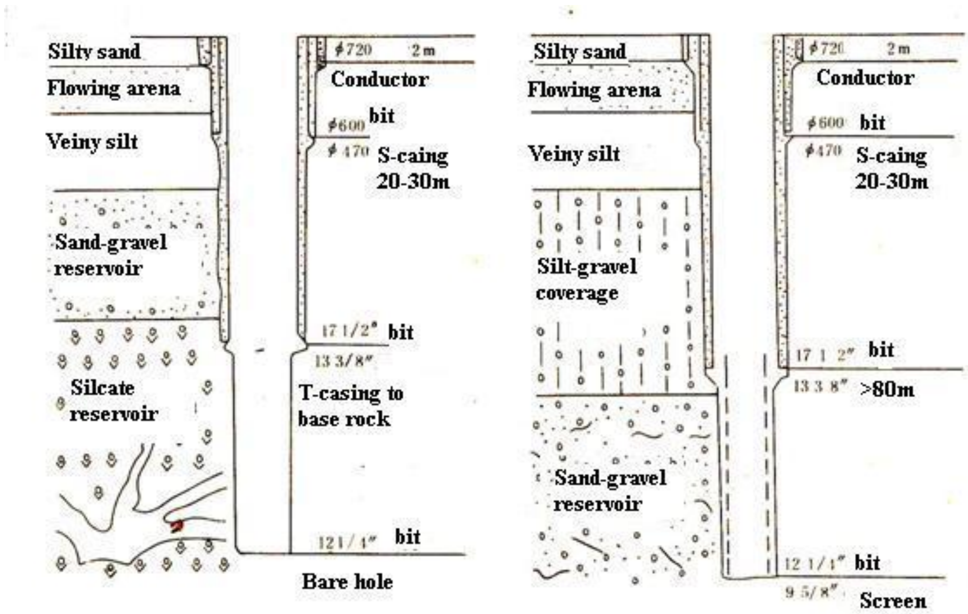
From Fig. 5 and equation (1) it is concluded that this reservoir is shallow and can be met at only 2-3 m depth and thick,from hundreds to thousands of meters. The coverage formation is thin and fragile, which indicates that pressure control is the main drilling challenge, such as preventing blowout with low density drilling fluids and lost circulation with high density mud (Zheng. 2000). The classification and characteristics of drilling techniques are summarized in Table 2. The first three types are common in the Yangbajing geothermal field, i.e. shallow high or low pressure and deep normal or low pressure reservoirs.

2.3.2 The Well Structure and Casing Procedures in the Yangbajing Geothermal Field

Due to the shallow glacier sediment, the lithology and stratum structure are complicated, thus the casing depth is quite variable. In the southern area the geothermal reservoir can be encountered at 30-50 meters depth, where there is a high pore pressure gradient which declines sharply with depth. tThe length of barefoot, the surface casings and the technical casings are limited. Furthermore, the supply and machining of casing with specific screws are difficult logistically. Figures 6 and 7 show the casing programmes for geothermal wells in Yangbajing fields.

2.3.3 The Drilling Fluids in Yangbajing Geothermal Field

Ate conditions of high temperature, heavy changes in pore pressure gradient, and high porosity, drilling fluids circulate at a high temperature in holes with large diameters at relatively low velocity, thus it is important to apply sophisticated drilling fluid technologies to control formation pressures, and the determination of drilling fluid properties and their maintenance are critical to the success of drilling geothermal wells in Yangbajing.



(a) Stable silicate reservoir (b) Unstable sand-gravel reservoir

Fig. 7 The casing procedures in the southern area of Yangbajing geothermal wells

Drilling fluid density is critical for pressure control. The design principle for drilling fluid density is to maintain the stability of the borehole, along with avoiding reservoir damage, demanding that drilling fluid density is greater than that corresponding to the formation pressure but lower than than that corresponding to the fracture pressure, and as close to that corresponding to the formation pressure as possible.

Drilling fluid rheology is very important to guarantee the wells. This determines annular pressure, capacity for carrying cuttings, surge pressure and swab pressure, etc. The funnel viscosity of the drilling fluids was about 22-28 s with annular velocity greater than 0.5 m/s, and 35-45 m/s of annular velocity between 0.1 and 0.3 m/s. For weighted mud the initial gel strength was about 0-5 Pa and the final gel strength 5-10 Pa, whereas the initial gel strength was 0-2 Pa and the final gel strength 2-5 Pa for non-weighted drilling fluids.

API filtration volume was controlled within 5-10 ml/30 min with a 0.1-1.0 mud cake.

The drilling fluid system was basically ferrochromelignosulphonate (FCLS), oxalic- charcoal acid and Na-carboxymethyl cellulose (CMC), which was stable up to 160-170°C. For stable formation and low pressure formation clear water could be used.

In the 1990's wells with higher temperature were drilled, e.g. ZK 4002 with 330°C drilled in 1993 but it failed because of some accidents caused by lost circulation, collapse of upper well sections and a viscosified colloid at high temperature. For the later well ZK4001 a new drilling fluid system was adopted, made up of high quality bentonite, wall stabilizer and lost control additives, with the following properties: 1.05-1.10 g/m^3 of density, 10-20 mPa effective viscosity, 6-10 ml/30min API filtration, and less than 30% relative expansion rate of shale (Zheng. 2000).

3. DRILLING FOR GEOTHERMAL RESOURCES STORED IN SEDIMENTARY BASINS

Low and low-medium geothermal resources stored in sedimentary basin are the dominant geothermal energy sources which can be effectively developed and utilized in China. This type of geothermal conduction system exists widely in China, in the Songliao basin (26×10^4 km^2), Bohai basin (20×10^4 km^2), Hehuai basin (10×10^4 km^2), Subei basin (3.6×10^4 km^2), Jianghan basin (2.8×10^4 km^2), Fenwei basin (2.4×10^4 km^2), Eerduosi basin (3.2×10^4 km^2), Sichuan basin (2.0×10^4 km^2) (Tian. 2006).

The pioneer cities to tap geothermal resources stored in sedimentary basins include Tianjin, Beijing and Xi'an. Geothermal exploitation of oilfields is increasing by integration of the advanced technologies for oil and gas development.

3.1 Development of Drilling Technologies for Geothermal Wells in Beijing

Beijing is one of a few capitals which possess geothermal resources and is located in Huabei plain belonging to the Bohai basin (20×10^4 km^2). Its exploitation of geothermal resources began in the 1970's, and it has been through some development stages. According to the Beijing Land and Resource Bureau now more than 250 geothermal wells with depths from hundreds to 3 600 meters and temperatures from more than 30℃ to 88℃ have been completed (Peng. 2004).

In the beginning of the 1970's Beijing started geothermal prospecting and drilling with well depths from 500 to 1000 meters, for which a core drilling rig XB-1000 was commonly used with BW250/50, BW240/60 and BW240/40 mud pumps. With interval coring of slim hole and multiple stages reaming geothermal wells were completed with about 110-170 mm final borehole diameter. At this stage geothermal wells were completed at low drilling efficiency, for a well of 1 000 m about 8-12 months were needed.

From the late 1970's to the early 1980s some new rigs were introduced to meet deeper wells and more extensive prospecting areas. The typical rigs at this time were a THJ-1500 core drilling rig and a TB-50 petroleum work-over rig, the latter was imported from Romania in 1981, and with it the casing programme was simplified and non-coring drilling could be conducted with roller and blade bits. For a 1500 m well about 1-1.5 months were needed.

From the mid1980s equipment for geothermal drilling, including rig, drill string assembly and completion tool, was developed in a series and drill string, drill collar and casing were standardized. Rigs for water well and oil well drilling are commonly being used, including RPS-2500, RPS-3000, TSJ-660/6, TSJ-2000 and Daqing II-140, etc., with high pump volumes up to 600-1200 L/min, whereas drill strings cover φ73, φ89, φ114, φ127 mm and φ114, φ127 mm dual-wall drill string, and drill collar in φ121, φ146, φ159, φ165, φ178 and φ203, mm. At this stage multiple drilling technologies were adopted with high efficiency and completion quality, and a 2000 m well can be completed with 3-6 months.

Rotary drilling with mud is still the dominant drilling technology for geothermal wells in Beijing, for which the mud properties can be describe as follows: API filtration about 10-15 mL/30min with 0.5-1 mm mud cake, density about 1.05-1.5 g/cm^3, funnel viscosity about 25-32 s, pH about 8-10. For shale formations a filtration reducer should be added to limit API filtration to less than 10 mL and viscosity about 20-25 s, along with the application of a shale shaker and a hydraulic cyclone to control solids.

Two types of drill string assemblies adopted are listed as follows.

Type A:

- φ445mm (orφ311mm)drill bit + 2-4 φ203 mm drill collars + 6 φ178 mm drill collars + n φ127 mm drill rods
- φ215 mm drill bit + 6 φ178 mm drill collars + n φ127 mm drill rods

Type B:

- φ445 mm(orφ311 mm, φ215mm)drill bit + 4 φ159 mm drill collars + 4φ146mm drill collars + 4 φ121mm drill collars + n φ89 mm andφ73 mm drill rods
- φ152 mm drill bit + 6-12 φ121 drill collars + n φ73 drill rods

Technical challenges encountered by rotary drilling with mud are collapse, balling, and lost circulation. Inhibitive drilling fluid technology and greater annular velocity provided with one BW1200 or two BW600/60 pumps are introduced to overcome collapse and balling. Various measures are taken to control lost circulation, such as flow drilling with water, gas-lift reverse circulation drilling technology, foam and gaseous mud, or casing to seal fractured zone.

The gas-lift reverse circulation drilling technology in Beijing is used relatively broadly in Beijing in later years, and this can avoid reservoir damage caused by mud and eliminate lost circulation problems, even well flushing chemicals can be saved. In 1984 Beijing began with testing of gas-lift reverse circulation drilling technology with different rigs in different formations, and then it was applied further. In 1994 the deepest well of 1117.36 meters with this technology was completed, and with which now 2000 meters can be reached. The gas-lift reverse circulation drilling technology needs some supplementary facilities, such as air compressor, gas-water mixture, dual-wall drilling rods, dual-wall kelly and a responsive swivel, for a well deeper than 1000 m an air compressor with greater power is needed, and the sealing of dual-wall drilling string is critical.

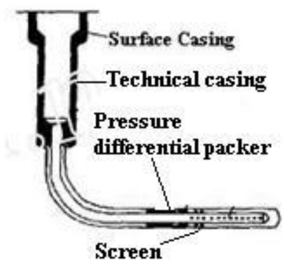


Fig. 8 Scheme of horizontal geothermal well in Daqing Oilfield

The drill string assembly for gas-lift reverse circulation drilling technology is usually as follows:

- φ311mm(φ215 mm, or φ152 mm) drill bit + drill collars + drilling rods + mixture +φ114 mm orφ117 mm dual-wall drill rods + dual-wall Kelly

High pressure jet drilling technology with the jet-type rolling cutter bits for deeper wells was introduced for geothermal wells, and the penetration rate was increased from 1 to 2 times and low solid mud can be used, with which a greater water volume can be further gained. An example is an artesian geothermal well with a flow of 2000m^3/d of 68°C hot water obtained from a 3 800 m deep geothermal well completed with jet drilling technology.

3.2 Geothermal Resources Developed by Petroleum Corporations in Oilfields

it is relatively more favourable for petroleum corporations to tap geothermal resources with oil drilling and completion technologies, such as under-balanced drilling, jet drilling, directional drilling, and perforated hole, etc. Figure 8 shows a scheme for a horizontal geothermal well in Daqing Oilfield (Sun. And Gao 2004).

A further more favourable advantage for the development of geothermal resources is transforming abandoned oil wells into geothermal wells. Zhen and Mo 2007) introduced three methods, including window opening lateral drilling method, perforation method by rebuilding pump chamber and direct perforation method (Figures 9-11), that are characterized by low cost and short construction period. The feasibility of the transformation methods is verified by application examples of transforming abandoned oil wells into geothermal wells in the Dagang and North China Oilfields. The transformed geothermal wells can be used to supply hot water for local production and services, which give an excellent economic and social benefit (Zhen and Mo. 2007).

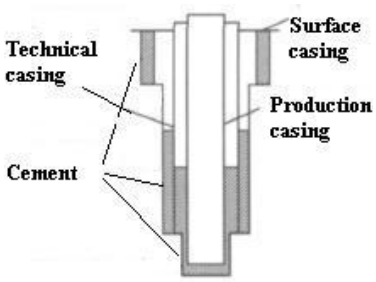
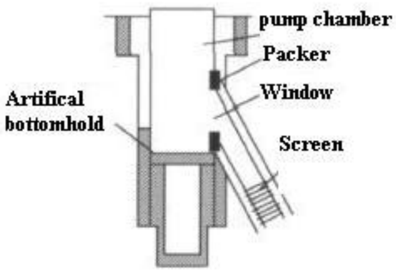


Fig. 9 Section of oil well before transformation



Firg. 10 Section oil well transformed with window opening lateral drilling method

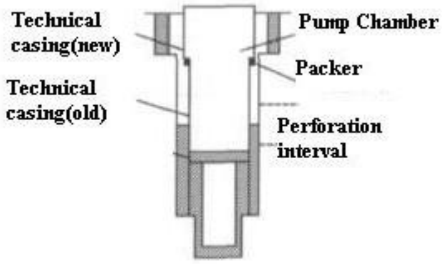


Fig.11 Section of oil well transformed with perforation method by rebuilding pump chamber

4. DRILLING METHODS FOR SHALLOW GEOTHERMAL HEAT PUMP INSTALLATION

Nowadays there is not yet any specific drilling method employed for geothermal heat pump installations in China. Though the GSHP has many unique characteristics for to which some attention should be paid, e.g. for a ground water heat pump, the reverse circulation method can ensure more reliable removal of drill cuttings through the pipe and helps to keep the borehole wall stable, along with gas-lift technology with which reservoir damage from mud can be mitigated (Sanner. 2001).

In large BHE fields, several problems have to be dealt with. To allow the completion of more than 100 BHE in a relatively short time, several drilling rigs have to be on site simultaneously. The available space, the supply of water, BHE pipes and grout, and the disposal of drilling mud all have to be planned diligently in advance. The problem of borehole deviation becomes serious in large plants. No borehole is exactly straight. With single boreholes, no problem arises, but with a number of boreholes close together like in an Underground Thermal Energy Storage system there are. Percussive drilling is particularly sensitive to borehole deviation. In order to avoid intersection of boreholes or damage of previously installed BHE, borehole deviation must be minimized. The only way is to limit the pushing force from the top of the hole, and to increase the weight directly above the drill bit. That way the drill string is kept straight.

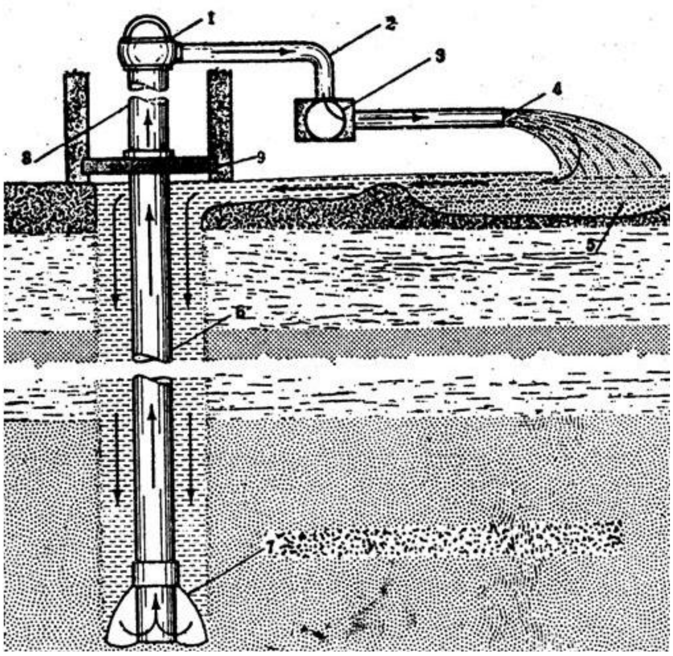


FIGURE: 12: Scheme of reverse circulation drilling

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