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Research on Transforming Abandoned and Low-production wells into Geothermal Wells in Oil-Gas Field in Northwestern Ordos Basin

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ABSTRACT

After years of production, there are a large number of abandoned and low-production wells in oil and gas fields in the northwest of the Ordos Basin. Transforming those wells into geothermal wells could not only utilize abandoned wells and reduce pollution, but also greatly reduce the cost of exploring and developing geothermal wells. According to geothermal geological data and structure characteristics of oil and gas wells in the research area, the advantages and disadvantages of various heat exchanging methods were compared and . The deep borehole heat exchanger (coaxial casing heat exchanger) technology was selected to transfer the oil wells into geothermal wells. As an example of studying, the well name of CX was selected to carry out corresponding analyses. Using numerical simulation methods, a single well heat transfer numerical model has been established, the long-term heat transfer performance of the well was predicted. Based on the prediction results of the numerical model and the existing technical conditions, the well transformation plan is formulated. The construction purpose and requirements were successfully achieved. This study was the first time that the deep borehole heat exchanger technology was used to develop geothermal resources in oil and gas fields in Ordos Basin. The feasibility of transformation plan and corresponding technology was studied. A relatively complete set of well transformation technology was formed. The studied case could act as an example for similar projects. In addition, it could help oilfields achieve low-carbon heating, and provide new methods for petroleum industry to utilize geothermal resources in oil and gas fields.

1. INTRODUCTION

Geothermal energy is a clean and renewable green energy. China's petroliferous basins are rich in geothermal resources. The exploration and development mode of geothermal resources is similar to that of oil and gas [1]. The oil and gas fields have detailed geological data and infrastructure, which are favorable for development. The development of geothermal energy in oil and gas fields can not only save energy and reduce emissions, but also build green and ecological oil fields [2], promote the realization of China's "peak carbon dioxide emissions and carbon neutrality" goal, improve the energy consumption structure, and help ensure energy security.An important factor restricting the development of medium and deep geothermal resources in oil and gas producing areas is the high development cost, mainly due to the high drilling cost of geothermal wells. If the cost of geothermal well construction can be reduced, the development of geothermal resources in oil and gas production areas will be promoted.In the maturing oil and gas field development area, due to resource depletion and high water content of production wells, there are a large number of shut in wells and abandoned wells.

At present, there are two ways to utilize geothermal energy resources of abandoned wells or long shutdown wells, one is "water production and reinjection" mode dominated by heat convection, and the other is "sealed downhole heat transfer" mode dominated by heat conduction.The first method has been tested in recent years. Zhou Xiaoqi et al.(2017) [3] took Magu 6 Well in Dongpu Sag of Zhongyuan Oilfield as the target well, and carried out pilot test of transformation, which proved that the technology of transforming abandoned or shut down wells into geothermal wells is feasible and the cost is low.The "sealed downhole heat exchange" mode is also known as "medium-deep buried pipe heat exchange", which is mainly used to install central tube heat exchanger in the downhole to achieve the purpose of obtaining geothermal energy from the formation through the flow of working medium in the concentric tube heat exchanger.The second method of heat extraction is characterized by obtaining underground heat without exploiting ground fluid, which has less interference to the formation. This technology originates from the exploration in Guanzhong area of Shaanxi Province in the past decade, especially in city of Xianyang, where many new drilling engineering applications have been carried out, but in oil and gas production areas, the existing abandoned wells or long shutdown wells are used for reconstruction, and the relevant engineering practice and research are still few.This paper mainly studies how to use the second heat exchange method to utilize geothermal energy from abandoned wells or long shutdown wells in the oilfield. The research well name is CX. It is located in the northwest oil and gas region of Ordos Basin.

2. GEOLOGICAL AND ENGINEERING CONDITIONS

The groundwater resources in the northwest oil and gas region of Ordos Basin are not rich enough, and the salinity of the formation water is high, which is not conducive to the use of "water production and reinjection" for geothermal resources development. It is a feasible technical route to adopt the "sealed downhole heat exchange" mode to transform abandoned or long shutdown oil and gas wells.Ordos Basin is an important energy production base in China, which gather oil,gas, coal and uranium in one basin and is extremely rich in resources. The basin is located in the west of North China platform, across Shaanxi, Gansu, Ningxia, Mongolia and Shanxi provinces, and is a nearly rectangular superimposed basin.The deep structure in the basin edge is active, the deep structure in the basin tends to be stable, and the cap rock structure is not well developed. According to the structural evolution and thermal evolution history, the areal structure can be divided into six primary structural units. The central part of the basin is the northern Shaanxi slope, and to the east is the west Shanxi flexure zone, to the west is the Tianhuan depression, and to the west is the western margin thrust structural zone, to the north is the Yimeng uplift, and to the south is the Weibei uplift. The research area in this paper is located in the northwest of Ordos Basin, the southern part of Dingbian County in Shaanxi Province is the border area of Shaanxi, Gansu and Ningxia, and structurally, it belongs to the junction of Tianhuan depression and northern Shaanxi slope. After years of oil and gas exploration and development in this area, there are a large number of abandoned wells and long shut down wells.

2.1 Geological and Engineering conditions

The geological stratification of the well site in this study area is shown in Table 2-1. The strata from old to new mainly include Triassic, Jurassic, Cretaceous and Quaternary. The lithology include：

(1) Triassic : The grayish white and grayish green medium fine feldspar sandstone deposited in rivers, lakes and marshes is mixed with thin layers of grayish black siltstone, mudstone and calcareous mudstone, and a small amount of yellow green shale.

(2) Jurassic : White and yellow green sandstone interbedded with gray black, gray green, variegated mudstone and argillaceous shale of different thickness, containing several coal seams, with cross bedding developed.

(3) Cretaceous : Purple red coarse medium feldspathic sandstone, partially mixed with thin mudstone, relatively loose.

(4) Cretaceous : Grayish yellow silty fine sand, silt, silty clay.

Table 2-1 Geological stratification in well site of research area

Geological stratification				Vertical depth	Formation thickness
Group	System	Series	Formation		
Cenozoic	Quaternary			115.0	109.8
Mesozoic	Cretaceous	Upper	K_1Z_4	442.2	327.2
			K_1Z_3	809.7	367.5
			K_1Z_2	1224.8	415.1
	Jurassic	Middle	J_2a	1342.9	118.1
			J_2z	1719.6	376.7
		Lower	J_1y	1993.6	274.3
	Triassic	Upper	T_3y	2676.5	682.6

The formation temperature of the well site in the study area is measured by geophysical logging method, and the measured formation temperature is shown in Figure 2-1. In the figure, the red is the measured logging data, and the blue curve is the result of linear fitting. The average measuring well temperature gradient is 2.89 ℃/hm. The bottom of well temperature is 79.9 ℃ at 2354m. The formation temperature gradient is 2.69 ℃/hm when the depth less than 500m. The formation temperature gradient is 3.109 ℃/hm when the depth higher than 1000m.

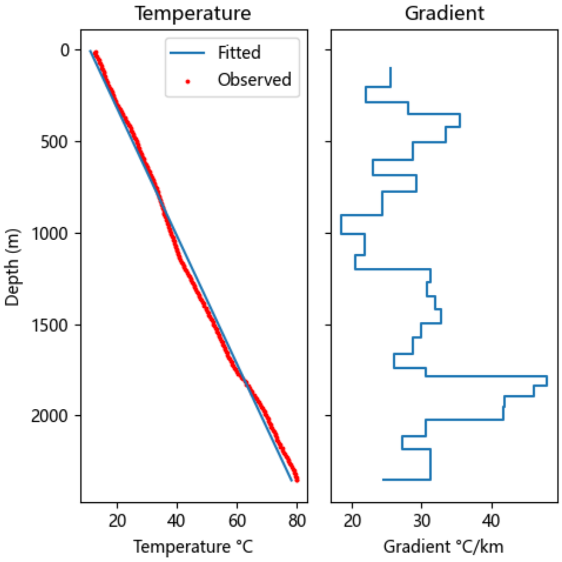

Fig.2-1 Formation temperature gradient of measuring well

See Table 2-2 for the thermal physical parameters of the main formations in the well pad in the research area. The thermal physical parameters are obtained mainly by testing the downhole core and the outcrop samples of the same formation. Due to the limitation of sampling quantity and sampling horizon, thermal physical parameters of some formations are still lacking. Due to the different content of sand and mud in the rock stratum, the thermal physical properties of the samples obtained in the same stratum are also different. Table 2-2 lists the range values obtained from the test.

Table 2-2 Thermal conductivity in well site of research area

Geological stratification		Thermal conductivity		Specific heat capacity	
System	Formation	sandstone	mudstone	sandstone	mudstone
Cretaceous	K_1Z_4	1.36-1.89	/	0.86-1.26	/
	K_1Z_3				
	K_1Z_2				
Jurassic	J_2a	1.97-2.23	1.77-1.87	0.82-0.95	0.94-0.99
	J_2z				
	J_1y	2.04-2.97	1.41-2.07	0.83-0.90	0.83-0.94
Triassic	T_3y	2.49-2.82	2.12-2.34	0.80-0.84	0.82-0.83
Permian	P_2sh	2.07-2.40	1.97-2.71	0.84-0.91	0.84-0.91

Table 2-3 Engineering parameters of the existing abandoned or long shutdown wells

Well depth range（m）	2000-3000						
Casing	Surface casing	Bit diameter（mm）	Casing outside diameter（mm）	Wall thickness（mm）	Steel grade	Setting depth（m）	Cemented to（m）
		311.2	244.5	8.94	J55	100-200	Ground
	Production casing	Bit diameter（mm）	Casing outside diameter（mm）	Wall thickness（mm）	Steel grade	Setting depth（m）	Cemented to（m）
		215.9	139.7	7.72	J55/N80	Total depth driller	Above surface casing shoe
Cement job quality		Qualifiedly					

2.2 Engineering situation of oil well in research area

See Table 2-3 for the main engineering parameters of the existing abandoned or long shutdown wells in the research area. Most of these wells are production wells.The well structure includes the surface casing and the production casing.The outer diameter of one spud in wellbore is 311.2mm, the outer diameter of surface casing is 244.5, and the wall thickness of surface casing is 8.94mm. The outer diameter of the second spud in the wellbore is 215.9mm, the outer diameter of the production casing is 139.7mm, and the wall thickness of production casing is 7.72mm.

3. SIMULATION AND PREDICTION OF HEAT EXCHANGE EFFECT OF SINGLE WELL

3.1 Establish physical model

The abandoned or shutdown oil wells in the research area will be constructed by by medium -deep buried pipe heat exchange technology.See Fig. 3-1 for the well bore and wellhead structure of the heat exchange well after reconstruction, and Fig. 3-2 for the cross section of the heat exchange well.

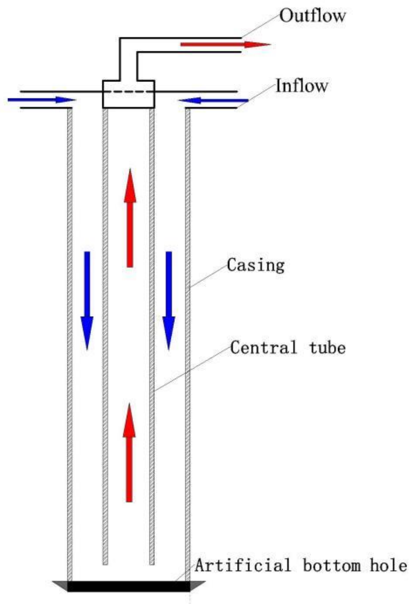

Fig.3-1 Schematic Diagram of Physical Model hole Structure of heat exchange well

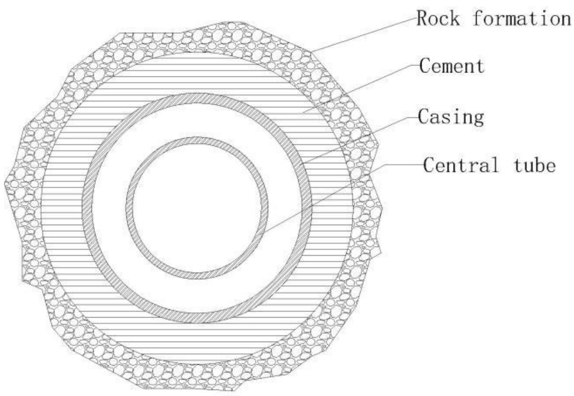

Fig.3-2 Cross section of heat exchange well

3.2 Establish numerical model

OpenGeoSys (OGS) software is used to establish the numerical model. OGS is an open source numerical simulation software based on finite element analysis and object-oriented development.

3.2.1 Mathematical model

The heat exchange control equations of the deep well heat exchange model are mainly composed of two parts, which are used to describe the heat transfer in the well pipe and the heat transfer in the surrounding well cement and rock.

The Ωk is used to characterize different calculation domains after the numerical well.For the upstream pipe (k=ol) and the downstream pipe (k=il),the heat transfer in the well pipe is mainly controlled by the heat convection when the water circulating rate r in the well pipe moves at the flow rate u. The control equation of (k=il, ol) heat transfer in the upper and lower water pipes is equation (1).

$$\rho^r c^r \frac{\partial T_k}{\partial t} + \rho^r c^r \mathbf{u} \cdot \nabla T_k - \nabla \cdot (\Lambda^r \cdot \nabla T_k) = H_k \; in \; \Omega_k \tag{1}$$

Where ρ^r,c^r,T_k,Λ^r, $\nabla$are the water density in the well pipe, the specific heat capacity of water in the well pipe, the water temperature in the pipe, the water circulation flow, the thermal diffusion coefficient of water, the Hamiltonian operator.The boundary condition of equation (1) on boundary Γk is equation(2).

$$-(\Lambda^r \cdot \nabla T_k) \cdot n = q_n T_k \; on \; \Gamma_k \tag{2}$$

Λ^r is hydrodynamic thermal diffusivity of circulating water

$$\Lambda^r = (\lambda^r + \rho^r c^r \beta_L \|\mathbf{u}\|)\delta \tag{3}$$

The governing equation of heat conduction of cement mantle (k=g1, g2,...) is equation(4).

$$(1 - \epsilon^g)\rho^g c^g \frac{\partial T_k}{\partial t} - \nabla \cdot [(1 - \epsilon^g)\lambda^g \cdot \nabla T_k] = H_k \; in \; \Omega_k \tag{4}$$

Where ρ^g,c^g, λ^g,T_k are cement density, cement specific heat capacity, cement thermal conductivity, cement temperature.

$$-[(1 - \epsilon^g)\lambda^g \cdot \nabla T_k] \cdot n = q_n T_k \; on \; \Gamma_k \tag{5}$$

The movement of heat in the rock and soil around the well pipe is affected by both heat conduction and heat convection. Given the flow rate of groundwater as v, the control equation for the process of heat conduction and heat convection in the rock and soil around the well pipe is equation(6).

$$\frac{\partial}{\partial t}\left[\epsilon \rho^f c^f + (1 - \epsilon)\rho^s c^s\right] T_s + \nabla \cdot \left(\rho^f c^f \mathbf{v} T_s\right) - \nabla \cdot (\Lambda^s \cdot \nabla T_s) = H_s \tag{6}$$

Where v,ρ^f,c^f,ρ^s,c^s,T_s,Λ^s,H_s are are groundwater flow rate, groundwater density, groundwater specific heat capacity,density of rock, rock specific heat capacity, temperature of rock, rock thermal conductivity, heat generation or consumption in rock.The boundary condition of is equation(7).

$$-(\Lambda^s \cdot \nabla T_s) \cdot n = q_n T_s \tag{7}$$

3.2.2 Establish numerical model of CX well

The CX well in an oilfield in the research area is taken as the research object. The depth of CX well is 2354m, the bottom hole temperature is 79.9 ℃, the average well temperature gradient of the whole well is 2.89 ℃/hm, the outer diameter of the production casing is 139.7mm, the wall thickness is 7.72mm, and the inner diameter is 124.3mm.Based on the corresponding modeling analysis of CX well, through numerical discretization, the distribution of initial underground temperature field is shown in Figure 3-3, and the ground temperature gradient is 2.89 ℃/hm. The three-dimensional structure of the strata around the study well is shown in Figure 3-3. The buried depth of the overall model is 2650m, and the length and width of the numerical model is both 300m. The CX well at the center of the model.The depth of CX well is 2354m, which is indicated by the red line, as shown in Figure 3-4. See Table 3-1 for the parameters used to build the model.

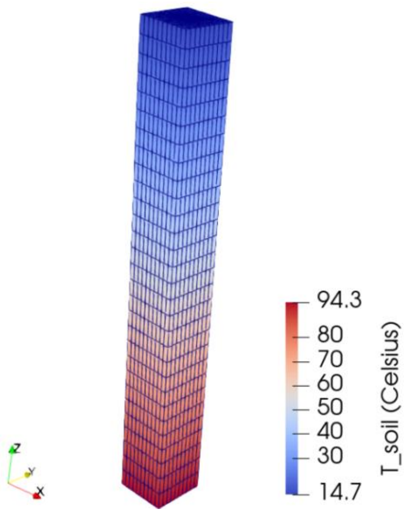

Fig.3-3 Triaxial geometric figure of research well

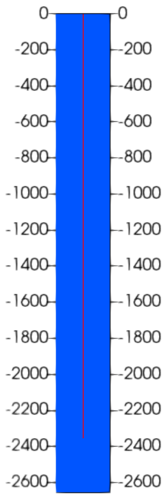

Fig.3-4 Side view of research well numerical model

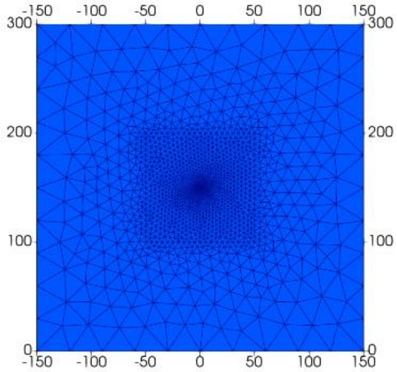

Fig.3-5 Plan view of research well numerical model

Table 3-1 Numerical model Parameters

Parameters	Symbol	Number	Unit
Well depth	L	2354	m
Central tube diameter	d_i	0.072	m
Central tube wall thickness	b_i	0.0135	m
Casing diameter	d_o	0.139	m
Casing wall thickness	b_o	0.00772	m
Central tube thermal conductivity	λ_i	0.2	W/(m·k)
Casing thermal conductivity	λ_o	52	W/(m·k)
Rock average thermal conductivity	λ_s	2.49	W/(m·k)
Rock average specific heat capacity	$(\rho c)^s$	2.4×10^6	J/(m^3·K)
Cement thermal conductivity	λ_g	0.73	W/(m·k)
Cement specific heat capacity	$(\rho c)^g$	3.8×10^6	J/(m^3·K)
Circulating water thermal conductivity	λ_f	0.59	W/(m·k)
Circulating water specific heat capacity	$(\rho c)^f$	4.19×10^6	J/(m^3·K)
Circulating water viscosity coefficient	μ	1.14×10^{-3}	kg/(m·s)
Circulating water Prandtl coefficient	Pr	8.09	/

3.2.3 Simulation and prediction of heat exchange capacity of single well

Using the established model, the single well heat exchange of CX well is simulated and predicted. The actual demand for local heating is 5 months per year. The working condition is set to operate for 5 months per year and shut down for 7 months.

Prediction of heat exchange in linear meter of single well.According to the prediction of linear meter heat exchange of single well under different circulating flow rates, the average annual linear meter power is about 27W/m, 52W/m and 72W/m under the working conditions of 6.0 m3/h, 12.0 m3/h and 30.0 m3/h, as shown in Figure 3-5.

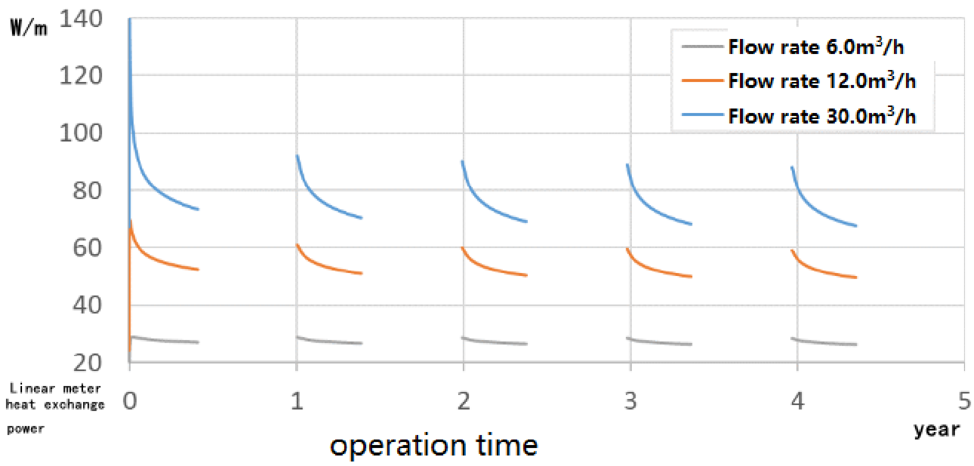

Fig.3-5 Time varying curve of linear meter heat exchange in the first five years under different circulation flows

Prediction of total heat exchange of single well.See Table 3-2 for the prediction of heat exchange of a single well in 15 years of operation at circulating flow rates of 6.0m^3/h, 12.0m^3/h and 30.0m^3/h. It can be seen from the table that the total heat extracted every year increases with the operation time and gradually tends to a stable value. When the circulating flow rate is 6.0m^3/h, the average annual heat exchange is 0.80 $\times$ 10^{12}J, 15 year total heat exchange 12.02 $\times$ 10^{12}J； When the circulating flow rate is 12.0m^3/h, the annual average heat exchange is 1.49 $\times$ 10^{12}J, total heat exchange in 15 years 22.48 $\times$ 10^{12}J； When the circulating flow rate is 30.0m3/h, the annual average heat exchange is 1.98 $\times$ 10^{12}J, 15 year total heat exchange 30.74 $\times$ 10^{12}J.

Table 3-2 Prediction of heat exchange of single well

Running time（year）	**Quantity of heat exchange**（$\times10^{12}$J）		
	Circulating flow rate 6.0(m^3/h)	Circulating flow rate 12.0(m^3/h)	Circulating flow rate 30.0(m^3/h)
1	0.83	1.60	2.24
2	0.82	1.56	2.15
3	0.81	1.53	2.12
4	0.81	1.52	2.09
5	0.80	1.51	2.07
6	0.80	1.50	2.06
7	0.80	1.49	2.03
8	0.80	1.48	2.02
9	0.80	1.48	2.01
10	0.80	1.48	2.01
11	0.79	1.47	2.00
12	0.79	1.47	1.99
13	0.79	1.47	1.99
14	0.79	1.46	1.98
15	0.79	1.46	1.98
Annual average	0.80	1.49	1.98
Total	12.02	22.48	30.74

4. FORMULATION OF WELL RECONSTRUCTION PLAN AND ON-SITE CONSTRUCTION

4.1 Formulate transformation plan of CX well

According to the prediction results of the numerical model and the well parameters of CX well, the reconstruction plan of the well is formulated.Well reconstruction scheme mainly includes well drifting, running string,cementing plug, tag on cement ,the pressure test, clean well , running central tube and flange up completion, as shown in figure 4-1.

Well drifting is to remove debris from the production casing wall, check the deformation and damage of the well wall, and use the gauge ring and tubing string from bottom to top for operation.If the well is blocked in the midway, analyze the situation or print the actual measurement to confirm the cause of the blocking, and then conduct the well drifting after modification.Cementing plug operation shall be carried out after the completion of well drifting. The Cementing plug is used to plug the oil layer and ensure the wellbore sealing. Firstly, running the plugging string to the designed depth according to the requirements, connect the pumping equipment, and mix the cement slurry evenly without impurities.Grade G oil well cement is used to plug the oil reservoir section, and the cement plugging surface is 2300m after plugging.The pressure testing is to verify the plugging effect of the wellbore cement plug. The pressure testing working medium is clean water. The wellbore pressure test is 15Mpa, and the pressure drop is less than 0.5Mpa within 30min.Clean well is required after pressure testing. Clean well is to remove the solid substances or heavy oil and wax adhering to the inner wall of the casing to ensure that the wellbore is clean, so as to facilitate the circulation of wellbore heat exchange working medium fluid during operation.

The central tube is installed after clean well.The central tube is used to provide passage for downhole working fluid circulation and avoid heat conduction of circulating working fluid in upper wellbore circulation.The selection of center tube shall meet the following requirements: ① the center tube shall have the lowest thermal conductivity;②The mechanical properties under actual working conditions shall meet the requirements;③ Low tubing wall surface friction; ④ Certain corrosion resistance.A composite central tube is selected in this scheme, which can meet the above requirements, with thermal conductivity of 0.2W/(m·k), compressive strength of 1.6MPa at 60 ℃ and 1.0MPa at 90 ℃.After the central tube is put into the well, the wellhead device shall be installed to ensure smooth working fluid inflow and return, and the anti drop device shall be installed to prevent falling objects.

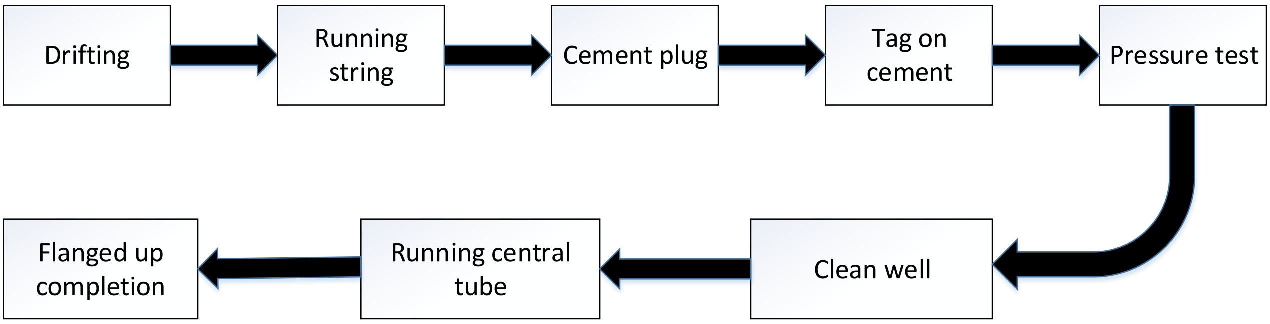

Fig.4-1 CX well reconstruction program flow

4.2 On site transformation of CX well

According to the construction plan, the CX well has been reconstructed. See Figure 4-2 for the CX well wellbore reconstruction design schematic.

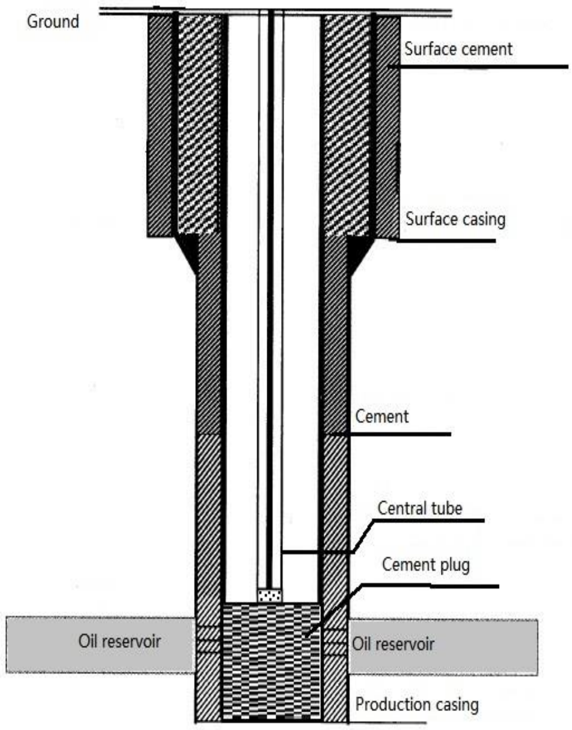

Fig.4-2 CX well wellbore reconstruction design schematic

Fig.4-3 Site construction photos of CX well bore reconstruction； **Fig.4-4 Photos of the Wellhead of CX Well after Reconstruction**

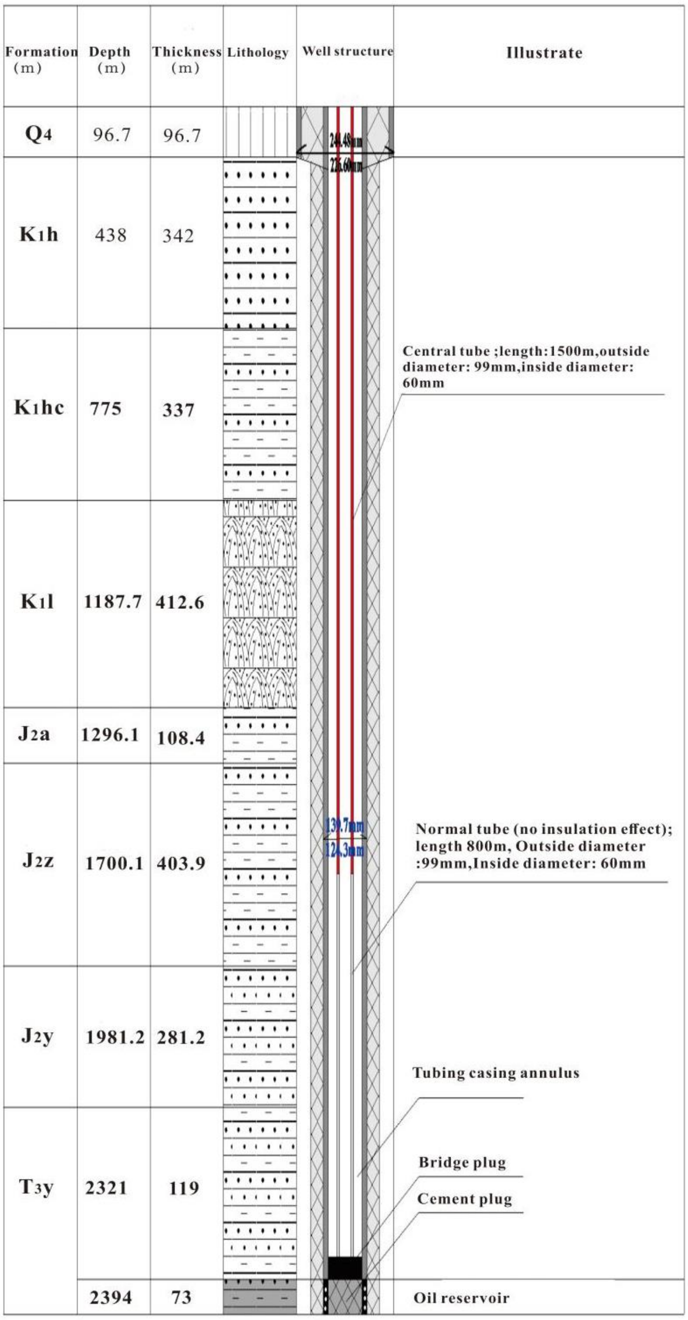

Fig.4-5 CX well stratigraphic conditions and downhole structure after completion of wellbore modification

After the down hole reconstruction, the artificial well bottom depth is 2300m. The construction of underground reconstruction is shown in Figure 4-3. Figure 4-4 after installation of wellhead equipment. Figures 4-5 show the stratigraphic conditions and the down hole structure of the CX well after the completion of the reconstruction.The oil reservoir has been plugged by way of cement plug injection, and the cement plug face is sealed by lowering into the bridge plug.The outside diameter of the second section casing is 139.7mm and the inside diameter is 124.3mm. The length of the center tube is 1500m, outside diameter is 99mm, inside diameter is 60mm. The length of the common oil tube is 800m, outside diameter is 99mm, inside diameter is 60mm.

A simple heat exchange test run was carried out after the completion of the CX well reconstruction. The temperature of the wellhead and the temperature of the heating water at the heating customer side of the test run can be seen in Figure 4-6. The heat exchange test verified the feasibility of converting abandoned oil well or frequently stopped oil well into geothermal well.However, due to the small test heating load, the maximum heat exchange capacity of the CX well has not been verified and will continue to be tested in the next step of the work.

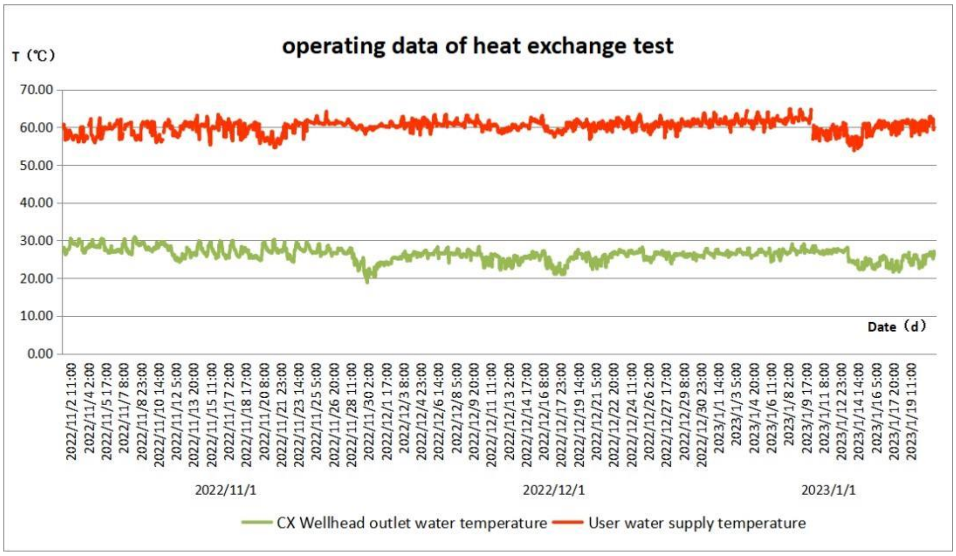

Fig.4-6 Operating data of heat exchange test

5. CONCLUSION AND DEFICIENCY

This paper studies the geothermal utilization of CX well in a well site in the northwest oil and gas development area of Ordos Basin. The geological and engineering conditions of well CX in the research area are introduced. According to the actual geological and engineering parameters of the well, the single well heat exchange and underground temperature field changes of CX oil well in the geothermal utilization mode of medium-deep buried pipe heat exchange are predicted by means of numerical simulation. According to the prediction results of the numerical model, combined with the on-site process and technical conditions, the technical plan for well transformation was formulated, and the single well reconstruction construction was completed.

The average geothermal gradient of the whole well of CX well in the study area is 2.89 ℃/hm, the geological stratification is clear, the rock stratum lithology has a certain thermal conductivity, and the geothermal geological conditions for geothermal development using medium-deep geothermal borehole heat exchanger technology are available.

The well depth of CX well in the study area in this paper meets the requirements, wellhead equipment in good condition, the casing is not failure and perforation, and the cementing quality is qualified. CX well has the engineering conditions for geothermal utilization and transformation using the medium-deep geothermal borehole heat exchanger technology.

Through the method of numerical simulation, using the actual geological and engineering parameters of CX well, a numerical model of single well heat transfer simulation is built, and the prediction of heat transfer of single well for many years of operation is carried out. The prediction results show that the heat transfer of single well after reconstruction can meet the demand.

According to the numerical simulation results and combined with the on-site process conditions, the reconstruction plan of CX well was prepared, and the reconstruction construction of the well was completed according to the plan, which verified the feasibility of the plan. A simple heat exchange test run was carried out after the completion of the CX well reconstruction. The heat exchange test verified the feasibility of converting abandoned oil well or frequently stopped oil well into geothermal well.However, due to the small test heating load, the maximum heat exchange capacity of the CX well has not been verified and will continue to be tested in the next step of the work.

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