Geothermal characteristics of two deep U-shaped downhole heat exchangers in the Weihe Basin, China

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Abstract. Geothermal resources are abundant in the Weihe Basin, which provides great potential for winter district heating in the Guanzhong area in western China. As a demonstration project for deep geothermal exploitation and utilization, four boreholes of over 2,000 m were drilled and paired to form two U-shaped downhole heat exchangers (DHEs) in the Xi’an Depression of the Weihe Basin. In this paper, the borehole equilibrium temperatures of these two DHEs, measured two years after the systems had been completed, are presented. The analysis of the borehole temperatures show that: (1) the thermal and hydrological regimes of the study area are stable, as indicated by the highly consistent borehole temperatures among the four boreholes, both horizontally and vertically. (2) the geothermal gradient range down to the depth of 2,000 m in this area is 3.45 ~ 3.47°C/hm with an average of 3.46 ± 0.01°C/hm, substantially higher than the regional mean and implying a great geothermal energy exploitation potential; the high geothermal gradient anomaly can be attributed to the rather thin crust in the Weihe Basin with a relatively high mantle heat flow and hydrothermal convection systems involving fluid circulation in nearby discordogenic fault zones. (3) the Lantian-Bahe Formation has the features of stable distribution, good aquifer yield, high transmissivity, high permeability and high thermal conductivity, and hence, it is a good hosting stratum to the horizontal section of U-shaped DHEs in this area to maximize heat exchange efficiency and sustainability.

Keywords: Deep U-shaped downhole heat exchanger, borehole temperature measurement, Geothermal gradient, Geothermal anomaly, Weihe Basin

1. Introduction

Geothermal energy is a new type of energy, which is clean, renewable, recyclable and environmentally friendly. The average terrestrial heat flow in Weihe Basin is 78.8 mW·m², 8.2 mW·m² higher than the background value (heat flow in North China) of 70.6 mW·m² and significantly higher than those of other regions in China [1]. This makes the Weihe Basin a very favourable area for geothermal development and utilization. The total heat stored in the Weihe Basin is $3.23 \times 10^{18}$ kcal, equivalent to
4.61 \times 10^{11} \text{tce}, and the available heat is 1.93 \times 10^{18} \text{kcal, equivalent to} 2.76 \times 10^{11} \text{tce} [2]. The large size of this geothermal resource will greatly assist its developability.

Many researchers have discussed the geothermal characteristics of the Weihe Basin and there have been some notable contributions to the understanding of the basin’s geothermal potential. The anomalous distribution of heat flow and geothermal gradients in the Weihe Basin were studied by man-made investigation [3], the relationship between the geothermal field variation and the structure in the Weihe Basin [4], the characteristics of the geothermal field in different areas of the Weihe Basin were studied [5-8]. These studies have laid the foundation for the study of the basin’s geothermometers, but are limited to the shallower depths, and they did not involve the investigation of deep geo-temperatures. The characteristics of geothermal field division and its geological influencing factors in the Weihe Basin were studied [1, 9, 10], but the static well logging time was within 48 hours, the static well time was relatively short, and the well temperature measurement error was relatively large. For the temperature measurement of deep geothermal well (> 1,500 m), the current static well time is obviously insufficient, and the well temperature obtained by logging cannot reflect the original geo-temperature, which affects not only the analysis of regional geothermal field, but more importantly the simulation calculation of DHE heat transfer, and further the design of building heating capacity. In this study, two pairs U-shaped horizontal butted wells of greater than 2,000 m deep have been drilled in the Xi’an Depression of the Weihe Basin. The vertical wells are paired and connected respectively at the bottom by two low horizontal sections of 200 m long to form two U-shaped closed loop DHEs and provide heating for building, which is the first in China and abroad. The borehole equilibrium temperatures of the two DHEs were measured after the boreholes had been completed and static for two years. This study provides the basis for the development of geothermal resources in the Weihe Basin.

2. Regional geology and intersected wells

The Xi’an Depression is one of the sedimentary accumulation centres of the Weihe Basin, which is bounded by four deep and large fault zones, the Weihe fault to the north, the Chang’an-Lintong fault to the east, the Qinling piedmont fault of the Qinling Mountain to the south, and the Yabai fault to the west. The four geothermal wells are located in the Caotan secondary structural depression in the north of the Xi’an Depression of the Weihe Basin (Figure 1).

![Figure 1. Study area location, geological and stratigraphic characteristics of the Weihe Basin.](image)

2.1 Regional strata

Confirmed by stratigraphic wells in this area, the strata from new to old are the Qinchuan Group, Sanmen Formation, Zhangjiapo Formation and Lantian-Bahe Formation of the Neogene. The Lantian-Bahe Formation is the main thermal reservoir in this area (Figure 1).
2.2 Geothermal U-shaped intersected wells
The well R1v and R1x, R2v and R2x drilled in this area are connected at 2,100 m and 2,500 m respectively (Figure 1). Each intersected well has a horizontal section of about 200 m long to increase the heat transfer capacity. It is planned to provide heating for 100,000 m² area of residential and office buildings. Figure 2 shows the structure diagram of R1v and R1x intersected wells. The wellbore itself acts as a DHE. The cold water enters the underground through the inclined shaft, and the heat exchange is completed through the circulation, which provides heating for the building and creates a new way of geothermal development and utilization in this area.

![Figure 2. Schematic diagram of heat transfer in the U-shaped geothermal DHE.](image)

3. Borehole temperature measurement

3.1 Measuring devices and methods
In order to meet the research needs, the SS2560 temperature probe manufactured by Spartek Company of Canada was used. Its temperature measuring range is 0 ~ 150°C, pressure range is atmospheric pressure to 70 Mpa, temperature resolution is 0.001°C, precision was 0.01°C, pressure precision is 5 psi, and sampling frequency is 1 sample/second.

3.2 Temperature measurement results
The total vertical temperature measurement depth of the four geothermal wells tested in this study was 8,738.6 m, of which the vertical temperature measurement depth of well R2v is the deepest (2,406.48 m) and the hole bottom temperature is the highest (96.2°C). The temperature measurements of the four wells are shown in Table 1 and Figure 3. Well R1v temperature measuring section is 6.03 ~ 1,995.87 m and corresponding temperature range is 20.39 ~ 83.10°C; well R1x temperature measuring section is 0 ~ 1,958.90 m and corresponding temperature range is 21.40 ~ 81.74°C; well R2v measuring section is 24.95 ~ 2,377.35 m and corresponding temperature range is 18.35 ~ 95.12°C; well R2x measuring section is 0 ~ 2,406.48 m and corresponding temperature range is 24.35 ~ 96.20°C.

![Figure 3](image)

**Table 1. Temperature measurement data.**

| Well No. | Depth(m) | Well type | Depth measured(m) | Deepest T/°C | Well deviation |
|----------|----------|-----------|------------------|--------------|---------------|
| R1v      | 2,100.00 | Vertical  | 1,995.87         | 83.10        | No            |
| R1x      | 2,206.88 | Horizontal| 1,958.90         | 81.74        | Corrected     |
| R2v      | 2,497.40 | Vertical  | 2,377.35         | 95.12        | No            |
| R2x      | 2,587.90 | Horizontal| 2,406.48         | 96.20        | Corrected     |
The horizontal distances between well R₁v and R₁x and between well R₂v and R₂x are about 200 m. From the comparison of geothermal well temperature curves (Figure 3), the temperature measurement curves of well R₁v and R₁x (after well deviation correction) can be regarded as coincident, and the same is true for well R₂v and R₂x. In addition, the temperature curves of well R₁v and R₂v are basically identical. At the same depth of 1,995.8 m, the temperature of well R₁v is 82.63°C and that of well R₂v is also 82.83°C. For well R₁x and R₂x, their temperature basically coincides, at the vertical depth of 1,958.9 m, the temperature of well R₂x is 81.67°C and that of well R₁x is 81.74°C [11]. Therefore, the borehole temperatures of the two pairs of wells measured in this area (including the horizontal wells) show a high degree of overlapping, indicating that the geothermal and underground heat flow field in this area is very stable and will most likely guarantee successful geothermal development and utilization.

![Figure 3. Comparison of four geothermal well temperature curves.](image)

4. Discussions

4.1 Geothermal gradient calculation

Well temperature data was measured in the four geothermal wells and statistically analysed. Based on this, geothermal gradients were calculated for depths from 100 ~ 2,400 m. With the exception of temperatures from the shallow near surface layers which are easily affected by climate and surface water flows, the temperature measurement curves of all four wells show the characteristics of a conductive geothermal field, which corresponds to the characteristics of thick Cenozoic sedimentary stratum overlying the Weihe Basin. Therefore, the geothermal gradient can be calculated by linear regression.

Vertically, the gradients of the four wells present higher anomaly in the depths of 100 ~ 200 m and 1,400 ~ 1,800 m, and the highest at 1,500 ~ 1,600 m, and present lower anomaly in the depths of 200 ~ 500 m and 500 ~ 1,400 m, of which all gradients are above 4.35°C/m. The geothermal gradient range of single well is 3.45 ~ 3.48°C/m, with an average of 3.46 ± 0.01°C/m.
The results of single-layer calculations show that Lantian-Bahe Formation has the minimum geothermal gradient and Zhangjiapo Formation has the maximum geothermal gradient.

4.2 Geothermal gradient anomaly analysis

Since the Late Eocene, the Weihe Basin had been under continuous tensile stress with lithospheric crust rupture and continuous basin subsidence, this has made it one of the areas with the strongest fault depression occurrence in the Ordos Basin. Lithospheric rupture caused the upper mantle to uplift and the asthenosphere to upwell passively, and mantle heat flow continued to increase. The continuous reduction of the thickness of "hot" lithosphere enables the deep heat flow to transfer to the shallow part more rapidly, and makes the Weihe basin heat flow higher than that in the neighboring Ordos Basin. This provides the most fundamental heat source for the formation of medium-low temperature geothermal field in the Weihe Basin [1]. Within the whole Weihe Basin, different tectonic settings shows different areas of enhanced geothermal energy. Generally, the graben flank is the main geothermal enrichment zone, which was caused mainly by the rise of the asthenosphere during the graben formation process, and the heat is conducted vertically to both sides of the graben and then to the rock blocks there [12]. The Qinling piedmont fault of the Qinling Mountain, Weihe fault and other deep and large faults are major contributors to the heat conduction and geothermal enhancement in the study area, presenting in the form of linear anomalies superimposed on the high regional heat flow.

The study area is located in the secondary structural depression of Caotan which is in the north of Xi'an Depression and adjacent to Weihe deep fault (extending about 330 km). Here, the Moho surface is 33 km deep, which is about 12 ~ 14 km higher than that in the north and south sides of the Weihe Basin. The heat conduction of the relatively high mantle heat flow and a hydrothermal convection system, with water communication with the nearby deep and large faults, combined together in this area (Figure 4), resulting in a high geothermal anomaly with geothermal gradient higher than 3.45°C/hm.

![Figure 4. Characteristics of heat source in the Weihe Basin (modified from [1]).](image)

4.3 Suggestions on horizontal section of intersected wells

The temperature-depth trend chart (Figure 3) shows that at 1,866 m, the temperature is greater than 80°C, the temperature increases with the depth, but the increasing rate is relatively lower further downwards. The pattern of change is consistent with the trend of gradient decreasing from shallow to deep in the basin. The larger the gradient, the greater the decreasing rate in the shallower part of the Weihe Basin, for example, geothermal gradients of well R2Y and R3X is 4.0°C/hm at 1,700 m and quickly reduce to 3.2°C/hm at 2,200 m. The pattern of change is closely related to the control of the deep crust
structure of the basin to its geothermal field. This indicates that the heat source mainly comes from the deep heat flow through conduction and the heat storage is stable below this depth in the area. Furthermore, the Lantian-Bahe Formation is deeper than 1,866 m and widely distributed in the Weihe Basin. It has the features of good aquifer yield properties, high transmissivity, high permeability and high thermal conductivity; it is the main thermal reservoir in the area. Therefore, the part of the Lantian-Bahe Formation, deeper than 1,866 m, can be used as the horizontal section of the intersected well. The high temperature of the surrounding rock ensures maximum heat source and enough heat exchange. Combined with other factors, such as the drilling cost, it is recommended that the horizontal section of the U-shaped well, be completed within the Lantian-Bahe Formation, in this area.

5. Conclusions
The thermal and hydrological regimes of the study area are stable, as indicated by the highly consistent borehole temperatures among the four boreholes, both horizontally and vertically, and the geothermal gradient range down to the depth of 2,000 m in this area is 3.45 ~ 3.47°C/hm with an average of 3.46 ± 0.01°C/hm, substantially higher than the regional mean and implying a great geothermal energy exploitation potential; the geothermal gradient anomaly can be attributed to the rather thin crust in the Weihe Basin with a relatively high mantle heat flows and hydrothermal convection systems, involving fluid circulation in nearby discordgenic fault zones; the Lantian-Bahe Formation has the features of stable distribution, good aquifer yield, high transmissivity, high permeability and high thermal conductivity, and it is a good hosting stratum to the horizontal section of U-shaped DHEs in this area to maximize heat exchange efficiency and sustainability.

Acknowledgments
This study was supported by Shaanxi Provincial Natural Science Foundation of China (Grant No. 2020-JC-YB-2666) and Key Laboratory of Coal Exploration and Comprehensive Utilization, Ministry of Natural Resources (Grant No. SMDZ2019-2). We would like to present gratitude to Todd Sercombe for offering revision and recommendation to the last version.

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