The Influence of Fold Structure on Heat Accumulation in Hot Dry Rocks

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The influence of fold structure on heat accumulation in hot dry rocks

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Abstract Hot dry rock resources as one of the most promising clean energy in the future, with large reserves, renewable and other advantages, since the 1970 s, many countries all over the world have explored and practiced a lot on the exploration and development of hot dry rock resources, however, few studied the heterogeneity of the rock and the underground geologic structures of hot dry rock resources influence domain enrichment regularity of heat transfer mechanism. Therefore, this article considered the thermal conductivity of rock anisotropy, and set up a horizontal stratum and a fold strata 2D geological model, through numerical simulation with the field rock samples indoor triaxial rock thermal conductivity test results, introducing the thermal conductivity of rock anisotropy index $A = K_{\text{vertical bedding}} / K_{\text{parallel bedding}}$ and analyze the underground geologic structures' influence on heat transfer in the rock. The results show that the anisotropy of rock thermal conductivity has no influence on the heat transfer process in underground rock strata when the rock layer is horizontal, which can be regarded as one-dimensional multilayer wall heat transfer. Fold structure will influence the underground heat transfer direction, so it is not simply seen as a one-dimensional multilayer flat wall heat transfer process in numerical simulation. At the inclined interface of rock strata, "heat flow refraction" usually occurs, which further affects the direction of heat transfer. As a result, heat is concentrated in the syncline of the fold structure in the deep and anticline in the middle and deep layers, while the temperature distribution in the shallow layer is almost unaffected by the structure. The research results of this paper are of great significance to the delineation of the target area and the development and utilization of the hot dry rock resources.

Keywords fold structure; hot dry rock; numerical simulation; heat accumulation

Introduction

Among geothermal resources, hot dry rock (HDR) is the high-temperature rock mass with the largest reserves and the most promising geothermal resources, which is at a general temperature over 200°C, a buried depth of 3-10 km, and with little fluid [1-3]. The development and utilization of hot dry rock requires artificial reservoir and extraction of heat from rock mass by heat exchange [4-6], which is also called Enhanced Geothermal Systems, EGS. The research on hot dry rocks began in the United States in the 1970s, and then many countries successively carried out scientific research on hot dry rock. Up to now, there have been 41 research projects on hot dry rock all over

the world[7], but few studies took into account the influence of anisotropy of rock thermal conductivity and structure on the exploration and development of hot and dry rocks. On the one hand, the formation of hot dry rock and tectonic activities are inseparable [8], tectonic activities take matter and energy in underground deep to shallow crust, for the formation of hot dry rock geological conditions and the heat source (such as local melting body and radioactive granite magma). Early American Fenton Hill and Japan Hijiori, Ogachi EGS projects are located around active volcanoes, molten lava as the heat source [9]. The French Soultz EGS is located in the regional extensional environment of the earth's crust thinning of the Upper Rhine Graben, deep underground heat quickly passed to the shallow crust, thus has high heat flow value [10], and Australia Cooper Basin is selected younger radioactive granite as the heat source of hot dry rock reservoir [11]. In mainland China in favor of hot dry rock zone south Tibetan area, western Yunnan Tengchong, southeast coast (instance, Zhejiang), north China, Bohai Basin, the southeast edge of Ordos Basin Fen nutrient-laden graben, northeast (Songliao Basin), and other areas [12] is also because of the strong tectonic activities in China. The east of China has inserted under the subduction of the Pacific Plate, the southeast has inserted under the Philippine Plate subduction, in the southwest, the Indian Plate subducted under the Eurasian Plate, and tectonic activities provided favorable high-temperature geothermal background for these favorable zones [13]. On the other hand, after the underground tectonic activities brought matter and energy from deep earth to shallow crust, the overlying sedimentary strata between the heat source, reservoir and in combination can also affect the heat accumulation of hot dry rock reservoir, thus in the "heat source - reservoir - cap" basin area of the vertical structure of combination is advantage of hot dry rock exploration area [14]. Overlying sedimentary rock, however, its structure is usually homogeneous, especially bedding structure, makes the rocks along the bedding direction will cause the thermal conductivity of the rock anisotropy [15, 16], which affect the heat transfer in underground rock formations, so researchers thought tectonic movement caused by physical - thermal conductivity transverse inhomogeneity is the master factor causing high geothermal [17]. In addition, the heat source - reservoir - caprock vertical favorable structural combination is in terms of macroscopic, and most of the research is based on the exploration and development of hot dry rock considering isotropic and homogeneous temperature of reservoir within the scale of development[18-21], once rock near the reservoir anisotropy of thermal conductivity is relatively obvious, then what will be the mechanism of the influence of structural morphology on the characteristics of the temperature field distribution of heat source, reservoir and cap under the ground, hence, the research on the influence mechanism of underground structure on underground heat transfer will be of great significance to the guidance of hot dry rock exploration and development.

In consequence, this paper based on the anisotropy of rock thermal conductivity, a two-dimensional geological model of horizontal strata and fold structure with "heat-reservoir-cap" vertical tectonic combination was established, and analyzed the influence of the fold structure on the temperature field distribution of underground hot dry rock reservoir and nearby rock strata using numerical simulation, and then the thermal enrichment rule of underground structure near the hot and dry rock reservoir was analyzed, which is of great significance for further exploration favorable underground structural positions in the target area of hot dry rock.

Rock thermal conductivity test

Rock Sample

At present, the hot dry rocks are mainly crystalline rocks with low thermal conductivity anisotropy, such as granite and metamorphic rocks [22], but these rocks will increase the development cost for the current development mode, and they are brittle and prone to cause earthquakes [23-25]. However, the carbonate rocks in sedimentary rocks have favorable natural fractures and easier fracturing and dissolution [22], so the medium-thick carbonate rocks under high thermal background can be the preferred reservoir [26-28]. Therefore, rock samples used in this study were taken from the Yingeryan and Liaojiapo areas in Tianfu, Beibei, Chongqing (Fig. 1), where the upper Permian Longtan Formation, Changxing Formation and lower Triassic Feixianguan Formation are mainly exposed. The structure is an anticline (namely Guanyinxia anticline) with a northeast to southwest strike, the oldest stratum in the core is the Permian Longtan Formation, a broken axial and longitudinal fault is developed in the core, and its strike is consistent with the anticline. A total of four field rock samples were taken, of which two were limestone (Fig. 2b and c) and two were calcareous mudstone (Fig. 2a and d). The colors were greyish-green and greyish-white. In order to facilitate the testing of the triaxial thermal conductivity of the rock sample, the rock sample was cut and processed into $19.5 \times 5 \times 5$ (cm) cubes (Fig. 2e) with the z-axis from the old to the new direction of the formation and the X-axis and Y-axis of the bedding direction.

The experimental instrument is a DRE-III multifunctional fast thermal conductivity tester, using transient plane heat source method, based on TPS transient plane heat source technology, with Hot Disk probe, unit dedicated high-precision instrument testing and sensing technology, and computer high-speed data processing technology to probe for rapid data collection, through the perfect fast calculation, the mathematical model can quickly test the accurate and reliable results. The instrument design is precise and reliable, easy to operate and maintain, and the relative error of test equipment is less than 3%. Finally, through the triaxial thermal conductivity test, the triaxial thermal conductivity data of 19 rock samples were obtained (Tab. 1).

Experimental results and analysis

The results show that the average thermal conductivity of the triaxial thermal conductivity test samples in the X axis was $2.4384 \text{ W}/(\text{m} \cdot \text{K})$, the average thermal conductivity of the Y axis is $2.4478 \text{ W}/(\text{m} \cdot \text{K})$, and the average thermal conductivity of the Z axis was $2.4960 \text{ W}/(\text{m} \cdot \text{K})$. The average specific heat capacity of the rock is $0.3948 \text{ kJ}/(\text{kg} \cdot \text{K})$. On the whole, the difference of the triaxial rock thermal conductivity of the samples is mainly concentrated between 0.1 and 0.2, and the difference is not obvious. Davis et al.[16] defined rock thermal conductivity anisotropy

parameter A as the ratio of the thermal conductivity value in the direction of parallel bedding to the thermal conductivity value in the direction of vertical bedding. For further analysis of the difference in thermal conductivity in this paper, using the same mathematical method, the X, Y, Z ratio of each process was conducted on the thermal conductivity, the thermal conductivity of the rock anisotropy is more obvious (Fig 3) : these experiment samples anisotropy value mainly between 0.9 to 1.1, there was a sample value reached 1.4, in all the 38 data points, 21 points is less than 1, on the whole can be seen that the direction of the vertical level thermal conductivity lower than the thermal conductivity of the bedding direction. Anisotropy of rock thermal conductivity is controlled by rock mineral composition and structural structure [29], in the course of sedimentary diagenesis, the consolidation of mineral deposits is not uniform, as a result, the thermal conductivity of rocks at different locations of the same rock layer will be different [30], at the same time, the bedding structure of sedimentary rocks will make the thermal conductivity of rocks appear different values in the vertical bedding direction and bedding direction. Generally, the thermal conductivity of rocks in the bedding direction is higher than that in the vertical bedding direction [16,29]. Hence, the transfer of heat in the underground rock should show the anisotropy of heat transfer with the anisotropy of heat conduction in the rock. However, it is difficult to simulate the effect of rock thermal conductivity anisotropy on the heat transfer anisotropy in underground rock strata in laboratory, so it is more convenient to simulate by numerical simulation.

Numerical simulation

Geological model

Based on the anisotropy of rock thermal conductivity and combined with the complex structure of underground rock strata, the influence of rock thermal conductivity anisotropy and underground rock strata structure on thermal enrichment of dry hot rock is further studied, in this paper, the intrusion of medium and deep magma several thousand meters underground is only considered, after the intrusive body is cooled, a certain scale of granite hot dry rock reservoir are formed, and the thermal conductivity of rocks is merely considered along the direction of the strata (X) and the direction of the vertical strata (Y, that is, depth Z, a 2D geological profile model of 10×20 km is established, considering whether the magma intrusion formed folds (Fig.4), then the influence of rock thermal conductivity anisotropy and underground structure morphology on geothermal field is analyzed. From top to bottom, they are siltstone, sandstone, mudstone, dolomite, cap layer, reservoir, limestone, crystalline rock as a stratigraphic combination. The following treatments are made for the geological model : (1) the influence of regional faults is not considered, but only a certain vertical structural form is considered; (2) The surrounding rock of crystalline rock and the granite of heat source are isotropic homogeneous rocks; (3) The reservoir and overlying strata show different degrees of anisotropy; (4) All rock strata are considered as pure solids; (5) The transient process after the intrusion of the magma body is not considered, but only the steady-state heat transfer process after the geothermal field reaches stability.

Mathematic model

There are three basic forms of heat transfer in nature, namely heat conduction, heat convection and heat radiation, while the main way of heat transfer in rocks deep underground is solid heat transfer. In geothermics, the underground rock layer is regarded as multi-layer flat wall, and its heat transfer process can be expressed by Equation 1 according to Fourier law:

$$q = \frac{T_1 - T_{n+1}}{\sum_{i=1}^n \frac{D_i}{K_{r_i}}} = -K \frac{dT}{dZ} \quad (\text{Equation 1})$$

q -- Terrestrial heat flow (W/m²)

K_{r_i} -- Thermal conductivity of rock layer i (W/(m·K))

D_i -- Thickness of layer i (m)

T -- Temperature (K)

dT/dZ -- Geothermal gradient (K/m)

Due to the influence of various factors such as the structure and mineral composition inside the rock, the thermal conductivity of the rock is also anisotropic, which will affect the heat transfer of the rock. Without considering radioactive heat generation in rocks, heat conduction in underground rocks can be described in Equation 2:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(Kx \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(Ky \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(Kz \frac{\partial T}{\partial z} \right) \quad (\text{Equation 2})$$

ρ -- Rock density (kg/m³)

c -- Capacity of rock (J/(kg·K))

T -- Temperature (K)

t -- Time (s).

Kx -- Rock thermal conductivity in the X direction (W/(m·K))

Ky -- Rock thermal conductivity in the Z direction (W/(m·K))

Kz -- Rock thermal conductivity in the Z direction (W/(m·K))

Therefore, in the exploration and development of hot and dry rocks, the anisotropy of rock thermal conductivity controls the distribution of underground temperature of rock mass, which cannot be ignored, in this study, only the influence of different thermal conductivity of parallel and vertical layers on heat conduction in underground rock strata is considered, i.e

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(Kx \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(Ky \frac{\partial T}{\partial y} \right) \quad (\text{Equation 3})$$

Boundary conditions

In order to understand the heat conduction process in underground rock strata and take geological factors into consideration, the boundary conditions are set as follows:

(1) Since only the influence of formation structure on heat distribution is considered, all rock strata are treated as pure solid, so the heat transfer process is solid heat transfer;

(2) Considering the influence of regional terrestrial heat flow, 100mW/m² of the magma intrusion and 80mW/m² of the crystalline rock basement are set at the bottom of the geological section as the boundary heat source boundary.

(3) The surrounding rock and the heat source granite are set as isotropic thermal conductivity,

while the reservoir, cap layer and all the overlying strata are set as anisotropic thermal conductivity to varying degrees.

(4) The initial geothermal gradient is set as $2^{\circ}\text{C}/\text{hm}$, and the surface temperature was set as 20°C ;

(5) To be closer to the real geological situation, the top boundary is set as natural convection heat transfer, while the two sides are set as open boundaries.

The relevant thermophysical parameters are shown in Table 2[31-33].

Results and discussion

Characteristics of horizontal strata geothermal field

According to the set of geothermal gradient, the model of formation temperature contour initial situation should be a series of parallel lines, the numerical simulation results show that under the same background of terrestrial heat flow, without fold structure, the underground temperature isoline is basically parallel to the rock layer and has little difference from the initial temperature isoline morphology, the geothermal gradient basically changes little with the horizontal position, but increases from $2^{\circ}\text{C}/\text{hm}$ to about $4.31^{\circ}\text{C}/\text{hm}$ numerically, the limestone reservoir temperature is 279.2°C at a depth of 5km, although the anisotropy of the thermal conductivity of rocks in each rock layer is set, only slight concave changes occur near the contact between the reservoir and the heat source (Fig.5). This indicates that rock thermal conductivity anisotropy has almost no influence on underground heat transfer at the occurrence level of rock strata, and the main direction of heat transfer is from deep to shallow, so the heat transfer in underground rock strata at the level of rock strata can be regarded as a one-dimensional heat transfer process described in Equation 1.

Characteristics of temperature field of fold strata

When the underlying rock layer is a folded structure, the shape of the underground temperature isoline changes significantly, while in the shallow layer (1-2km), the shape of the temperature isoline is parallel and similar to the initial condition; in the middle and deep strata (2-8km), the temperature at the same depth varies with the change of horizontal position, in which the temperature isoline form in dolomite and limestone reservoir strata is concave downwards, while in mudstone, the temperature isoline form is convex upwards. The limestone reservoir temperature is 269.3°C at a depth of 5km, but in the syncline region of the fold structure, the deepest temperature is 376°C , 11°C higher than that of the horizontal rock layer, and the geothermal gradient also changes due to the different tectonic positions. The geothermal gradient at the fold anticline (horizontal position 5km) is about $4.3^{\circ}\text{C}/\text{hm}$, and the geothermal gradient at the fold syncline (horizontal position 14km) is higher, up to $4.45^{\circ}\text{C}/\text{hm}$. Although the syncline of the fold has a higher temperature gradient, the high-temperature rocks are mainly distributed in depth below 4km, while the high-temperature rocks in the anticline are more shallow than the syncline (3-5km), but the temperature isolines at the two wings of the fold are folded at the rock interface (Fig. 6). It can be seen that fold structure has a strong influence on underground heat transfer, especially at the two wings of fold structure, the

distribution of underground strata temperature becomes very complex, and it cannot be simply regarded as a one-dimensional heat transfer process in multilayer flat walls.

In fact, the heat transfer in the medium is generally the same as the wave, when heat flow passes through the rock layer interface with different thermal conductivity, refraction of heat flow is inevitable, which just is the same as refraction of light, the relationship between heat flow and refraction angle is [34] :

$$q_1/q_2 = \cos \theta_1 / \cos \theta_2$$

$$\tan \theta_1 / \tan \theta_2 = K_1/K_2$$

Where K_1 and K_2 are rock thermal conductivity, q_1 and q_2 are heat flow values, and θ_1 are θ_2 included angles of boundary normal. Therefore, when the heat from the local depth is transferred to the shallow surface, the heat flow refraction will occur in the inclined rock strata due to the difference in the thermal conductivity of the rocks, and the thermal conductivity of each rock layer in the model in this paper is different to some extent. The two wing layers of folded rock are inclined, in addition, thermal conductivity anisotropy is set in each rock layer, and the mudstone anisotropy value is large, thus the following processes exist (Fig. 7).

1) When heat source heat is transferred to limestone reservoir, on the one hand heat flow refraction will occur, and on the other hand, heat will be preferentially transferred along the direction of high thermal conductivity, so that the distribution form of reservoir temperature isoline is opposite to the structural form;

2) In the reservoir and mudstone cap rock, due to the existence of a certain formation dip angle, there is a great difference in their thermal conductivity, so the heat is preferentially transferred along the plane direction to the structural low point of the fold, resulting in a rapid increase in the temperature in the deep part of the syncline. Due to the rapid rise of temperature in the syncline, it continues to transfer heat to the shallow part on the one hand and to both sides on the other.;

3) The heat continues to be transferred to the dolomite rock layer, which forms a temperature isoline form opposite to the structural form. Since the dolomite is covered with mudstone with strong anisotropy, the heat will be transferred to the direction of the tectonic high point;

4) When it comes to the shallow rock strata, the temperature of the rock strata basically does not differ much, and the heat will no longer be transferred preferentially. Therefore, the temperature of the shallow rock strata will no longer changes with the structural morphology, thus forming the underground temperature distribution characteristics of the folded rock strata model. It is because of the refraction of heat flow and the anisotropy of heat conduction that the underground rock stratum has different temperature distribution characteristics under the same geological background.

Therefore, in the study of geothermal geological features in the region, the underground rock strata cannot be simply regarded as multilayer flat walls and the underground heat transfer process can be described by equation 1, but the thermal conductivity anisotropy of underground rock strata should be considered and the heat transfer process in underground rock strata should be analyzed in combination with the underground structural morphology. According to the numerical simulation results, the limestone as a hot dry rock reservoir, fold structure has a certain control effect on the accumulation of underground heat, the high position of the mid-deep structure will be the heat accumulation area, if the overburden layer on the reservoir has strong anisotropy (the thermal conductivity in the direction of the parallel layer is greater than that in the direction of the vertical layer), the low position of the deep structure will also become the heat accumulation area. Therefore,

the uplift of the basin will be the most favorable heat accumulation area.

Conclusion

In this paper, the triaxial thermal conductivity of rocks in the field is tested, the corresponding geological model is established based on the experimental data and the following conclusions can be obtained through numerical simulation:

1) The heat transfer in the formation is anisotropic and is not simply a one-dimensional heat transfer process from deep underground to shallow surface. Unless it is at the level of the rock layer, it can be directly regarded as a one-dimensional heat transfer of multilayer flat walls;

2) Due to the difference between rock thermal conductivity and anisotropy of thermal conductivity, heat flow refraction will occur at the two wings of folded structure, and heat will be transferred preferentially along the direction of high thermal conductivity of rock, so that the formation temperature will be different at different levels at the same depth;

3) Fold structure plays an important role in controlling the heat concentration of underground rock strata, especially in the vicinity of hot-dry rock reservoirs. Heat concentration of the deep layer (below 5km) usually occurs in the syncline of the fold, while in the middle and deep layer (3-5km) occurs in the anticline.

4) In the exploration of hot dry rock, the underground structure, especially the structural characteristics near the reservoir, should be considered. The uplift of the basin basement is the most favorable structural location for heat accumulation, and will also be the most favorable structural location for the exploration and development of dry hot rocks.

Declarations

Availability of data and material

All the data in this paper is in file "Table1".

Competing interests

In this paper, indoor triaxial rock thermal conductivity test was carried out on the field rock samples. We consider the anisotropy of rock thermal conductivity. Combined with the related theories of structural geology, geothermy and heat transfer, the influence mechanism of folded structure in two-dimensional section on the law of heat accumulation in dry hot rocks is analyzed by numerical simulation, which is of great significance to the exploration and development of hot dry rock.

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Authors' contributions

Sample collection and thermal conductivity test are all by Leng Wenxiang, and then Hu Ming and Wang Yingchun guide Leng Wenxiang through the writing of this paper.

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Figures

Figure 1

Figure 2

Figure 3

(a) Geological model of horizontal stratum

(b) Fold geological model

Figure 4

Figure 5

Figure 6

Figure 7

Supplementary Files

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