Research Article

Heat Flow Correction for the High-Permeability Formation: A Case Study for Xiong’an New Area

Zhutong Wang,1 Peng Gao,2 Guangzheng Jiang,3 Yibo Wang,3 and Shengbiao Hu3

1School of Mines, China University of Mining and Technology, Xuzhou 221116, China
2Oil & Gas Survey, China Geological Survey, Beijing 100083, China
3Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

Correspondence should be addressed to Peng Gao; ps1_gao@163.com

Received 20 April 2021; Accepted 17 July 2021; Published 25 August 2021

Academic Editor: Songjian Ao

Copyright © 2021 Zhutong Wang et al. Exclusive Licensee GeoScienceWorld. Distributed under a Creative Commons Attribution License (CC BY 4.0).

The Xiong’an New Area is located at the western Bohai Bay Basin, 150 km south of Beijing, China. The area has tremendous high heat flow value within the sedimentary layer, and the average value can reach 90 mW·m⁻² within the Niutuozhen Uplift. However, combining the basal heat flow at the top of the metamorphic layer with the heat flow value which was contributed by the radiogenic heat production from the overlying formation, the surface heat flow value was only 65.1 mW·m⁻² in this area. Thus, the heat flow value within the sedimentary layer was greatly influenced by other factors. In this study, based on the continuous temperature measurements data from 4 boreholes, thermos-physical parameters (conductivity, radioactive heat production, density, and heat capacity) from 90 rock sample measurements, and the regional stratigraphic development, a two-dimensional thermal-hydraulic modelling was carried out to study the influence of the heat refraction and groundwater convection on the heat flow value. According to calculation results, the heat flow disturbance caused by heat refraction was 10 mW·m⁻², and the disturbance value was 20 mW·m⁻² for the groundwater convection. Furthermore, when the high-permeability layer thickness was a certain value, with the increasing high-permeability layer buried depth, the influence of the groundwater convection on the temperature field which was used for the heat flow calculation became weak. While when the high-permeability layer buried depth was set up, the influence of the groundwater convection on the above temperature field became stronger with the increasing high-permeability layer thickness.

1. Introduction

Terrestrial heat flow is one of the most important parameters for analysis of the temperature field, thermal structure of lithosphere, and regional geodynamics process [1–4]. Therefore, measurement and calculation of high-quality heat flow value are indispensable in theoretical and applied geothermal research. Usually, heat flow was calculated by multiplying the geothermal gradient with the thermal conductivity. One important factor for understanding heat flow value is the recognition that only the conducted heat flow can be used for lithosphere thermal structure analysis. However, many influencing factors can cause the heat flow value perturbations, such as the groundwater circulation, abnormally high radioactive heat generation, topography, erosion, and sedimentary [5–7]. These factors will affect the heat flow by influencing the geothermal gradient or thermal conductivity value, which caused the heat flow anomaly high or low. So, when we use the above heat flow value to analyze the thermal structure of lithosphere and regional geodynamics process, a wrong calculation result will come. Therefore, a correct understanding of these factors’ influence on heat flow value can be beneficial for geothermal-related research.

Different scholars had carried out the heat flow correction work, which tried to remove these factors’ influence on heat flow value as much as possible. For example, Mausure et al. [8] proposed a heat flow correction method for the presence of groundwater convection. Xiong et al. [9] analyzed the refraction and redistribution of heat flow on the near-surface structures with the lateral thermal conductivity variations, and the conclusion was drawn that the refraction can influence the temperature field and, in particular, heat flow
distribution in the upper sedimentary layer. Henry et al. [10] talked about the heat flow distribution under the presence of topography; three represented examples were illustrated in the article. Afanda et al. [11] discussed the influence of magmatic activity on subsurface temperature, and Serban et al. [12] studied the paleoclimate influence on the temperature field. The abovementioned heat flow correction methods can make the calculated heat flow value more reliable to reflect the regional thermal background, thermal structure, and geodynamics [8–12].

In this article, we will take the Xiong’an New Area as an example to discuss the influence of the existence of heat refraction which was caused by the lateral thermal conductivity variations between the sandstones with the dolomite on the shallow temperature distribution, and the influence of groundwater circulation within the high-permeability formation on the heat flow calculation was also considered in this study. Xiong’an New Area is located in the middle of Jizhong Depression, western Bohai Bay Basin. Controlled by the tectonic thermal events in Meso-Cenozoic, a higher thermal state of the lithosphere was generated in Bohai Bay Basin which the average heat flow value was 69 mW·m⁻² around [13, 14]. However, while in research of geotherm, abnormally high heat flow value was detected in Xiong’an New Area; especially in the Niutuozhen tectonic unit, the average heat flow can even reach 90 mW·m⁻² [15, 16]. When we use this heat flow value for the regional thermal structure analysis, such as the crustal temperature, an incredibly high temperature field will yield, making it very hard to understand. So, the heat flow value calculated from the sedimentary layer in this area may be influenced by several factors, especially the existence of the high-permeability dolomite layer, which makes the heat flow value within the upper sedimentary layer not suitable for the regional thermal structure calculation.

Luckily, the formation temperature of metamorphic in this area which was under the sedimentary and dolomite layers was measured in this study, and after calculating, the heat flow value was 63.8 mW·m⁻² within the upper metamorphic layer; by accumulating this heat flow value with the heat flow which was contributed by the radioactive heat generation rate from the upper sedimentary and dolomite layers, the surface heat flow was 65.1 mW·m⁻² around in this area. Huge heat flow value difference between the metamorphic layers with the sedimentary layer in this area may be caused by the stratum distributions and the geological characteristics of the formations. According to the actual measurement data, which included the drilled formation, the thermal conductivity, and radioactive heat production rate of rock in this study, the stratum of Xiong’an New Area has two typical characteristics. One is the tremendous lateral thermal conductivity variations between the dolomites with sandstone which can cause strong thermal refraction, and the other is that the dolomite has abnormal high permeability which can allow the groundwater circulation. These two parts were the main reasons which caused the high heat flow value within this area, and we will talk about the influence of these two parts on heat flow calculation and explored the correction method for them.

Besides, the regional heat flow distribution characteristics can also be an important basis for the geothermal resource exploitation. Prompted by the discovery of underground hot water while in research of geotherm, development and utilization of geothermal resources have been carried out for many years in this area, which was mainly used for the agriculture and district heating. The thermal reservoir mainly included the sandstone and carbonate layers. Especially for the dolomite thermal reservoir, it has high formation temperature and permeability, and the high enthalpy and groundwater circulation leads to the abundance of geothermal resources in this reservoir, which was treated as the representative for the hydrothermal resources. Given the abundance of geothermal resources there, geothermal energy will definitely play an important role in the construction of Xiong’an New Area.

2. Geological Setting

Xiong’an New Area is located in the middle of Jizhong Depression, western Bohai Bay Basin. Affected by the subduction and roll-back subduction of the pacific plate in Meso-Cenozoic, the stratum had undergone intensive folding and extension. Especially during the Mesozoic, the stratum was uplifted and then had been highly eroded [15, 17, 18]. Undulation of bedrock makes the secondary structural units developed well in this area, such as the Niutuozhen Uplift, Rongcheng Uplift, and Baxian Depression [19, 20]. The huge difference in the Cenozoic sedimentary thickness between these substructural units results in the great lateral thermal conductivity variations, which make the heat refract to the substructural uplift area [9]. Because the Xiong’an New Area had undergone multiple epoch structural movements, faults developed well in this area, such as Daxing Fault, Niudong Fault, Niunan Fault, and Gaoyang Fault (Figure 1). These faults mark the boundary between the uplift and depression, such as the Niudong Fault which forms the division between the Niutuozhen Uplift and Baxian Depression. Depth of the faults varies a lot; some of them can even reach the crystalline basement ([21, 22]). As for the stratum, the Cenozoic strata were mainly the sandstone and clay which are overlying on the Proterozoic dolomite directly, and the Archean strata were mainly the gneiss that was under the dolomite stratum. The Mesozoic and Palaeozoic strata were totally missing in this area (Figure 2).

3. Data

3.1. Temperature Logging. The continuous steady-state temperature measurement was one of the most critical parts for high-quality heat flow determination, so system temperature measurements had been carried out for 4 deep geothermal boreholes in this study, and detailed formations for these boreholes are shown in Table 1. As the time between the cessation of drilling and the temperature measurement had been exceeded more than one year, the effects of drilling-induced thermal perturbations can be negligible, which the measurement temperature data can be considered
as the equilibrium temperature of formation. The borehole temperatures were measured by using a cable system, consisting of a 42.9 mm diameter sensor (max. temperature 176°C, max. pressure 124 MPa) and a 5000 m long cable (2.54 mm single conductor); the response time of the sensor probe due to the thermal mass of the sensor assembly is...
The depth interval in the brackets, such as the 400–3500 m, means the section for geothermal gradient calculation.

Table 1: Detail information for boreholes.

| Borehole | Longitude | Latitude | Depth (m) | Bottom hole temperature (°C) | Geothermal gradient (°C/km⁻¹) | Sandstone | Carbonate | Metamorphic |
|---------|-----------|----------|-----------|------------------------------|------------------------------|-----------|-----------|-------------|
| AX2     | 115.8208  | 38.8678  | 0–3500    | 123.10                       | 32.2 (400–3500 m)             | None      | None      | None        |
| X35     | 115.9524  | 38.8663  | 0–3750    | 121.62                       | 29.5 (850–3500 m)             | None      | None      | None        |
| X01     | 116.0934  | 38.9550  | 0–2991    | 99.74                        | 48.6 (200–1200 m)             | 0 (1200–1700 m) | 18.6 (1800–2900 m) |
| WQ1     | 116.0479  | 38.9630  | 0–1798    | 75.24                        | 48.6 (200–1200 m)             | 0 (1200–1750 m) | None      | None        |

The measurement results show that the radiogenic heat production of the formation to the surface heat flow, the measurement work of concentrations of uranium, thorium, and potassium in the rock samples was measured in this study. Combining the concentration values of the radioelements with the rock density data for each sample, the radiogenic heat production value was calculated by using the following equation [30, 31]:

\[
A = 10^{-5} \cdot \rho (9.25 C_U + 2.56 C_{Th} + 3.48 C_K),
\]

where \(A\) is the heat production in \(\mu W m^{-3}\), \(\rho\) is the rock density in kg m⁻³, \(C_U\) and \(C_{Th}\) are the concentrations of U and Th in ppm, and \(C_K\) is the content of K in percentage, respectively.

The measurement results show that the radiogenic heat production of the sandstone ranges from 0.15 to 2.02 \(\mu W m^{-3}\) with an average value of 1.08; for the dolomites, the value was from 0.02 to 1.58 \(\mu W m^{-3}\) with an average value of 0.32. Moreover, for the metamorphic, the value was from 0.16 to 4.18 \(\mu W m^{-3}\) with an average value of 1.07. Detailed
information for radiogenic heat production and thermal conductivity of different rock types is listed in Table 2, where the number in the brackets gives the number of the measured samples and the SD means the standard deviation.

3.3. Heat Flow Determination. Basing on the Fourier’s law, the heat flow value was calculated by multiplying the geothermal gradient with the thermal conductivity value (Equation (2)) [32]. On the other hand, the surface heat flow value can also be calculated by combining the basal heat flow value at the bottom of formation with the heat flow value which was contributed by radiogenic heat production within the overlying formation (Equation (3)) [33].

\[ Q = \lambda \frac{dT}{dZ}, \]  

(2)

\[ Q_b = Q_0 - A \cdot \Delta Z, \]  

(3)

where \( Q \) is the heat flow in mW·m\(^{-2}\), \( dT/dZ \) is the temperature gradient in °C·km\(^{-1}\), \( \lambda \) is the thermal conductivity, \( Q_b \) and \( Q_0 \) were the heat flows at the bottom and top of the formation, \( \Delta Z \) is the formation thickness in km, and \( A \cdot \Delta Z \) is the heat flow value which was contributed by the overlying formation.

According to the methods mentioned above, we calculated the heat flow value for these 4 boreholes. In the AX2 borehole, the heat flow was calculated from the depth interval of 400 m down to the 3500 m, in which the rock type was mainly the sandstone and the heat transfer was dominated by the heat conduction. The temperature gradient of this interval was 32.2°C·km\(^{-1}\) and the thermal conductivity was 1.82 W·m\(^{-1}\)·K\(^{-1}\) as mentioned above, so the surface heat flow value was 58.6 mW·m\(^{-2}\) for this borehole by using Equation (2). The same method was also used for the X35 borehole, and the heat flow value was 53.4 mW·m\(^{-2}\). Here, we focused the heat flow value on the X01 borehole. Firstly, when we used Equation (2) for heat flow calculation within the sedimentary layer in this borehole, the heat flow value was 88.5 mW·m\(^{-2}\) which the geothermal gradient value was 48.6 and the thermal conductivity value was 1.82. On the other hand, when we used the metamorphic layer for the heat flow calculation, which the gradient value was 18.6 and the thermal conductivity value was 3.43, the value was 63.8 mW·m\(^{-2}\). Using Equation (3), by adding up the value 63.8 mW·m\(^{-2}\) with the heat flow which was contributed by the radiogenic heat production elements within the formation that was overlying on the metamorphic layer, the surface heat flow value was only 65.1 mW·m\(^{-2}\).

From the above discussion, we can find one interesting question about the surface heat flow value of the X01 borehole. That is, when we use Equation (2) to calculate the heat flow value within the sedimentary layer, the value was 88.5 mW·m\(^{-2}\). However, when we use Equations (2) and (3) for the calculation, the surface heat flow value was only 65.1 mW·m\(^{-2}\). The huge difference between these two calculation methods will lead to misunderstanding the regional thermal background for us and furthermore the thermal structure of lithosphere and geodynamic analysis. Luckily, we can make sure the value 65.1 was reliable because the metamorphic layer has very low porosity and permeability which can guarantee the heat transfer within this formation was dominated by heat conduction. As for the heat flow value within the sedimentary layer, the value 88.5 was mainly influenced by two aspects. One is the thermal refraction which was caused by the lateral thermal conductivity variations between the sandstone and dolomite. The other is the presence of the dolomite formation which was between the sedimentary and metamorphic layers; because the dolomite has incredibly high permeability, the groundwater circulation can exist within this formation which can significantly influence the temperature field and furthermore the heat flow value within the upper sedimentary layer. Moreover, we will talk about the influence of these two aspects on the heat flow value detailedly below.

4. Method

4.1. Model Equations. In order to carry out the research for the heat flow influence factors, a two-dimensional thermal-hydraulic numerical simulation was selected, and the formation was treated as the porous permeable media [34, 35]. As for the heat transformation process, the porous media heat transfer which contains heat conduction and convection was selected. Fluid flow in porous media can be described by the Darcy law [35–37]. In this study, the sedimentary and metamorphic layers are considered impermeable, which the permeability is very small and heat transfer was dominated by heat convection. While for the dolomite, the permeability was very high that the underground water could circulate within it and the heat transfer was dominated by heat convection. Heat transfer equation is written as follows:

\[ \left( \rho \cdot C_p \right)_e \frac{dT}{dt} + \rho_i \cdot C_p,i \cdot \nabla \cdot \Delta T = \Delta \left( \lambda_{eff} \cdot \Delta T \right) + Q, \]  

(4)

Table 2: The thermal conductivity and radiogenic heat production of the main lithology.

| Borehole | Rock type    | Thermal conductivity Range | Mean ± SD (N) | Heat production Range | Mean ± SD (N) |
|----------|--------------|----------------------------|---------------|-----------------------|---------------|
| X35      | Sandstone    | 0.62-2.96                  | 1.82 ± 0.51 (38) | 0.15-2.02             | 1.08 ± 0.43 (26) |
| X01      | Dolomite     | 2.26-8.48                  | 4.95 ± 1.23 (40) | 0.02-1.58             | 0.32 ± 0.37 (40) |
| X01      | Metamorphic rock | 1.89-5.52                | 3.43 ± 1.02 (17) | 0.16-4.18             | 1.07 ± 1.0 (17)  |
where \( T \) is the temperature in °C, \( Q \) is the heat source, \( \mu \) represents the Darcy velocity, and \( \rho \) and \( C_p \) are the density and specific heat of the saturated porous medium, respectively.

The saturated porous medium properties obey a simple mixing rule between the fluid (F) and solid (S); heat capacity of the porous medium is described as follows where \( \varphi \) is the porosity:

\[
\lambda_{\text{eff}} = (1 - \varphi) \cdot \lambda_s + \varphi \cdot \lambda_f.
\]

The effective thermal conductivity is shown as follows:

\[
(\rho \cdot C_p)_{\text{eff}} = (1 - \varphi) \cdot \rho_s \cdot C_{p,S} + \varphi \cdot \rho_f \cdot C_{p,F}.
\] (5)

For the fluid flow which the fluid motion is driven by pressure and buoyancy, Darcy’s law was adopted in this study:

\[
\frac{\partial}{\partial t} (\rho_f \cdot \varphi) + \nabla \cdot (\rho_f \cdot \mu) = Q_m,
\] (7)

\[
\mu = -\frac{\lambda}{\mu} \cdot (\Delta \rho_f + \rho_f \cdot g \cdot \Delta z),
\] (8)

where \( \mu \) is the fluid mass.

4.2. Computational Model and Parameters. In this section, we only focused on two parts for the heat flow correction. One is the heat refraction which was caused by the lateral thermal conductivity variations and the other is the groundwater convection caused by the high permeability of the dolomite. As for the heat refraction, according to the vertical stratigraphy which was revealed through well drilling, the difference of the sedimentary layer thickness between the structural uplifts with the adjacent depression area was 2.4 km and the thickness of the dolomite formation was set as \( D \) km (Figure 2).

So, the calculation model can be simplified as Figure 4(a) and the value \( D = 0.8 \) km was defined as the reference case. In order to quantify the influence of the heat refraction on the heat flow value, all the formation layers were considered as impermeability. And the thermal conductivity value measured above was used which the discrepancy between the sandstones with the dolomite was 3.13 W·m⁻¹·K⁻¹; the other parameters are listed in Table 3. For the heat flow influence of the groundwater convection within the dolomite formation, two aspects were discussed. One is when the dolomite formation thickness \( D \) was determined; the influence of the heat refraction on the temperature distribution under different values of \( D \) was set, like 1.5, 2, and 3 km (Figure 4(b)). On the other hand, when the buried depth of dolomite formation \( L \) was set, the groundwater influence on the temperature distribution under different dolomite formation thicknesses \( D \) will be talked.

As for the parameters selected for the computational model, the data was mainly from the core sample measurement, such as the rock thermal conductivity, density,
radiogenic heat production, and heat capacity. Other parameters, such as the rock porosity and permeability, were collected from the former research [38–40]. Because the groundwater properties will change with the formation temperature, such as the water density and viscosity, the relationships between these parameters with temperature were also considered in this study, which we will not talk about in detail here [41]. Detailed parameter information for different formations is listed in Table 3.

4.3. Boundary Condition and Initial Condition. According to the temperature field of Xiong’an New Area, which the temperature gradient is around 35.0°C km⁻¹, the gradient value was then selected as the temperature gradient along the Y direction [15, 42]. As for the surface temperature, the value 287 K was selected, representing the regional annual average temperature. The value 63.8 mW m⁻² within the metamorphic layer was set as the basal heat flow at the bottom of the model. Thermal insulation condition was adopted for the right and left boundaries of the model. For the groundwater, a standard atmospheric pressure was imposed on the top surface which the value is 10⁵ Pa, and a 10⁸ Pa m⁻¹ stratum pressure gradient was applied to the Y direction. No flow was imposed on the right and left boundaries.

5. Results and Discussions

5.1. Influence of the Heat Refraction and Heat Redistribution on Heat Flow Value. In general, the influence of heat refraction and heat redistribution on heat flow value was mainly controlled by two parts. One is the lateral thermal conductivity variation value: the greater the difference of the variation and the stronger effect of the thermal refraction will result. The other is the difference of the sedimentary layer thickness between the structural uplifts with the adjacent depression area: the greater the difference of the sedimentary layer thickness and the stronger effect of the thermal refraction will be caused [9, 43]. Because the discrepancy of the thermal conductivity between the sandstones with the dolomite was 3.13 W m⁻¹ K⁻¹ in this study, the influence of heat refraction on heat flow calculation under different sedimentary layer thickness differences between the uplift and depression with the adjacent depth will be talked about by defining different values D. Different thickness differences can be achieved, like when the value D was 0.8, the sedimentary layer thickness difference was 2.4 km, and the difference was 1.4 when the value D was 2 km (Figure 4(a)). The calculation result is shown in Figure 5; from the figure, we can see that heat flow like the water will always move towards a place with less resistance or high thermal conductivity. Here, the results of Figure 5(a) were treated as the reference case; when the depth was from 4.0 down to 4.8 km, the right was the dolomite formation and the left was the metamorphic rock. Because the dolomite has a higher thermal conductivity value than the metamorphic rock, the heat will flow prior to the right dolomite layer, and a higher temperature field resulted within this part. On the other hand, when the depth was from 1.2 to 2.0 km, the sandstone was on the right and the dolomite was on the left. The dolomite has a higher thermal conductivity value than the sandstone, so that the heat will flow prior to the lift area and a higher temperature field resulted within this part, such as the isothermal shape of 80°C. Furthermore, when the depth was less than 1.2 km, there was no thermal conductivity discrepancy on the horizontal; with the buried
depth decreasing, the formation temperature tends to be the same. Last but not the least, with the dolomite layer thickness \(D\) increasing, the model thermal resistance was decreasing in the vertical direction, so the heat at the bottom of the model can transfer quickly to the surface, and thus, the isotherm will move downward as a whole, such as the buried depth of the 160°C from Figures 5(a)–5(d).

According to the above calculation results, the temperature-depth data within the 1.2 km in the \(Y\) direction was extracted and drawn as Figure 6(a); the solid lines represent the data from the structural uplift area and the dotted lines represented the depression; the coordinates of the lines were \((3.0, 0), (3.0, 1.2)\) and \((6.0, 0), (6.0, 1.2)\) for the uplift and depression, respectively. The conductive heat flow value was also extracted from the surface line of the model and drawn as Figure 6(b), and the coordinates of the surface line were \((0, 0), (12, 0)\). From Figure 6, we can see that with the increasing dolomite layer thickness \(D\) or the decreasing differences of sedimentary layer thickness between the structural uplifts with the depression area, the thermal resistance of the model was decreasing in the \(Y\) direction and the effect of thermal refraction was also becoming weakened. So, with increasing value \(D\), the temperature at a certain depth was decreasing for the structural uplift area, and the temperature gradient was also decreasing. The opposite character of temperature field exists in the structural depression area (Figure 6). Based on the calculation result, the temperature-depth data from the symmetry line of the model was extracted within 1.2 km and plotted as Figure 8(a), and the conductive

5.2. Influence of the Groundwater Circulation on Heat Flow Value

5.2.1. Under Different Buried Depths of the Dolomite Formation. In this part, we will talk about the influence of the groundwater circulation within certain thickness of dolomite on the formation temperature distribution under different dolomite formation buried depths. While in the calculation, the dolomite formation has an especially high permeability which the value increases up to one or three orders of magnitudes compared with the upper sandstone and lower metamorphic layers in this study, so the groundwater can circulate within this formation. Because of the existence of the positive geothermal gradient in the \(Y\) direction, and at the same time, the groundwater density decreased with the increasing temperature, the negative buoyancy was produced in the vertical direction, and the groundwater convection came into being (Figure 7). The intensity of groundwater convection also increased with the formation temperature, such as the streamline became more obvious from Figures 7(a)–7(d).

Based on the calculation result, the temperature-depth data from the symmetry line of the model was extracted within 1.2 km and plotted as Figure 8(a), and the conductive
heat flow value on the surface of the model was also extracted and plotted as Figure 8(b). From Figure 8(a), we can see that the temperature at a certain depth was decreasing with the increasing dolomite layer buried depth; when the buried depth was 1.2 km, the temperature was 86°C at a depth of 1.2 km, while when the buried depth was 3.2 km, the formation temperature was only 73°C (Figure 8(a)). On the other hand, the surface heat flow value of the model came being stable with the increasing dolomite layer buried depths; for example, when the buried depth was 1.2 km (the legend of Figure 8(b) is the same as that of Figure 8(a)), the heat flow value fluctuates from 85 mW·m⁻² to 100 mW·m⁻² around, and the average heat flow value of the model surface was 92 mW·m⁻². However, when the dolomite layer buried depth...
increased to 3.2 km, the surface heat flow value of the model becomes very stable and only ranges from 80 mW·m$^{-2}$ to 82 mW·m$^{-2}$ (Figure 8(b)). So, we can conclude that with the increasing dolomite layer (high permeability) buried depth, the influence of the groundwater convection within the high-permeability formation on the shallow underground temperature field, especially in the depth range 0~1.2 km which was usually used for the heat flow calculation, became

**Figure 9:** Temperature field under different dolomite formation layer thicknesses $D$.

**Figure 10:** Temperature-depth data within the 2.0 km range and the conductive heat flow value for the model surface.
weaken, and the influence can be ignored when the buried depth was large enough. This conclusion was very important for the theoretical geothermics, because we can make sure the calculated heat flow value was reliable or not and furthermore for the lithosphere thermal structure and geodynamic analysis.

5.2.2. Under Different Thicknesses of the Dolomite Formation.

This part will talk about the influence of groundwater circulation within different dolomite layer thicknesses on the shallow temperature field under a certain buried depth of the dolomite layer. The layer buried depth was 2 km, and the thickness of the high-permeability layer was varied from 2 to 4 km. The genetic mechanism for the groundwater convection was introduced above. From the calculation results, we can see that with the increase of the dolomite layer thickness, the temperature at the bottom of dolomite layer was increasing, so the streamline was more obvious; when the dolomite layer thickness was 4 km, the isotherm became disordered. On the other hand, the number of convective cells decreased with the high-permeability formation thickness increasing; when the formation thickness was 2 km, the convective cell numbers were 6, and the number became 4 when the formation thickness was 4 km (Figure 9).

According to the above calculation results, the temperature-depth data was extracted from the middle line of the model, which the coordinate of the line was (10, 0) and (10, 10) and plotted as Figure 10(a). From Figure 10(a), we can see that, with the increase of the dolomite layer thickness, the geothermal gradient value within the 2 km was increasing. When the thickness was 2 km, the geothermal gradient value was $60 \degree C \cdot km^{-1}$, and the geothermal gradient value was only $50 \degree C \cdot km^{-1}$ when the dolomite layer thickness was 4 km. On the other hand, with the increasing dolomite layer thickness, the thermal resistance in the vertical direction of the model became smaller, and the heat from the bottom can transfer to the surface quickly; thus, the formation temperature became smaller in depth of the model; for
example, when the model depth was from 6 to 10 km, the formation temperature at a certain depth was smaller with the increasing value $D$. Especially when the buried depth was 10 km, the temperature was 280°C when the value $D$ was 2 km and the temperature decreased to 240°C when the value $D$ was 4 km (Figure 10(a)). Furthermore, the conductive heat flow from the surface of the model was also extracted and plotted as Figure 10(b), and the fluctuation of the heat flow value was decreasing with the increasing value $D$. The average heat flow value of the model surface was 88.5, 91.6, and 94.1 mW·m$^{-2}$ when the values $D$ were 2, 3, and 4 km, respectively (Figure 10(b)). If there is no heat convection within the high-permeability formation, the surface heat flow value should be 70 mW·m$^{-2}$ around. If we take the lowest value $D$ (2.0 km) as a reference value, the influence of the heat convection within the high-permeability formation on the surface heat flow value in Xiong’an New Area was 20 mW·m$^{-2}$ around (Figure 10(b)).

5.3. Comparison of Heat Flow Map before and after the Correction. From the above talking, we can see that the heat refraction and heat convection can cause high heat flow disturbance within the sedimentary layer, which the disturbance value was 10 mW·m$^{-2}$ for the heat refraction and 20 mW·m$^{-2}$ around for the heat convection within the Xiong’an New Area. So, under the above conditions, the surface heat flow value which was calculated by multiplying the temperature gradient with the thermal conductivity value within the sedimentary layer was not the real heat flow that was from the conduction, and furthermore, the value was not suitable for the lithosphere thermal structure and geodynamic analysis. So, the heat flow calculation (Equation (2)) cannot be used directly for the sedimentary layer in this area. Luckily, the stratigraphic characteristics which were revealed through well drilling were collected from 75 boreholes, and the radiogenic heat production for different rock types was measured and shown as Table 2.

The most important was the basal heat flow which was obtained by the X01 borehole within the metamorphic layer, and the value was 63.8 mW·m$^{-2}$. Because the area was very small, the thermal regime should be similar to each other and the value 63.8 mW·m$^{-2}$ was applied to the whole Xiong’an New Area. As for the boreholes which were not drilling through the dolomite layer, the heat flow value which was contributed by the radiogenic heat production from the unrevealed formation was ignored, and because the radiogenic heat production rate was very small for the dolomite rock, the value which was ignored was very small.

Finally, combining the basal heat flow value within the metamorphic layer with the heat flow value which was contributed by the radiogenic heat production from the overlying formation, the surface heat flow value was recalculated for the Xiong’an New Area and the heat flow contour map was plotted as Figure 11. Figure 11(a) is the contour map after the heat flow correction and Figure 11(b) is the map before the recalculation.
From the comparison between these two contour maps, we can see that the heat flow value within the Niutuozhen Uplift changed drastically; the average heat flow value was 65 mW·m⁻² for Figure 11(a) and the heat flow value can even reach 90 mW·m⁻² for Figure 11(b); this is very important for the regional crustal temperature and the crustal and the mantle heat flow calculation. Take the crustal temperature and thermal lithosphere thickness as examples; before the surface heat flow correction, the temperature at the 40 km depth was almost 1200°C. However, after the surface heat flow correction, the temperature at the 40 km was just 750°C around. As for the thermal lithosphere thickness, the former was 55 km and the latter was 95 km around (Figure 12(a)). Within the same area, the huge crustal temperature difference which was under a situation of the surface heat flow correction or was not very important for the geothermal resources exploration, it can help us to avoid being misled by the illusion that the “high” heat flow value can be an indication for the abnormal high crustal temperature and furthermore great geothermal resources. On the other hand, the physical properties of the rocks from the deeper lithosphere have great relationship with the crustal temperature. So, correct recognitions for the crustal temperature can help us understand the regional lithospheric rheology and geodynamics. In this area, the heat flow value 65 mW·m⁻² after the correction can better meet the requirement for the thermal structure calculation and geodynamic analysis.

6. Conclusions

Based on the above discussion, the following conclusions can be made.

1. The heat flow value within the sedimentary layer was 88.5 mW·m⁻² for the X01 borehole, and the value was 63.8 mW·m⁻² within the metamorphic layer. Combining the basal heat flow value 63.8 with the heat flow contributed by the radiogenic heat production from the overlying formation, the surface heat flow value in the X01 borehole was only 65.1 mW·m⁻². By using the corrected heat flow value 65.1, the crustal temperature was 750°C at a depth of 40 km and the thermal lithosphere thickness was 95 km around. The heat flow value 65.1 can reflect the regional thermal regime and geodynamics more accurately compared with the heat flow value before the correction.

2. The thermal refraction which was caused by the thermal conductivity variation on the horizontal between the sandstones with the dolomite was one of the reasons for the surface heat flow disturbance within the Xiong’an New Area, and after the calculation, the heat flow disturbance was 10 mW·m⁻² around for the heat refraction in this area.

3. The groundwater convection within the high-permeability dolomite layer was the most important reason for the abnormal high heat flow value within the sedimentary layer, and the heat flow disturbance caused by the groundwater convection was 20 mW·m⁻² in this area.

4. With decreasing sedimentary layer thickness difference between the uplifts with depression area, the heat flow disturbance caused by the heat refraction was decreasing. Under a certain buried depth of the high-permeability formation, the influence of groundwater convection on heat flow value within the sedimentary layer was decreasing with the high-permeability formation thickness decreasing. When the high-permeability layer thickness was set, influence of groundwater convection on the heat flow value was also decreasing with increasing high-permeability layer buried depth.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by the Fundamental Research Funds for the Central Universities (2021-11032), the Research on Heat Disaster and Utilization Technology of Geothermal Resources in Deep Mine (2021210075), the National Key R&D Program of China (2018YFC0604302), and the Key R&D Program of Shandong Province (2019GSF109053).

References

[1] D. D. Blackwell, “The thermal structure of the continental crust,” Geophysical Monograph, vol. 35, no. 14, pp. 169–184, 1971.
[2] M. K. Dan, J. Jackson, and K. Priestley, "Thermal structure of oceanic and continental lithosphere," Earth & Planetary Science Letters, vol. 233, no. 3–4, pp. 337–349, 2005.
[3] C. J. Ebinger, D. Keir, I. D. Bastow et al., “Crustal structure of active deformation zones in Africa: implications for global crustal processes,” Tectonics, vol. 36, no. 12, pp. 3298–3332, 2017.
[4] K. P. Furlong and D. S. Chapman, “Heat flow, heat generation, and the thermal state of the lithosphere,” Annual Review of Earth and Planetary Sciences, vol. 41, no. 1, pp. 385–410, 2013.
[5] F. Lucazeau, “Analysis and mapping of an updated terrestrial heat flow data set,” Geochimica, Geophys, Geosystems, vol. 20, no. 8, pp. 4001–4024, 2019.
[6] J. Majorowicz and S. Wybraniec, "New terrestrial heat flow map of Europe after regional paleoclimatic correction application," International Journal of Earth Sciences, vol. 100, no. 4, pp. 881–887, 2011.
[7] P. Morgan and W. D. Gosnold, “Chapter 23: heat flow and thermal regimes in the continental United States,” Memoir of
the Geological Society of America, vol. 172, no. 1, pp. 493–522, 1989.

[8] A. J. Mansure and R. Marshall, “A vertical groundwater movement correction for heat flow,” Journal of Geophysical Research Solid Earth, vol. 84, no. B7, pp. 3490–3496, 1979.

[9] L. Xiong, “Mathematical simulation of refract and redistribution of heat flow,” Chinese Journal of Geology, vol. 25, no. 4, pp. 445–454, 1984.

[10] S. G. Henry and H. N. Pollack, “Heat flow in the presence of topography: numerical analysis of data ensembles,” Geophysics, vol. 50, no. 8, pp. 1335–1341, 1985.

[11] J. S’ afanda and V. Čermáč, “Subsurface temperature changes due to the crustal magmatic activity–numerical simulation,” Studia Geophysics et Geodaetica, vol. 44, no. 2, pp. 327–335, 2000.

[12] D. Z. Šerbăn, S. B. Nielsen, and C. Demetrescu, “Transylvanian heat flow in the presence of topography, paleoclimate and groundwater flow,” Tectonophysics, vol. 335, no. 3–4, pp. 331–344, 2001.

[13] S. B. Hu, L. J. He, and J. Y. Wang, “Heat flow in the continental area of China: a new data set,” Earth & Planetary Science Letters, vol. 179, no. 2, pp. 407–419, 2000.

[14] G. Jiang, S. Hu, Y. Shi, C. Zhang, Z. Wang, and D. Hu, “Territorial heat flow of continental China: updated dataset and tectonic implications,” Tectonophysics, vol. 753, no. 13, pp. 36–48, 2019.

[15] Q. Liu, L. He, F. Huang, and L. Zhang, “Cenozoic lithospheric evolution of the Bohai Bay Basin, eastern North China Craton: constraint from tectono-thermal modeling,” Journal of Asian Earth Sciences, vol. 115, no. 7, pp. 368–382, 2015.

[16] Z. Wang, G. Jiang, C. Zhang et al., “Thermal regime of the lithosphere and geothermal potential in Xiong’an New Area,” Energy Exploration & Exploitation, vol. 37, no. 2, pp. 787–810, 2019.

[17] Z. X. Li, Y. H. Zuo, N. S. Qiu, and J. Gao, “Meso-Cenozoic lithospheric thermal structure in the Bohai Bay Basin, eastern North China Craton,” Geoscience Frontiers, vol. 8, no. 5, pp. 977–987, 2017.

[18] B. Xia, Z. Liu, and G. Chen, Meso-Cenozoic tectonic evolution and tectonic styles in the Bohai Bay Basin, Natural Gas Industry, 2006.

[19] J. Pang, Z. Pang, M. Lv, and Y. Kong, “Geochemical and isotopic characteristics of fluids in the Niutouzhen geothermal field, North China,” Environmental Earth Sciences, vol. 77, no. 1, pp. 12–30, 2017.

[20] H. Yang, J. Dai, B. Wang, and J. Zou, “Development process of Niutouzhen Uplift,” Journal of Northeast Petroleum University, vol. 38, no. 6, pp. 22–29, 2014.

[21] D. He, S. Shan, Y. Zhang, R. Lu, R. Zhang, and Y. Cui, “3-D geologic architecture of Xiong’an New Area: constraints from seismic reflection data,” Science China (Earth Sciences), vol. 61, no. 8, pp. 1007–1022, 2018.

[22] W. Li, S. Rao, X. Tang, G. Jiang, and J. Wang, “Borehole temperature logging and temperature field in the Xiongxiang geothermal field, Hebei Province,” Scientia Geologica Sinica, vol. 49, no. 3, pp. 850–863, 2014.

[23] Z. Wang, C. Zhang, G. Jiang, Y. Wang, and S. Hu, “Effect of different exploitation schemes on production performance from the carbonate reservoir: A case study in Xiong’an new area,” Journal of Cleaner Production, vol. 314, no. 8, p. 128050, 2021.
Bohai Bay Basin, eastern North China Craton,” *Gondwana Research*, vol. 26, no. 3-4, pp. 1079–1092, 2014.

[41] J. D. Bredehoeft and I. S. Papaopulos, “Rates of vertical groundwater movement estimated from the Earth’s thermal profile,” *Water Resources Research*, vol. 1, no. 2, pp. 325–328, 1965.

[42] J. Chang, N. S. Qiu, X. Z. Zhao et al., “Present-day geothermal regime of the Jizhong Depression in Bohai Bay Basin, East China,” *Chinese Journal of Geophysics*, vol. 59, no. 3, pp. 1003–1016, 2016.

[43] D. Majcin, “Refraction of heat flow on the near-surface structures with thermal conductivity contrast,” *Contributions to Geophysics & Geodesy*, vol. 22, no. 1, pp. 67–81, 1992.

[44] D. S. Chapman and H. N. Pollack, “Regional geotherms and lithospheric thickness,” *Geology*, vol. 5, no. 5, p. 265, 1977.