Research Article

Analyzing and Estimating Thermal Conductivity of Sedimentary Rocks from Mineral Composition and Pore Property

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In this study, thermal conductivities of 128 rock samples located in the Xiong'an New Area and Tarim Basin were measured using the optical scanning and transient plane source methods. The thermal conductivities of the Xiong'an New Area samples range from 1.14 to 6.69 W/(m·K), in which the mean thermal conductivities of dolomite and sandstone are 4.95 ± 1.19 and 1.80 ± 0.44 W/(m·K), respectively. In the Tarim Basin, sandstone samples have thermal conductivities ranging from 1.21 to 3.56 W/(m·K) with a mean value of 2.51 ± 0.66 W/(m·K). The results can provide helpful reference data for studies of geothermics and petroleum geology. Calculation correction and water-saturated measurements were conducted to acquire in situ rock thermal conductivity, and good consistency was found between both. Compaction diagenesis enhances bulk thermal conductivity of sedimentary rocks, particularly sandstones, by decreasing the rock porosity and mineral particle size. Finally, correction factors with respect to mineral grains were proposed to correct the thermal resistance of intergrain contacts and degree of intactness of crystals, and an optimized formula was adopted to calculate the thermal conductivity of sedimentary rock based on rock structure and mineral constituents.

1. Introduction

Thermal conductivity directly characterizes rock's heat conduction capacity and plays an important role in the present thermal conditions including surface heat flow, geothermal field distribution, deep thermal structure, and thermal simulation, and it is also a significant parameter in engineering projects such as the construction of high-level radioactive waste repositories, buried heat exchangers of the ground source heat pump, tunnels construction, and oil, gas, and geothermal energy exploration [1–8]. Until recently, it still lacks completed measurement methods to get the in situ thermal conductivity, so laboratory-measured results have

been used to make corrections. Several factors, such as mineral composition, structure, porosity, moisture content, temperature, and pressure influence the rock thermal conductivity [7, 9, 10]. Therefore, it is crucial to understand each factor during the investigation of thermal conductivity.

Rock samples used for measurements of thermal conductivity were from the Xiong'an New Area and Tarim Basin. These two sampling areas have different geological conditions. The Xiong'an New Area belongs to rift basin background and the Tarim Basin belongs to craton basin background. In previous work, our research group did a lot of researches on both areas [11–13], and corresponding supporting projects allowed authors to obtain core samples. By

studying the features of samples' measurements from two different regions, it can help to avoid the impact of regional factors from the same region and find common laws suitable for most situations.

Located in the northwest of Bohai Bay Basin in the middle east of the North China Craton, the Xiong'an New Area featured by rich geothermal resources is one of the hot spots for geothermal energy study and utilization in China. It stands geographically in a triangle with Beijing and Tianjin cities, and was established as a state-level new area by Chinese government in 2017 which has important significance in politics and economy. Because of the shallowly burial depth, large storage, and complete reinjection rate of reservoirs, the exploration and exploitation of geothermal resources in Xiong'an New Area has already made great progress and has been built as a demonstration area for geothermal system utilization in China. The Tarim Basin located in northwest China is the largest petroliferous basin in China. Experiencing multiperiod tectonic movements, the Tarim Basin stores large quantities of oil and gas. Abundant gas resources make it become the main source area of the west-east natural gas transmission project which is a significantly strategic project set up by Chinese government. The thermal conductivities obtained in both areas could be used as important references for studies of regional heat flow and present-day thermal regime, and furthermore, they are nonnegligible parameters in thermal history simulation and geothermal, oil, and gas resource utilization.

There were several researches aiming to develop thermal conductivity estimation methods based on different factors. Woodside and Messmer [14] studied the variations in the thermal conductivity of consolidated rocks based on porosity, pore medium, and pressure. They found that the two-phase geometric mean (matrix and pore) agrees well with the measured results. Horai and Baldrige [15] estimated thermal conductivities of 19 igneous rocks based on their mineral and chemical compositions. Pribnow and Umsonst [16] built a layered model for crystalline rocks and investigated the effects of structure and anisotropy on the thermal conductivity. Furthermore, Fjeldskaar et al. [17] developed a model to estimate thermal conductivity of sedimentary rock. He et al. [18] used multiple models to estimate soil thermal conductivities. Based on these studies, it can be concluded that the mineral composition and interior structure of rocks are the main factors influencing the estimated thermal conductivity results. When discussing the relation between the thermal conductivity of rock and mineral composition, most previous researches have focused mainly on the igneous and metamorphic rocks comprising intact crystals with simple mineral compositions rather than sedimentary rocks with more complicated compositions and structures.

In this study, 128 samples of diverse lithologies, mostly in sedimentary rocks, were measured using the optical scanning (OS) method and transient plane source (TPS) technology. By identifying the porosity and composition of rock and combining both the estimation methods, factors affecting the thermal conductivity were comprehensively studied.

FIGURE 1: Schematic diagram of TCS instrument.

2. Methods

There are several approaches for measuring rock thermal conductivity, such as the line heat source, divided bar, OS method, and TPS method [5, 19–21], with the latter two methods being commonly used in the laboratory. The OS method is widely used in the geologic field owing to its rapid measurement and convenience [22, 23]. The TPS method is used to determine thermal properties of various materials, such as metals, minerals, and alloys, and is widely applied in engineering and production activities owing to its high precision and accuracy [24–26]. This study adopted OS and TPS methods which have different working procedures and handling methods to measure the thermal conductivity. Two methods can make cross-check analysis, ensure data integrity, and determine if there is a difference between both. By comparing characteristics of both methods, it is helpful to extend the testing conditions and make the measurement of thermal conductivity more efficient and high-quality.

2.1. Optical Scanning Method. The OS method has reached maturity owing to the efforts of Professor Popov [4, 20], and this method has been applied in a thermal conductivity scanner (TCS) with an accuracy of $\pm 2\%$ for thermal conductivities ranging 0.20–45 W/(m·K). The rock sample surface's plane variation must not exceed ± 0.5 mm during measurement. The core element comprises three or four temperature sensors and a heat source. The sample remains immobile on the countertop during measurement. The test is conducted by moving the scanning unit, with the front temperature sensors recording the temperature before heating, middle heat source heating the sample, and latter temperature sensors recording the maximum temperature increase after heating, as shown in Figure 1.

The temperature sensors and heat source can heat and record multiple samples lined up end to end as long as samples maintain a consistent distance and move at the same speed throughout the measurement process. The relational expression of a sample's maximum temperature increase (θ) is as follows [20]:

$$\theta = \frac{Q}{2\pi \cdot x \cdot K}, \quad (1)$$

FIGURE 2: Sketch map of hot disk sensor and sample support.

where θ is the sample's maximum temperature increase, Q is the source power, x is the distance between the heat source and sensor, and K is the sample's thermal conductivity.

If the maximum temperatures of standard samples are known, rock thermal conductivity can then be acquired as follows [20]:

$$K = K_R \cdot \frac{\theta_R}{\theta}, \quad (2)$$

where K_R and θ_R are the standard sample's thermal conductivity and maximum temperature increase, respectively.

The OS method has been widely used for measuring thermal conductivity, thermal diffusivity, and volumetric heat capacity and has given high-quality measurements. Thousands of samples including diverse rocks types and minerals from various areas have been measured by optical scanning techniques [4, 27–31]. Furthermore, this method has been used for researches of deep scientific boreholes in many parts of the world [27, 32–34].

The OS method has several advantages, such as fast measurement, convenient movement, continuous operation, and nondestructive test process. And it also allows to measure thermal conductivity components and determine anisotropy coefficient easily. However, it still possesses some limitations. For example, measured results are easily influenced by environmental conditions, such as wind or heat, which might change the measured values to some extent. Additionally, to enable samples absorb enough heat, sample surfaces must be painted black, which can cause differences in impurities. In principle, the OS method is only supposed to measure a dry sample, but if applied to saturated test samples, evaporation from the saturated samples during heating may cause deviations if the water was not removed from the rock sample surface or the heating power was chosen too high.

FIGURE 3: Schematic diagram of TPS (modified from ISO [35]).

2.2. Transient Plane Source Method. The TPS method can simultaneously measure thermal conductivity, thermal diffusivity, and specific heat. It uses a hot disk thermal constant analyzer. The core component of the instrument is a thin disk-shaped temperature-dependent sensor comprising a thin sheet with a double-helix structure etched by the conductive nickel inside and a double-layer Kapton protective layer outside, which can heat the samples and simultaneously record temperatures, as shown in Figure 2.

The instrument uses a resistance thermometer, wherein temperature dynamic change in a sample is reflected by the variations in the resistance of the sensor. The sensor is fixed on the sample surface within a specimen holder during testing, and a fixed power current is applied to the sensor. An increase in the temperature changes the sensor resistance (ΔR), giving rise to voltage variations at both ends of the sensor. There are different changes in voltage due to varying heat losses in different samples. By recording voltage variations over a limited period, rock thermophysical property can be obtained, as shown in Figure 3. The electrical bridge in the sensor is shown as follows [35]:

FIGURE 4: Sampling positions in the Xiong'an New Area, North China.

The relational expression between temperature variation and voltage can be expressed as follows:

$$\frac{I_0(R_S + R_L + R_0) - [I_0R_S - \Delta U(t)]}{I_0R_S - \Delta U(t)} = \frac{R(t) + R_L}{R_S},$$

$$\Delta T(t) = \frac{(R_S + R_L + R_0)\Delta U(t)}{[I_0R_S - \Delta U(t)]\alpha R_0}, \quad (3)$$

where $R(t)$ is the sensor resistance at time t , R_0 is the initial sensor resistance, I_0 is the initial current through the sensor, R_S is the resistance of a resistor in series with the sensor, R_L is the resistance of sensor leads, α is the temperature coefficient of sensor resistance, $\Delta U(t)$ is the mean voltage variation at time t , and $\Delta T(t)$ is the mean temperature increase at time t . R_S and R_L play important roles in keeping sensor power stable during measurements.

If the sensor's heat source is located in an infinite sample surface, the variation in the temperature increases in

the sensor combined with samples can be expressed as follows [35, 36]:

$$R(t) = R_0[1 + \alpha\Delta T(t)], \quad (4)$$

$$\Delta T(t) = \Delta T_1(t) + \Delta T_2(t),$$

where $\Delta T_1(t)$ and $\Delta T_2(t)$ are the temperature increase in the Kapton protective layer and sample surface, respectively.

From the viewpoint of the sensor's geometric characteristics, i.e., m concentric ring sources, the mean space temperature increase $\Delta T_2(\tau)$ can be defined as follows [37]:

$$\Delta T_2(\tau) = \frac{P_0}{\pi^{3/2}rK}D(\tau),$$

$$D(\tau) = [m(m+1)]^{-2} \int_0^\tau \sigma^{-2} \left[\sum_{l_1=1}^m l_1 \sum_{l_2=2}^m l_2 \exp\left(\frac{-(l_1^2 + l_2^2)}{4m^2\sigma^2}\right) J_0\left(\frac{l_1 l_2}{2m^2\sigma^2}\right) \right] d\sigma, \quad (5)$$

FIGURE 5: Sampling positions in the Tarim Basin, Northwest China.

where P_0 is the output power of the sensor, K is the sample thermal conductivity, $D(\tau)$ is the dimensionless specific time function representing sensor geometric characteristics (a time-dependent equation is independent of size), σ is the integral variable of $D(\tau)$, l_1 and l_2 are sum variables not more than the number of total rings in the double-helix structure, and J_0 is the zero-order modified Bessel function. $\Delta T_2(\tau)$ is a function varying with τ , which is defined as follows [37]:

$$\begin{aligned}\tau &= \sqrt{\frac{t}{\theta}} \\ \theta &= \frac{r^2}{\kappa},\end{aligned}\quad (6)$$

where θ is the specific time depending on sensor and sample conditions, r is the outermost radius of the double-helix structure, and κ is the thermal diffusivity.

Only a smoothly flat surface is acceptable for measurement using the TPS method. Furthermore, the incircle diameter of a sample surface must be four times larger than the

sensor radius and thickness must be no less than sample's radius. The TPS instrument can be equipped with multiple sensors, each having different radii. The measurement accuracy is 2% for 0.005–1800 W/(m·K) range.

Deviations in TPS method measurements occur mainly because the heat conduction equation is based on a sensor on an infinite surface and thus not controlling measurement time to keep heat away from sample's edge. There is a thermal contact resistance between the sample and sensor, leading to an additional 200 points of increasing temperature; however, removing some of these initial points should eliminate the influence of this thermal contact resistance.

There are different sizes of sensors measuring samples with various sizes. And the hot disk has multiple modules to conduct analyses of the anisotropy and specific heat capacity and measurements of the thin film, slab, powder, and liquid materials. The TPS method possesses several advantages, such as high measurement accuracy and repeatability, simple specimen requirements, nondestructive measurement capabilities, and the ability to measure at high temperatures. It has been used in engineering domains to test various materials, such as metals, rock, ceramic, powder, film, plastic,

TABLE 1: Thermal conductivity of sedimentary rocks measured by TPS.

District	Rock type	Sample Number	Range [W/(m·K)]	Mean $\pm$ STD [W/(m·K)]
Xiong'an New Area	Dolomite	57	1.44-6.69	4.95 ± 1.19
	Sandstone	16	1.14-2.69	1.80 ± 0.44
	Leptynite	7	1.62-3.14	2.48 ± 0.54
	Gneiss	9	1.67-3.05	2.48 ± 0.43
	Mudstone	4	1.23-2.22	1.64 ± 0.45
	Breccia	3	5.65-6.29	5.90 ± 0.34
Tarim Basin	Sandstone	32	1.21-3.56	2.51 ± 0.66

FIGURE 6: Distribution histogram of thermal conductivity of different rocks.

and liquids [24, 36, 38–40]. In recent years, TPS has entered the geological domain. However, it is still less used than the OS method. TPS method has been used in a few recent studies. Di Sipio et al. [41] discussed the necessary parameters for establishing a geothermal model using thermophysical data measured by the TPS method. Aurangzeb and Maqsood [42] measured the thermal conductivity of olivenite at different temperatures to study their relation with each other. Li and Liang [43] analyzed factors affecting thermal conductivities of methane hydrate-bearing sediments using the TPS method.

3. Results

Herein, 128 samples were collected from the Xiong'an New Area and Tarim Basin located in North and North-west China, respectively. Sampling positions are shown in

FIGURE 7: Relation between thermal conductivity of rocks and depth in Xiong'an New Area.

FIGURE 8: Relation between thermal conductivity of rocks and depth in Tarim Basin.

TABLE 2: Comparison between TPS and OS methods.

Method	Transient plane source	Optical scanning
Apparatus	Hot disk thermal constant analyzer	Thermal conductivity scanner
Sample type	Solid/powder/liquid/film/coating	Solid
Ability to measure thermal anisotropy	Yes	Yes
Ability to measure fluid-saturated rocks	Yes	Yes
Sample requirements	Flat plane	Flat or cylindrical surface (better to be painted with a black coat)
Sample size	Depends on sensor size and no less than 0.5 mm * 2 mm (thickness * diameter) for block	Commonly no less than 30 mm
Accuracy	2%	2%
Range	0.005–1800 W/(m·K)	0.2–45 W/(m·K)
Measuring time	Generally 3–5 minutes per sample	Flexible (generally 3–5 samples at a time within 3–5 minutes)
Move	Difficult to move	Flexible to move
Operation interface	Facility	Facility
Testing condition	In atmospheric and vacuum environments at various temperatures (–253°C~1000°C) and pressures	At around room temperature and pressure

TABLE 3: Thermal conductivity of OS standard samples measured by TPS.

OS standard sample code	A1	B1	C1	D1	E1
OS thermal conductivity [W/(m·K)]	0.708	1.35	2.38	6.41	13.00
TPS thermal conductivity [W/(m·K)] for a 95% confidence level	0.707 ± 0.006	1.350 ± 0.008	2.378 ± 0.037	6.409 ± 0.014	13.121 ± 0.085

Figures 4 and 5. In the Xiong'an New Area, we collected 96 samples from 34 boreholes from depths of 700–6000 m, including Archaean gneiss and leptynite, middle Proterozoic dolomite rock, and Paleogene and Neogene sandstone and mudstone. Samples from the Tarim Basin comprised 32 sandstones that were obtained from 13 boreholes over a wide area with sampling depths of 1120–6320 m, covering the main sedimentary layers from the Ordovician to Cretaceous.

Thermal conductivities of the rock samples were measured using the OS and TPS methods at room temperature (21°C) and normal atmosphere. All samples were quite complete. Although the thermal conductivity is an anisotropic parameter, for many sedimentary rocks, the testing difference caused by anisotropy is small and close to the measurement accuracy [20, 44], so the anisotropy of sedimentary rocks is not discussed here. The anisotropy of gneiss is obvious and nonnegligible [20], but this article aims at thermal characteristics of sedimentary rocks, the thermal conductivity of gneiss is mainly used for increasing the thermal data.

Descriptive results of thermal conductivity are shown in Table 1 and Figure 6. The thermal conductivities of Xiong'an New Area samples range from 1.14 to 6.69 W/(m·K). Dolomite rock values range from 1.44 to 6.69 W/(m·K) but are mainly distributed in 4.00–7.00 W/(m·K) with a mean value of 4.95 ± 1.19 W/(m·K) ($n = 57$). For sandstones, thermal conductivity results range from 1.00 to 3.00 W/(m·K) with a mean value of 1.80 ± 0.44 W/(m·K) ($n = 16$). Leptynites and gneisses have similar values at 1.60–3.20 W/(m·K) with

mean values of 2.48 ± 0.54 ($n = 7$) and 2.48 ± 0.43 W/(m·K) ($n = 9$), respectively. There are only few mudstone and breccia samples, with the former and latter having the lowest and highest mean values of 1.64 ± 0.45 ($n = 4$) and 5.90 ± 0.34 W/(m·K) ($n = 3$), respectively. The sandstones from the Tarim Basin range 1.00–4.00 W/(m·K) evenly with a mean value of 2.51 ± 0.66 W/(m·K) ($n = 32$).

Figures 7 and 8 show the varying thermal conductivities of the main rocks with depth. For rocks in the Xiong'an New Area, the thermal conductivity of sandstones increases obviously with depth. However, this tendency is not present in dolomite rock, which shows hardly any variation with depth. There are no obvious relations between depth and thermal conductivity for other rocks in the Xiong'an New Area since the number of samples is less. In the Tarim Basin, sandstone thermal conductivity slightly increases with depth.

4. Discussion

4.1. Cross-Check of OS and TPS. Both OS and TPS methods have own unique characteristics for measuring thermal conductivity (Table 2) and have successfully achieved measurements. Upon comparing the two methods, the TPS method is able to measure more materials and smaller size than the OS method, and the TPS can directly obtain the specific heat capacity by adjusting the special module. The OS method should be conducted in an enclosed space because it is more easily affected by the environment such as the wind, and the TPS method could remove environmental impacts by being

FIGURE 9: Comparison of thermal conductivity of dry samples measured by TPS and OS methods.

covered with a specific lid. The testing efficiency of the OS is faster than that of TPS because the OS can test many samples simultaneously. When testing the same sample several times, variations in the results obtained by the TPS method could be limited to two or three decimal places, whereas those obtained by the OS method changed one or two decimal places under the same conditions.

Five different OS standards whose thermal conductivity had been already known were measured by the TPS. All the relative deviations of results are below 1% (Table 3); therefore, it is available to measure the thermal conductivity by the TPS.

The TPS and OS methods measured thermal conductivities of dry samples. And both method values are consistent with each other, as shown in Figure 9. Their overall deviations are between -11.1% and 16.54% , and mean deviations range from -3.5% to 5.97% with an integration of 2.59% . This demonstrates that the results for both methods should be valid because their relative deviations are less than 4% , which is the sum of the test accuracy of both methods at 2% . Hence, the OS and TPS methods could be combined in different measurement conditions based on their various features.

4.2. Effect of Pore Property on Thermal Conductivity. Factors affecting the rock thermal conductivity can be divided into two classes: internal factors, which depend on aspects of the rock itself, such as mineral composition, structure, intergrain contact, and porosity; and external factors, which are determined by outer conditions, such as temperature, pressure,

FIGURE 10: Distribution of porosity varied with depth.

FIGURE 11: Comparison of thermal conductivity obtained by formula and experiment.

pore medium, and medium saturation. Both dry and in situ samples have the same internal factors, but external conditions change significantly. To obtain in situ thermal conductivity from dry samples in the laboratory, external factors must thus be corrected.

FIGURE 12: Comparison between corrected and uncorrected thermal conductivities. (a) Dolomite in Xiong'an New Area. (b) Sandstone in Xiong'an New Area. (c) Sandstone in Tarim Basin.

Thermal conductivity increases with an increase in the pressure and decreases with an increase in the temperature, suggesting that the two effects might offset each other under certain conditions [29, 45, 46]. Hence, for the ease of convenience, the correction for temperature and pressure was not used here, and only the effect of pores on thermal conductivity was discussed. Pore characteristics arise from three aspects, namely, the porosity, pore medium, and medium saturation.

All the samples in situ were under the water table and had pores filled with water. The measured thermal conductivity value was the integration of the thermal conductivities of

the rock matrix and air filled in pores. Therefore, it is necessary to make water saturation corrections to attain in situ thermal conductivity values reflecting real heat conduction processes.

Variations in the porosities of the main rocks with depth are shown in Figure 10. All porosities were tested by the helium porosimeter named CAT113 manufactured by the American Core Lab Company. The dolomite rock porosity varies irregularly with depth having a low range of 0%–6%. Sandstones in the Xiong'an New Area and Tarim Basin both have obviously higher porosity than dolomite with porosities of 2%–25% and 1%–6%, respectively. It is noticeable that the

FIGURE 13: Thermal conductivities before and after correction varied with porosity. (a) Dolomite in Xiong'an New Area. (b) Sandstone in Xiong'an New Area. (c) Sandstone in Tarim Basin.

porosity decreases with an increase in the depth in the Xiong'an New Area, which agrees with compaction diagenesis. The compaction effect enhances gradually as depth increases, making the rock structure more compact and decreasing porosity. However, this trend does not exist in the Tarim Basin because its proportion, which is 40 million km², significantly larger than that of the Xiong'an New Area (2000 km²). In a small scale, samples present a continuous variation with depth due to being in a similar tectonic unit. On the contrary, samples in a wide scale belong to different tectonic units and are far apart. Therefore, no continuous change among porosities exists.

Two methods were adopted to perform water saturation corrections for thermal conductivity. The first method was to calculate the geometric mean as follows [14]:

$$K = K_m^{1-\Phi} \times K_p^\Phi, \quad (7)$$

where K is the rock bulk thermal conductivity, K_m is the matrix thermal conductivity, K_p is the thermal conductivity of medium (such as water or air) in the pores, and Φ is the porosity. According to Equation (7), the matrix thermal conductivity was obtained based on thermal conductivities of dry

TABLE 4: Thermal conductivity of the main compositions [17, 45, 48–50].

Compositions		Range [W/(m·K)]	Thermal conductivity [W/(m·K)]
Mineral	Quartz	6.1-11.3	7.69
	Orthoclase	2.3-4.6	2.31
	Anorthite	1.68-2.72	2.10
	Albite	1.63-2.34	2.14
	Pyrite	19.2-41.4	19.2
Debris	Acidic magma	1.25-4.5	3.02
	Andesite and basic magma	1.12-5.4	2.30
	Carbonate sediment	0.6-6.6	2.86
	Flint	3.67-4.81	3.71
	Tuff	1.4-2.1	1.8
Interstitial material	Dolomite		5.3
	Calcite		3.3
	Silica		7.7
	Clay		1.0

TABLE 5: Determination of the main mineral composition in dolomite rock slice.

Sample	Mineral composition						Grain size					
	Dolomite (%)	Clay (%)	Silica (%)	Pyrite (%)	Sand (%)	0.001-0.01 mm (%)	0.1-0.05 mm (%)	0.05-0.1 mm (%)	0.1-0.5 mm (%)	0.5-1 mm (%)	1.0-2.0 mm (%)	Mean size (mm)
N5-1	93.5	6	0.5				9			91		0.687
N7-1	79.9	10		0.1	10			40		50	10	0.595
G10-5	97	3				50	50					0.028
G10-6	77	3	20			30	10	60				0.052
G11-1	95.8	4		0.2				30	20			0.248
N10-1	95	5					100					0.050
N11-1	45		55			27.5	27.5			45		0.353
G13-1	96	2	2			10	10				80	1.606
G13-2	96	4				50	50					0.028
G13-3	95	3	2			20	20			60		0.461
G13-4	97	3				50	50					0.028
G13-5	85	15				88	10			2		0.024
G13-6	97	3						90	10			0.275

sample and air and porosity firstly; then, the water-saturated thermal conductivity was acquired by combining the water thermal conductivity.

The second method was to measure saturated samples simulating the true underground situation using the TPS method by saturating them with water under vacuum for more than 72 h until the pores were full of water.

The correlation of results between these two methods is shown in Figure 11. Their relative deviations are between −10.53% and 10.16%, with a mean range of −3.24%–4.32%. No obvious difference can be noted, so either method could be chosen to make corrections. For convenient analysis, all corrected thermal conductivities in the rest of this paper adopted the geometric mean.

TABLE 6: Descriptive statistics of the main mineral composition in dolomite rock.

Mineral	Range	Mean ± deviation
Dolomite (%)	45-97	88.44 ± 14.74
Clay (%)	0-15	4.69 ± 3.88
Silica (%)	0-55	6.12 ± 15.67
Mean grain size (mm)	0.024-1.606	0.341 ± 0.445

Analysis and comparison of thermal conductivities before and after correction (Figures 12(a)–12(c)) find that the correction of the dolomite rock changes little, with a mean of 5.20%, which is closely related to its low porosity

TABLE 7: Determination of the main mineral compositions in sandstone slice.

Sample	Terrigenous clastic (%)						Interstitial material (%)			
	Quartz	Feldspar Alkali feldspar	Plagioclase	Acidic magma	Debris Andesite-basic magma	Carbonate sediment	Calcite	Dolomite	Clay	Mean grain size (mm)
G6-1	24	20	2.4	16	2.4	6.4			20	0.15
N13-1	34.4	18.9	2.46	12.3		5.74			13	0.25
N14-1	32	16	1.78	32.04	1.78	3.56	2	2	1	0.15
G7-2	41.2	36.8	1.84	7.36	0.92		0.5	2.5	4	0.08
N2-1	33.4	17.6	4.4	23.76		0.88	3	4	5	0.20
N12-2	25.6	28	1.6	20		0.8			16	0.25
G15-1	34.4	32	1.64	8.2		4.92	8	2	7	0.15
G17-1	55.3	14.45	2.55	7.65	0.85	0.85	2	3	10	0.10

at 1.64%. The accuracy of the TPS method is close to the correction difference, so water corrections have no significance in the dolomite rock. The mean correction difference of sandstones in the Xiong'an New Area and Tarim Basin with a mean porosity of 7.8% and 7.31% is 29.3% and 27.2%, respectively. The correction differences and porosities of both areas are higher than those of the dolomite rock. As we know, the higher the porosity is, the higher the correction difference is [47]. The sandstone's thermal conductivity shows a rising tendency with depth before correction, but after correction, this trend weakens, and because of the separated distribution in the Tarim Basin, the positive correlation is also weaker than in the Xiong'an New Area.

Variation in thermal conductivity with porosity (Figures 13(a)–13(c)) shows that the dolomite rock has no evident regular changes with porosity, which is lower than 6%. Thermal conductivity of sandstone in the Xiong'an New Area and Tarim Basin decreases as porosity increases without corrections, whereas after correction, this tendency weakens. This indicates that when pores are filled by media with low thermal conductivities, the rock bulk conductivity could show a negative correlation with porosity. However, once medium conductivity rises, the change in relation will be inconspicuous.

4.3. Effect of Mineral Composition on Thermal Conductivity. Mineral compositions and structure are key factors affecting rock thermal conductivity. Different lithologies comprising varying mineral compositions have different thermal conductivities. Additionally, the thermal conductivity of the same rock type depends mainly on the mineral type and content.

Previous researches have studied the conductivity of various minerals, debris, and interstitial materials in detail (Table 4) [17, 45, 48–50]. Among the main rock-forming minerals, thermal conductivity is obviously higher for quartz than others, i.e., 7.69 W/(m·K). On the contrary, clay minerals are apparently lower than others, at generally less than 1.0 W/(m·K). Accounting for mineral anisotropy, the values listed in Table 4 are integral results synthesizing every direction.

To clarify the relation between thermal conductivity and mineral type, 13 dolomite rocks and 8 sandstones from the

TABLE 8: Descriptive statistics of the main mineral compositions of sandstone.

Mineral	Range	Mean $\pm$ deviation
Quartz (%)	24.00–55.25	35.05 $\pm$ 9.78
Alkali feldspar (%)	14.45–36.80	22.96 $\pm$ 8.22
Plagioclase (%)	1.60–4.40	2.33 $\pm$ 0.92
Acidic magma (%)	7.26–32.04	15.91 $\pm$ 8.88
Carbonate sediment (%)	0.00–6.40	2.89 $\pm$ 2.56
Calcite (%)	0.00–8.00	1.94 $\pm$ 2.71
Dolomite (%)	0.00–4.00	1.69 $\pm$ 1.53
Clay (%)	1.00–20.00	9.50 $\pm$ 6.48
Mean grain size (mm)	0.075–0.250	0.166 $\pm$ 0.064

Xiong'an New Area were made into slices to determine their mineral compositions and grain sizes under the microscope (Tables 5–8). Table 6 shows that dolomite rock is characterized by dolomites, clays, and silicas with a small amount of pyrites and sands. The dolomite content ranges 45%–97% with a mean value of $88.44 \pm 14.74\%$, the clay content is relatively less at 0%–15% with a mean value of $4.69 \pm 3.88\%$, and silica exists in some of these samples, with content varying significantly from 0% to 55%. The dolomite rock has a mean grain size of 0.024–1.606 mm, which was calculated using the arithmetic mean according to particle diameter distributions.

The sandstone is characterized by quartz, feldspar (alkali feldspar and plagioclase), and debris (acidic magma, andesite-basic magma, and carbonate sediments) in terrigenous clastic, and calcite, dolomite, and clay in the interstitial material (Table 7). Among these, quartz has the highest ratio at 24%–55.24% with a mean value of $35.05 \pm 9.78\%$. Alkali feldspar is the second most common at 14.45%–36.80% with a mean value of 22.96%. In the debris, acidic magma accounts for the highest proportion at 7.26%–32.04% with a mean value of 15.91%. The highest content in the interstitial material is the clay ranging 1%–20% with a mean of 9.50%. The remaining compositions are less than 3%. The sandstones

TABLE 9: Correlations between thermal conductivity and composition of dolomite.

		Thermal conductivity	Dolomite	Clay	Silica	Grain size
Thermal conductivity	Pearson correlation	1	-0.120	-0.702**	0.402	-0.210
	Sig. (2-tailed)		0.697	0.007	0.174	0.492
Dolomite	Pearson correlation	-0.120	1	0.097	-0.933**	0.042
	Sig. (2-tailed)	0.697		0.753	0.000	0.891
Clay	Pearson correlation	-0.702**	0.097	1	-0.411	0.160
	Sig. (2-tailed)	0.007	0.753		0.163	0.602
Silica	Pearson correlation	0.402	-0.933**	-0.411	1	-0.194
	Sig. (2-tailed)	0.174	0.000	0.163		0.526
Grain size	Pearson correlation	-0.210	0.042	0.160	-0.194	1
	Sig. (2-tailed)	0.492	0.891	0.602	0.526	

**Correlation is significant at the 0.01 level (2-tailed). Calculation process and theory of Pearson correlation coefficient is following George and Mallery [51].

are mainly fine, medium, and silt sandstones with grain size of 0.075–0.250 mm and mean value of 0.166 ± 0.064 mm.

Correlation analysis was employed to discuss the relation between the rock thermal conductivity and mineral composition. Keeping aside the low porosity of the dolomite rock, the measured dry thermal conductivities are directly applied to compare with mineral compositions (Table 9). Thermal conductivity negatively correlates with clay mineral content with a correlation coefficient of -0.702 and reaches a statistically significant level ($P = 0.007 < 0.01$), indicating that dolomite rock's thermal conductivity decreases significantly with increasing clay content (Figure 14). The thermal conductivity correction coefficient of dolomite is $0.120 < 0.3$ and there is no correlation between both. The coefficient for silica is 0.402 , but obviously exceeds the level of statistical significance at $0.174 > 0.05$. There is no obvious correlation between dolomite rock conductivity and grain size with a correlation coefficient of -0.210 .

Owing to the effect of the high porosity of sandstones on rock bulk thermal conductivity, the matrix thermal conductivity computed using the geometric mean was used to analyze the relations between thermal conductivity and mineral composition (Table 10). Results show that sandstones have thermal conductivity that positively correlates with quartz content with a correlation coefficient of 0.759 and a level of statistical significance of $0.029 < 0.05$ (Figure 15). The coefficient of acidic sediments and thermal conductivity is -0.632 , but the statistical significance level is $0.092 > 0.05$. Other compositions are not evidently correlated with thermal conductivity because the absolute value of their coefficient is less than 0.4 and significant level is more than 0.3 . There is also a negative relation between thermal conductivity and grain size with a coefficient of -0.764 (Figure 15).

Pearson correlation analysis studies the relation between two variables; however, sometimes the correlation coefficient cannot reflect the real relation due to the influence of a third variable. Therefore, it is necessary to conduct a partial correlation analysis. Previously, it is found that there is a strong negative relation between dolomites and silicas with a coefficient of -0.933 (Table 9), but the two have nothing to do with

FIGURE 14: Thermal conductivity of dolomite with varying clay content.

thermal conductivity of dolomite rock. Considering the dolomite and silica as a mutual controlling variable, the correlation between them and thermal conductivity is again analyzed employing partial correlation analysis (Table 11). The partial correlation coefficient between thermal conductivity and dolomite is 0.755 with a significance level of 0.003 when silica is taken as a controlling variable, indicating an obviously positive correlation between them. When dolomite is the controlling variable, thermal conductivity increases with silica content with a partial coefficient of 0.812 , which is an identical trend as the dolomite.

Above all, the dolomite rock has increasing variance with higher dolomite and silica contents, decreasing variance with higher clay content, and thermal conductivity variance has no association with grain size. For the sandstone, thermal conductivity increases with an increase in the quartz content and decreases with an increase in the grain size. Based on the mineral thermal conductivity shown in Table 4, dolomite

TABLE 10: Correlations between thermal conductivity and composition of sandstone.

	Thermal conductivity	Quartz	Alkali feldspar	Plagioclase	Acidic magma	Carbonate sediment	Dolomite	Calcite	Clay	Grain size
Thermal conductivity	Pearson correlation Sig. (2-tailed)	1 0.759*	0.094 0.824	-0.384 0.348	-0.632 0.092	-0.169 0.690	0.127 0.765	-0.095 0.823	-0.061 0.885	-0.764* 0.027
Quartz	Pearson correlation Sig. (2-tailed)	0.759*	1 0.753	0.099 0.816	-0.515 0.191	-0.455 0.257	0.593 0.121	0.150 0.724	-0.381 0.352	-0.584 0.128
Alkali feldspar	Pearson correlation Sig. (2-tailed)	0.094 0.824	-0.133 0.753	1 0.204	-0.463 0.249	-0.209 0.619	-0.094 0.826	0.206 0.625	-0.087 0.838	-0.214 0.611
Plagioclase	Pearson correlation Sig. (2-tailed)	-0.384 0.348	0.099 0.816	-0.503 0.204	1 0.629	-0.171 0.685	0.526 0.181	-0.016 0.971	-0.088 0.836	0.167 0.692
Acidic magma	Pearson correlation Sig. (2-tailed)	-0.632 0.092	-0.463 0.191	0.203 0.629	1 0.972	0.015 0.972	0.021 0.960	-0.159 0.707	-0.237 0.573	0.375 0.359
Carbonate sediment	Pearson correlation Sig. (2-tailed)	-0.169 0.690	-0.455 0.257	-0.171 0.685	1 0.972	0.015 0.972	-0.583 0.129	0.123 0.772	0.399 0.327	0.256 0.541
Dolomite	Pearson correlation Sig. (2-tailed)	0.127 0.765	0.593 0.121	0.526 0.181	0.021 0.960	-0.583 0.129	1 0.262	0.451 0.262	-0.751* 0.032	-0.507 0.200
Calcite	Pearson correlation Sig. (2-tailed)	-0.095 0.823	0.206 0.625	-0.016 0.971	-0.159 0.707	0.123 0.772	0.451 0.262	1 0.293	-0.426 0.293	-0.190 0.653
Clay	Pearson correlation Sig. (2-tailed)	-0.061 0.885	-0.381 0.352	-0.088 0.836	-0.237 0.573	0.399 0.327	-0.751* 0.032	-0.426 0.293	1 0.400	0.400 0.326
Grain size	Pearson correlation Sig. (2-tailed)	-0.764* 0.027	-0.584 0.128	0.167 0.692	0.375 0.359	0.256 0.541	-0.507 0.200	-0.190 0.653	0.400 0.326	1

*Correlation is significant at the 0.05 level (2-tailed).

FIGURE 15: Thermal conductivity of sandstone with varying quartz content and grain size.

rock and sandstone thermal conductivities are obviously correlated with dolomite (5.51 W/(m·K)), silica (4.53 W/(m·K)), and quartz (7.69 W/(m·K)), which have thermal conductivities significantly higher than other common rock-forming minerals, ranging 2–4 W/(m·K) [45]. The reason why there is no direct relation between thermal conductivity variance and dolomite and silica contents is that they have close thermal conductivity values, thus playing the same role in heat conduction, and can be considered the same unit. The reason for the decreasing tendency seen in dolomite rock with clay might be spilled into two ways. On the one hand, shaly clay with low thermal conductivity (generally <1 W/(m·K)) [17] correlates negatively with thermal conductivity in dolomite rock. On the other hand, the dolomite rock mainly comprises dolomite, silica, and clay, and as dolomite and silica contents fall, clay content naturally rises, making it difficult to find which mineral is a leading factor.

Since quartz has a significantly higher thermal conductivity than the other minerals, all types of minerals in the sandstone could be categorized into two groups, namely, quartz and others. The mean ratio of quartz is 35% and that of dolomite and silica in the dolomite rock is at 95%. The proportion of the mineral with high thermal conductivity is lower in the sandstone than in the dolomite rock, which may be one of the reasons for sandstone's mean thermal conductivity being less than that of dolomite in general.

There is a decreasing trend in sandstone thermal conductivity with grain size. This is probably due to grain size in connection with compaction diagenesis. Higher pressure on the rock yields a greater degree of compaction and thus a smaller grain size [52]. As the structure within rock becomes more compact, thermal conductivity increases. The dolomite rock has hardly any grain size variance because it is formed

by secondary replacement with the same dolomite particles in contact with each other within the rock, rather than the different contact relations seen among the different particles in sandstone.

4.4. Estimation of Thermal Conductivity. In comparison with the thermal conductivities of the common minerals, a mineral with a significantly higher or lower thermal conductivity may have greater effect on rock bulk thermal conductivity. However, estimates of rock bulk thermal conductivity should not ignore the contribution of other minerals.

Based on the contribution of each mineral, the geometric mean (estimation method 1) (Equation (8)) was the method most commonly used to estimate matrix thermal conductivity based on their thermal conductivities and proportions [14]:

$$K_m = \prod_{i=1}^n K_i^{v_i}, \quad (8)$$

where K_m is the matrix thermal conductivity, K_i is the thermal conductivity of each mineral, and v_i is the volume fraction of each mineral. The theory is the same for both estimation method 1 and water correction formula, where the matrix and pore medium are considered separately and compared with the numerous mineral constituents.

Additionally, Horai and Baldrige [15] employed another formula to estimate the thermal conductivity of 19 igneous rocks and found that its results were better than those from the geometric mean. The formula (estimation method 2) (Equations (9–15)) is as follows:

$$K_{\max} = \max(K_1, K_2, \dots, K_n) \text{ and } K_{\min} = \min(K_1, K_2, \dots, K_n), \quad (9)$$

$$\alpha_{\max} = \frac{1}{3K_{\max}}, \quad (10)$$

$$\alpha_{\min} = \frac{1}{3K_{\min}},$$

$$A_{\max} = \sum_{\substack{i=1 \\ K_i \neq K_{\max}}}^n v_i \frac{1}{(1/(K_i - K_{\max})) + \alpha_{\max}}, \quad (11)$$

$$A_{\min} = \sum_{\substack{i=1 \\ K_i \neq K_{\min}}}^n v_i \frac{1}{(1/(K_i - K_{\min})) + \alpha_{\min}}, \quad (12)$$

$$K_M = K_{\max} + \frac{A_{\max}}{1 - \alpha_{\max} A_{\max}}, \quad (13)$$

$$K_S = K_{\min} + \frac{A_{\min}}{1 - \alpha_{\min} A_{\min}}, \quad (14)$$

$$K_f = \frac{1}{2}(K_M + K_S), \quad (15)$$

where $K_{\max}$ and $K_{\min}$ are the maximum and minimum thermal conductivities among all minerals, respectively, and K_M

TABLE 11: Partial correlation analysis results of dolomite rock.

Control variables			Thermal conductivity	Dolomite	Silica
None ^a	Thermal conductivity	Correlation	1	-0.12	0.402
		Significance (2-tailed)		0.697	0.174
	Dolomite	Correlation	-0.12	1	-0.933
		Significance (2-tailed)	0.697		0
	Silica	Correlation	0.402	-0.933	1
		Significance (2-tailed)	0.174	0	
Silica	Thermal conductivity	Correlation	1	0.775	
		Significance (2-tailed)		0.003	
	Dolomite	Correlation	0.775	1	
		Significance (2-tailed)	0.003		
Dolomite	Thermal conductivity	Correlation	1	0.812	
		Significance (2-tailed)		0.001	
	Silica	Correlation	0.812	1	
		Significance (2-tailed)	0.001		

Calculation process and theory of partial correlation analysis is following George and Mallery [51].

and K_s are the upper and lower limits of the matrix thermal conductivity, respectively.

Both methods mainly focused on estimating thermal conductivity in igneous rocks, and their use with sedimentary rocks has been rare in previous works. Hence, herein, the two methods were used to estimate matrix thermal conductivity of sandstones. The parameter values used in this estimation process are shown in Table 4.

Our results demonstrate that estimated values are abnormally higher than the measured values (Figure 16) and significant differences exist. The reason why previous studies obtained good results is that they focused on igneous or metamorphic rocks [5, 15]. The values listed in Table 4 were measured on single crystals or monomineralic aggregates, and igneous rock, whose crystals are in a basically intact condition, differs from sandstone with fragmented crystals. Thermal conductivity of rock integrated with intact crystals must disagree with that from fragmented crystals even with identical compositions. Additionally, igneous rocks have relatively simpler compositions and fewer impurities than sandstones. Therefore, it is simpler to attain good results from estimations in igneous rocks. However, sandstone has very complicated compositions with different minerals touching each other and raising thermal contact resistance, affecting thermal conductivity to some extent [53]. Based on these points, this study puts forward a matched simple correction factor to correct for the degree of intactness and contact relations among particles. The correction factor is multiplied by each composition's thermal conductivity to reduce the original values in Table 4, bringing them closer to the real situation in sandstone.

According to the ability of different compositions to resist deformation and damage, the more undamaged they can be, the higher their correction factors can be. In the meantime, in consideration of the thermal contact resistance could reduce the thermal conductivity of the bulk rock to a

FIGURE 16: Comparison between estimated and measured results.

certain extent, this affection was considered by lowering suitably correction factors. Therefore, correction factors were adjusted continuously to make estimated values approach the measured values. Based on experimental results from multiple parameter adjustments, the following empirical correction factors were determined: 0.85 for quartz due to its strong weathering resistance of weathering, 0.8 for feldspar due to its correspondingly weaker resistance, and 0.7 for debris and interstitial materials because debris is a broken product from the mother rock that was influenced easily by weathering and alteration and interstitial material is marked by clay with very low thermal conductivity. Results after adopting these factors are shown in Figure 17. The mean

FIGURE 17: Comparison between estimated and measured results after correction.

relative deviations of estimation methods 1 and 2 range -8.22% – 16.45% and -6.81% – 14.73% with an integrated mean value of 1.03% and 6.65% , respectively.

Estimation method 1 results are lower than those of method 2, but it is not wise to affirm which one is better because only a few samples were collected herein. Currently, both methods could attain good results, and the advantages and disadvantages among them may be discussed in the future after collecting more data. Additionally, the rock-forming minerals were formed in different environments, so their thermal conductivities would not be completely in accordance with the values listed in Table 4.

Employing these two estimation methods can almost obtain matrix thermal conductivity, verifying that each mineral has an essential contribution on bulk thermal conductivity. In comparison with igneous and metamorphic rocks, sandstone has complex compositions, broken crystals, and intricate contact relations, resulting in a difference in heat conduction.

5. Conclusion

- (1) The cross-check revealed that the results of TPS and OS methods were in correspondence with each other and had high precision and efficiency. The mean thermal conductivities of dolomites and sandstones in Xiong'an New Area and sandstones in Tarim Basin were 4.95 ± 1.19 , 1.80 ± 0.44 , and 2.51 ± 0.66 W/(m·K), respectively; these measured values can contribute to basin-related study. Since both the methods have their own unique characteristics, combining them would be suitable for measurements under various conditions

- (2) Water saturation correction demonstrated that there was little difference between the geometric mean and actual saturated measured results. There is no need to perform a water saturation correction for low porosity dolomite rock. But corrections must be used for high porosity sandstone. The thermal conductivity of sandstone increases as the depth increases or porosity decreases, and the tendency weakens after correction, while these relationships do not exist in dolomite
- (3) Correlation analysis showed that the dolomite rock's thermal conductivity was negatively correlated with shaly clay and positively correlated with dolomite and silica, and the sandstone positively correlated to the quartz content. When the mineral composition meets the requirement of significantly above (such as dolomite and quartz) or below (such as clay) the general range of thermal conductivity of 2–4 W/(m·K) and containing certain amount, there would be a significant correlation between matrix thermal conductivity and that of the constituents. Compaction diagenesis can make the grain size and porosity of sandstones smaller, and further make their thermal conductivities greater
- (4) Based on the contribution of mineral compositions on bulk thermal conductivity, considering the degree of intactness of crystals and complex relation of particle contact, empirical correction factors for quartz, feldspar, and debris and interstitial materials ranked from high to low were developed to estimate the sandstone's thermal conductivity as results from experimental parameter adjustments

Data Availability

The data used to support the findings of this study are available from the first author upon request (first author: Boning Tang; email: tangboning@foxmail.com).

Disclosure

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Conflicts of Interest

The authors declare no conflict of interest.

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