RETRACTED ARTICLE: Analysis of the relationships between the thermophysical properties of rocks in the Dandong Area of China

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\section*{ABSTRACT}

Data of this paper analysis indicates that the thermal conductivity increases with increasing water content. X-ray diffraction was used to analyze the mineral compositions of the rock samples. The rock samples were found to contain quartz, alkali-feldspar, and plagioclase. A theoretical equation was applied to calculate the skeleton thermal conductivity ($\lambda_s$) of the rocks in the Dandong region and the thermal conductivity of the saturated rocks ($\lambda_{sat}$) after conversion occurred, which were later compared to the quartz content. The quartz content was found to positively correlate with the skeleton thermal conductivity. Scanning electron microscopy was used to obtain images of the rock samples, which were used to determine the microscopic structure of the different rock types and to determine the relationship between the thermal conductivity and the porosity. We determined that the mineral content and porosity of igneous rocks is far higher than that of sedimentary rocks, and the thermal conductivity of igneous rocks is generally higher than that of sedimentary rocks. The relationship between thermal conductivity and porosity was investigated using eight different thermal conductivity-porosity models. The results indicate that thermal conductivity decreases with increasing porosity.

\section*{Introduction}

As global warming and energy resource depletion become more extensive, the need for exploration and development of geothermal energy is becoming more widely recognized, accepted, and valued. By 2010, there were 40 countries invested in the development and use of geothermal energy. Because geothermal energy is based on rich reserves, stable temperatures, and is environmentally friendly, it has attracted a lot of attention from many governments. In the last few decades, the development and use of geothermal energy (Figure 1) has rapidly increased, and the collection capacity of geothermal energy installations reached 19.8 GW in 2015 in Country.

In nature, thermal conduction, thermal convection, and thermal radiation are the three major mechanisms of thermal energy transmission. Currently, in the field of geothermal energy exploration, thermal convection and thermal radiation are thought to have a relatively small effect on geothermal energy transport. This paper primarily investigates the geothermal conduction of various types of rocks, and the primary thermophysical properties that control the thermal conduction process, e.g., the coefficient of thermal conduction (thermal conductivity), specific heat capacity, water content, porosity, mineral composition, Thermophysical properties play very important roles in many research fields (Cheng et al., 2013; Demir et al., 2004; Gao et al., 2015), such as oil and natural gas exploration and development; the development of hydrothermal resources and underground thermal energy; hydrogeological issues; civil engineering; composite material production and use; and environmental and geotechnical engineering.

Many studies have been conducted to determine the relationships between the various thermophysical properties of various types of rock. For example, when the influence of the shape and structure of the particles is not taken into consideration, a correlation is observed between the thermal conductivity and the porosity of the dry and saturated states. In addition, models were applied to analyze the relationship between the thermal conductivity and the porosity of low porosity (10–30\%) crystalline rocks (Aichlmayr & Kulacki, 2006; Keller et al., 1999; Schön, 2015). These studies demonstrate that the thermal conductivity of sedimentary rock is smaller in the dry state than in the saturated state (Abid et al., 2014; Cho & Kwon, 2010; Cho et al., 2009; Schärl & Rybach, 1984; Walsh & Decker, 1966), air (thermal conductivity: 0.025 W/(m$\cdot$K)) fills the pore spaces of rocks in the dry state, while water and/or other liquids (the thermal conductivity of water: 0.6 W/(m$\cdot$K); thermal conductivity of oil: 0.1–0.2 W/(m$\cdot$K)) fill the pores of rocks in the saturated state. Using the effective continuity method, Singh et al. (1990) proposed a model for the thermal...
conductivity of ternary unsaturated porous material; Cosenza et al. (2003) used a numerical simulation to investigate the influence of water content and the degree of saturation on the thermal conductivity; and Bakker (1997) used the finite element method to determine the thermophysical properties of a porous medium. Based on the results of previous studies and the relevant theoretical relationships, this study investigates the thermal physical properties of the rocks in the vicinity of Dandong, China. We use a variety of theoretical models, to analyze the relationships between each of the thermal physical parameters.

The study area is Dandong City in northeastern China. It is an intermediate-to-high altitude region characterized by low hills. The samples analyzed were primarily rocks from the main strata in the study area. A total of 97 groups of rock samples were collected including granodiorites, syenogranites, monzonitic granites, siltstones, fine sandstones, sandstones, and mudstones. In particular, the thermal conductivity, water content, and porosity of 26 groups of samples were analyzed to determine the relationship between the thermal conductivity and water content. The thermal conductivity, porosity, and mineral composition of six groups of samples were analyzed to investigate the relationship between the thermal conductivity and mineral composition. In addition, the thermal conductivity, porosity, and specific heat capacity of 20 groups of samples were analyzed to determine the relationship between the thermal conductivity, specific heat capacity, and porosity.

Article have done some work on the topic of this paper: 1. The main thermophysical property parameters involved in the formation rock mass in the geothermal energy conduction are studied, including thermal conductivity, specific heat capacity, water content, porosity, mineral composition. 2. With the increase of water content, the thermal conductivity tends to increase, and the granitic diorite has the least influence, while the sandstone has the most influence. 3. The X-ray diffraction technology analysis of rock samples, rock samples containing quartz, alkali feldspar and plagioclase, using the theoretical formula to calculate the rock skeleton conductivity (\( \lambda_s \)) and the thermal conductivity coefficient of thermal conductivity of saturated rocks (\( \lambda_{sat} \), where \( \lambda_{sat} \) is higher. 4. In order to comprehensively analyze the relationship between thermal conductivity and porosity, SEM technology was used to take photographs of rock samples to obtain the microstructure of different types of rocks. The mineral content and porosity of magmatic rocks were obviously better than that of sedimentary rocks, and the thermal conductivity of magmatic rocks was generally higher than that of sedimentary rocks. 5. The relationship between thermal conductivity and porosity was further studied theoretically more accurately, and 8 thermal conductivity – porosity relationship models were analyzed. The results showed that thermal conductivity tended to decrease with the increase of porosity.

**Research methods**

**Experimental methods**

The thermal conductivity of the rock was measured in the laboratory, using a thermal conductivity sensor (TCS) (Figure 2). The TCS was used to measure the...
anisotropic thermal conductivity of various types of rocks along each direction in space.

The specific heat capacity measurements were conducted using a BRR specific heat capacity device, the combined cooling method, and a high-precision temperature recorder and thermocoupler (Figure 2). The porosity was obtained using a KS-1 gas permeation device and the gas method with nitrogen as the testing medium. Sandstone and mudstone samples were imaged using a scanning electron microscope (SEM) in order to analyze the relationship between the thermal conductivity and porosity of the rocks. Field-emission environmental SEM (model XL30ESEM-FEG) was used to investigate the microscopic structures, the microscopic surface structures, and the distribution of the micro-pores within the various rocks, thus allowing for the complete characterization of the relationship between the thermal conductivity and porosity of the rocks. Mineral compositions were analyzed using X-ray diffraction.

**Analysis methods**

1) The water content of the rock samples was analyzed in order to determine the relationship between water content, thermal conductivity, and porosity. The relationship between the thermal conductivity of the different rock types and water content was obtained after these properties were measured for the collected samples. Based on the variations in thermal conductivity, water content, and porosity of the test specimens in the dry state (low water content) and the saturated state (high water content), the relationship between water content and thermal conductivity due to porosity was determined.

2) X-ray diffraction was used to analyze the mineral composition of representative rock samples. Fuchs et al. proposed a geometrical mean model of the thermal conductivity of the rock skeleton where the thermal coefficient of the rock skeleton is equal to the product of the thermal conductivity of each of the mineral components forming the rock. Based on the measured mineral contents of the different rock samples, modeling was used to calculate the skeleton thermal conductivity of each rock sample. The thermal conductivity of each rock skeleton was converted into the thermal conductivity of the saturated rock to compare the accuracy of the calculation results. The mineral component that affected the thermal conductivity the most was evaluated by comparing the skeleton thermal conductivity after the calculation was performed, the thermal conductivity of the saturated rock after the conversion was performed, and the measured laboratory thermal conductivity.

3) The thermal conductivity, porosity, and specific heat capacity of the rock samples were measured and compared to investigate the relationships between the various properties. The data was plotted to investigate how the thermal conductivity and the specific heat capacity of the rock varied with porosity. The SEM images were used to analyze the microscopic structure of different types of rocks and to compare their mineral compositions and porosities and determine the relationship between the thermal conductivity and the porosity.

Based on the aforementioned analysis, eight practical theoretical models were used to construct curves of the thermal conductivity versus porosity for the different types of rocks. The results were then compared with the measured values, and the fit of the two data sets was calculated. In addition, while summarizing the relationship between the thermal conductivity and the porosity, the most practical of the eight models was selected for use with the data from the study area. Part of the coefficient of thermal conductivity of the rock samples is consistent with the calculated results of the individual models. Research to try to decrease the skeleton of the thermal conductivity of the rock sample to the thermal conductivity of sandstone, 2.55 W/(m·K), if the matrix thermal conductivity of the sandstone is decreased to 2.55 W/(m·K), We have made relevant attempts. If the thermal conductivity of the sandstone skeleton is reduced to 2.55 W/(m·K), It is compared with various models, The comparison shows that the thermal conductivity of the sandstone fits the result of the Litovskii model well.

Theoretical models have been widely applied to study the relationship between porosity and thermal conductivity. Table 1 shows some theoretical research models in which the thermal conductivity of the porous material is a function of porosity. In these models, the thermal conductivity is a function of the skeleton...
thermal conductivity ($\lambda_s$), the thermal conductivity of the saturated fluid ($\lambda_f$), and the porosity ($\phi$).
Discussion

Properties that affect thermal conductivity

Relationship between thermal conductivity, water content, and porosity

The effect of water content on the thermal conductivity of a rock is mainly due to the fact that the thermal conductivity of water is higher than that of air. Thus, when a rock’s pores are filled with water, the thermal conductivity of the rock is higher than when the pores are filled with air. As shown in Figure 3, as water content increases, the thermal conductivity of the rock increases. Because water is the medium within the rock that conducts the heat, different water contents result in different thermal conductivities (Seipold, 1998).

Test results indicate that the thermal conductivity of rock samples in the dry state ranged from 1.2 to 3.1 W/(m·K), while the thermal conductivity of rock samples in the saturated state ranged from 1.8 to 3.3 W/(m·K). The thermal conductivity of the granodiorites in the dry state ranged from 2.6 to 2.8 W/(m·K), while that of granodiorites in the saturated state ranged from 2.7 to 3.1 W/(m·K). The thermal conductivity of the syenogranites in the dry state ranged from 2.2 to 2.8 W/(m·K), while that of syenogranites in the saturated state ranged from 2.8 to 3.3 W/(m·K). The thermal conductivity of the fine sandstones in the dry state ranged from 2.2 to 2.5 W/(m·K), while that of sandstones in the saturated state ranged from 2.7 to 4.3 W/(m·K). The thermal conductivity ranges of the different types of rocks in the dry state are not the same, and the thermal conductivity ranges of the different types of rocks in the saturated state are not the same, which is most likely due to factors such as the mineral composition and structure of the rocks. The difference in the water contents of the different types of rocks is related to porosity. For example, granodiorite has a low porosity and a correspondingly low water content of approximately 2%, while sandstone has a relatively high porosity and a correspondingly high water content of approximately 20%.

Based on the above analysis, the thermal conductivity of the dry and saturated states are not as different for lower porosity rocks, i.e., the lower the porosity of the rock, the less affect water content has on the rock’s thermal conductivity. Conversely, the greater the porosity, the greater affect water content has on the rock’s thermal conductivity (Figure 3).

Relationship between thermal conductivity and mineral composition

The thermal conductivity is a combination of the thermal conductivity of the minerals and that of the fluids within the pore spaces of the rock. Thus, the thermal conductivity of the rock is related to the thermal conductivity of the mineral components. X-ray diffraction was used to analyze the mineral components of representative rock samples (Table 2). The results indicate that all of the rock samples contain quartz, alkali-feldspar, and plagioclase, but the contents of these minerals vary among the rock samples.

Fuchs and Förster (2010) proposed a geometrical mean model in which the thermal conductivity of a rock’s matrix is the product of the thermal conductivity of each of the mineral components in the rock, which is illustrated by the following equation:

\[ \lambda_s = \lambda_1^{n_1} \lambda_2^{n_2} \cdots \lambda_n^{n_n} \]  

\[ (1) \]

In Equation (1), \( \lambda_s \) is the thermal conductivity of the rock skeleton in W/(m·°C); \( \lambda_i \) is the thermal conductivity of the ith mineral in the rock in W/(m·K), and \( n_i \) is the content of the ith mineral of the rock.

Based on the mineral contents of the different rock samples listed in Table 2, Equation (1) can be used to calculate the matrix thermal conductivity of each rock sample. Then, the geometrical mean model can be used to convert the thermal conductivity of the rock skeleton into the thermal conductivity of the saturated rock and to compare the accuracy of the calculations. Assuming that the pores are all filled with water (thermal conductivity: 0.6 W/(m·K), the conversion equation is as follows:

\[ \lambda_{sat} = \lambda_3^{1-\phi} \lambda_1^\phi \]  

\[ (2) \]

In Equation (2), \( \lambda_{sat} \) is the thermal conductivity of the saturated rock in W/(m·K); \( \lambda_1 \) is the thermal conductivity of the fluid in the pores in W/(m·K); and \( \phi \) is the porosity of the rock.

Table 3 presents the skeleton thermal conductivity of the rock samples, the thermal conductivity of the saturated rock after the conversion was performed, and the measured thermal conductivity. The matrix thermal conductivity is closely related to the quartz content of the rock (Table 3). Rocks with a high quartz content also have a relatively high matrix thermal conductivity because the thermal conductivity of quartz is higher than that of the other minerals. By comparing the calculated thermal conductivity and

| Sample # | Rock type   | Quartz | Alkali-feldspar | Plagioclase | Other |
|----------|-------------|--------|----------------|-------------|-------|
| HGSC4-7  | Granodiorite| 28     | 17             | 25          | 30    |
| HGSC9-16 | Granodiorite| 41     | 13             | 19          | 27    |
| ZCHG4-7  | Syenogranite| 55     | 19             | 24          | 3     |
| S1-6     | Sandstone   | 53     | 16             | 13          | 18    |
| X5S-7    | Fine sandstone | 31 | 5             | 4           | 60    |
| N3-7     | Mudstone    | 27     | 3             | 4           | 66    |

Table 2. Mineral contents of the rock samples.
the measured thermal conductivity of the saturated rocks, it becomes apparent that the two thermal conductivity values of the partial samples are similar. However, some samples still exhibit relatively large differences, which may be due to the accuracy of the equation used for the calculation and/or the error in the measured values introduced by the equipment used. Based on these comparisons, we conclude that there is a relationship between the thermal conductivity of the rock and its mineral composition, and thus, the thermal conductivity of a rock can be calculated based on its mineral composition.

**Relationship between thermal conductivity, specific heat capacity, and porosity**

The porosity of a rock is one of the most important variables that influence its thermophysical properties. By measuring the thermal conductivity, porosity, and specific heat capacity of the different types of rocks (Table 4), the variation in thermal conductivity and specific heat capacity can be determined as a function of porosity (Figure 4). As can be seen from Figure 4, there is no significant relationship between specific heat capacity and porosity, i.e., thermal conductivity is relatively low when porosity is relatively high. This is because the thermal conductivity of a liquid or a gas is far smaller than that of a mineral. For different types of rocks, the porosity can vary substantially due to differences in the conditions under which the rock formed. The porosity of the granite is the lowest (<5%), while the porosity of the sandstone is relatively high (>10%).

SEM imaging was performed on representative samples of granite, syenogranite, sandstone, and mudstone to more fully analyze the relationship between the thermal conductivity and porosity of these rocks. These SEM images (Figure 5) illustrate the differences in the microscopic structures of the different types of rocks. The mineral content and porosity of igneous rocks are far higher than that of the sedimentary rocks, which is reflected by the thermal conductivity of the rock, i.e., the thermal conductivity of igneous rocks is typically higher than that of sedimentary rocks.

Based on the aforementioned analysis, the models in Table 1 were used to create and compare the variance curves of thermal conductivity versus porosity of the different types of rocks. The curve that best fit the measured data is that of the model most suitable for determining the thermal conductivity.

In this study, the thermal conductivity in these models is a function of the skeleton thermal conductivity ($\lambda_s$), the saturated fluid thermal conductivity ($\lambda_f$), and the porosity ($\varphi$). The thermal conductivity model is related to the solid-to-fluid thermal conductivity ratio ($\lambda_s/\lambda_f$). Aichlmayr and Kulacki (2006) divided all of the theoretical models into three categories: 1) those with low solid-fluid thermal conductivity ratios ($1 < \lambda_s/\lambda_f < 10$); 2) those with intermediate solid-fluid thermal conductivity ratios ($10 < \lambda_s/\lambda_f < 10^3$); and 3) those with high solid-fluid thermal conductivity ratios ($10^3 < \lambda_s/\lambda_f$). For a rock that is not influenced by water content, i.e., a rock in the dry state, the thermal conductivity of the rock has a high solid-fluid thermal conductivity ratio.

By using the models in Table 1, Figure 6 compares the measured values and the curves of thermal conductivity vs. porosity for all seven models for the granite, syenogranite, and sandstone. As can be seen from Figure 7, the variance curves of the thermal conductivity versus porosity are different for the different types of rocks, which is primarily due to the different thermal conductivities of their rock skeletons. In addition, it can be seen that the variance curves of the syenogranite and the sandstone are both greater than the measured values, indicating that the thermal conductivity of the rocks cannot be effectively calculated by these models. Only the
thermal conductivity of the granodiorite is relatively close to the model of Sugawara and Yoshizawa; however, the models do not satisfactorily match the measured data, indicating that these models are not effective for the rock samples studied in this paper.

The thermal conductivities of the partial rock samples are consistent with the results of several models. The skeleton thermal conductivity of the rock sample used affects the fit of the models, and the variance curves of several models satisfactorily fit the measured values. For example, if the skeleton thermal conductivity of the sandstone is decreased to 2.55 W/(m·K), then the thermal conductivity of the sandstone fits the result of the Litovskii model well.

Figure 7 shows the thermal conductivity curves of the different types of rocks calculated using the Keller model, which accounts for the effect of the shape of the pores on the thermal conductivity. This model considers the impact of the ratio of the pore size to the particle size (b/a, where 2b is the pore size and 2a...
is the particle size) on the thermal conductivity. The curves of thermal conductivity versus porosity fit the measured results of the rock samples well; thus, we conclude that this model can be used to calculate the thermal conductivity of the various types of rocks.

Conclusions

(1) The thermal conductivity of the rock samples increased with increasing water content. The differences in the water contents of the various types of rock are related to differences in their porosities, i.e., lower porosity results in the saturated state affecting the thermal conductivity of the rock less.

(2) Rocks are composed of minerals and the pore space between them. Therefore, the thermal conductivity of a rock is the combined result of the thermal conductivity of the minerals forming the rock and the fluids in the pore spaces. Thermal conductivity is closely related to the quartz content of the rock because quartz has a high thermal conductivity.

(3) If two samples have the same mineral content, then the thermal conductivity of the high porosity sample will be lower. By comparing the plot of thermal conductivity versus porosity of the eight models of the different types of rocks with the corresponding measured values we assessed the effectiveness of the various models in determining the thermal conductivities of the different types of rocks. We conclude that the Keller model is the most appropriate model for the samples in the study area.

Because of the importance of heat conduction in the geothermal field, thermal conductivity is the key factor in studying geothermal energy transport. The thermal conductivity of the rock is closely related to its influencing factors. Therefore, even for the same rock sample, when different influencing factors are considered, the thermal conductivity determined by different scholars can be significantly different. Thus, in this paper, the rocks in the Dandong region were studied in detail to determine the relationship between the coefficient of thermal conductivity and its various influencing factors. Our results provide important information that can be used in the development of geothermal energy exploitation and development.

Key Points

- The interaction between thermal and physical parameters of rock was analyzed by using X-ray diffraction, SEM imaging and the model of thermal conductivity - porosity function.
The thermal conductivity of rock increases with the increase of water content. The quartz content of rock is high and the thermal conductivity is high. The thermal conductivity of rock decreases with the increase of porosity.

Our results provide important information that can be used in the development of geothermal energy exploitation and development.

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Disclosure statement

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