# CONSTRUCTION AND APPLICATION ANALYSIS OF THERMAL CONDUCTIVITY MODEL OF DEEP THERMAL STORAGE PORE STRUCTURE

by

***Zhiguo WANG, Tianzhen ZHANG*, Mingzhe TAN, and Meng XUE***

School of Civil and Architectural Engineering, Northeast Petroleum University, Daqing, Heilongjiang, China

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*In the process of geothermal energy exploitation and utilization, effective heat extraction, natural recovery and other key issues are affected and restricted by the thermal conductivity process of geothermal reservoirs, and the relevant thermal conductivity model research is not very comprehensive at present. In this paper, the deep heat storage in pore structure is divided into development zone, wave zone and original zone according to their thermal conductivity characteristics. Based on the representative elementary volume description analysis method, the thermal conductivity analysis model of pore structure of deep heat storage is established, including simplified thermal conductivity model and fine thermal conductivity model. Taking granite as an example, numerical calculation was carried out to analyze the effects of porosity, impurity content, water content and channel composition coefficient on heat storage and thermal conductivity. The model established in this paper lays a foundation for controlling thermal storage and thermal conductivity mechanism, accurately analyzing thermal conductivity characteristics, reserve estimation and mining dynamic changes.*

Key words: *geothermal reservoir, thermal conductivity, model construction, representative elementary volume, thermal storage interval division*

## Introduction

Geological bodies capable of storing geothermal energy are called geothermal reservoirs (referred to as thermal storage). The application prospect of geothermal resources is broad, but while people pay attention the economic and environmental benefits brought by geothermal energy, they cannot ignore the follow-up problems caused by continuous and over-exploitation. Studies have shown that the thermal conduction process of thermal storage has an important impact on the development, extraction and recovery of energy in geothermal reservoirs. Therefore, it is of great significance to study the thermal characteristics of geothermal reservoir and extract heat reasonably and efficiently for geothermal mining engineering [1-4].

Generally speaking, deep geothermal reservoirs are often located 3-10 km underground [5], mainly composed of rock and soil mass and groundwater system. Among them, the micro-structure of rock and soil can be expressed in the form of faults, joints, and cracks. The actual macroscopic rock and soil is a complex structure formed by the coupling of different micro-structures. Affected by the high temperature and high pressure environment, the macro-

* Corresponding author, e-mail: ztzsunbeam@163.com

scopic rock and soil have the characteristics of multi-scale, multi-phase flow, and multi-field coupling [6-8]. At present, scholars at home and abroad have carried out some research on the construction of porous media model of rock and soil. At the beginning of the research, Bear [9] proposed the concept of representative elementary volume (REV) in rock and soil mechanics for soil seepage analysis. On this basis, Louis [10] proposed an equivalent continuum model. Wilson and Witherspoon [11] regarded the fractured rock mass as a continuous medium and a discontinuous medium. After calculating and comparing it, he pointed out that when the ratio of the maximum fracture spacing to the minimum boundary size of the building is greater than 1/50, it should be considered as a discontinuous medium. Sinha [12] compared the continuum model with the discontinuous model and found that the continuum model can adequately reproduce the damage and deformation process of the reinforced rock mass. In recent years, based on practical application needs, domestic and foreign scholars have further improved related theoretical models based on fractal theory, normalization concepts, ANN, and thermal and moisture coupling in porous media. In response to different research backgrounds, a variety of flow models have been proposed, mainly including equivalent continuous medium model [13], dual medium model [14], random continuous medium model [15], discrete fracture network model [16], discrete fractured cavity Network model [17], hybrid model [18], and fractal improvement model [19], *etc.* In addition, the description and establishment methods of the porous media characterization unit are also constantly improved and developed.

The research on the heat transfer mechanism of thermal storage has made some achievements in theoretical model construction, experimental characteristic analysis, and thermal-fluid-solid three-field coupling numerical simulation. Jia *et al.* [20] proposed a rock-soil thermal conductivity model based on the serial-parallel thermal resistance method, which was verified by the thermal conductivity of 74 rock samples. The results show that the model can accurately predict the thermal conductivity of rock-soil media with different components and different water content under the condition of low permeability and high permeability. Comparison with experimental results shows that this method is effective for argillaceous rock. With the development and application of some sophisticated and micro-experimental instruments, some scholars began to study the internal structure and heat conduction of substances from the micro level. Li *et al.* [21] developed a microscopic model to describe the interface thermal resistance between the thermal probe and the sample surface in the scanning thermal microscopy measurement [22], used this model to correlate the probe current and thermal conductivity of the test sample, and performed quantitative thermal conductivity analysis. The influence of the size of graphene oxide nanosheets on their intrinsic thermal conductivity was explored through experiments, [23, 24] studies showed that the nanosheets with larger size had higher thermal conductivity because of fewer morphological defects. Wang *et al.* [25] tested granite samples before and after deep heat treatment using polarized light microscopy, nuclear magnetic resonance, and thermal constant analyzer. The study found that the porosity and thermal conductivity of rock have a great influence on the occurrence environment, mineral composition and particle size, and the increase of porosity and water content will lead to the decrease of thermal conductivity and specific heat capacity. The actual rock and soil are mostly under the condition of multi-field coupling. Liu *et al.* [26], Salimzadeh *et al.* [27] considered the spatial distribution of permeability and the heat capacity of rocks and other factors, and used finite element method, Galerkin method and other methods to establish a fully coupled thermal-hydro-mechanical porous media geothermal Reservoir model.

Constructing a more accurate thermal storage porous medium heat conduction analysis model will play a theoretical support role for fine exploration of geothermal application process, effective heat extraction and natural recovery. At present, the research on the heat conduction mechanism of thermal storage, the microscopic aspects are mostly analyzed through experiments, the mechanical properties of rock and soil and the structure of rock and soil. The macroscopic aspect divides the geothermal reservoir into hydrothermal type, shallow layer and dry hot rock, description. The analysis model has many shortcomings, and it is not enough to analyze the geothermal mining process in detail. In view of this, this paper analyzes the thermal conductivity characteristics of the thermal storage development process for magma-type geothermal reservoirs. Based on the porous media REV description analysis method, a simplified thermal conductivity model and a fine thermal conductivity model are constructed. The effects of porosity, pore impurity content, pore water content, channel composition coefficient*, etc.* on the thermal conductivity of thermal storage are analyzed.

## Analysis of dynamic development interval of deep thermal storage

### *Analysis of deep thermal storage composition and thermophysical properties*

Common reservoir rock mass materials mainly include granite, limestone, sandstone*, etc.* The thermophysical properties of the rock mass are judged mainly through structure and structure, surrounding rock pressure, temperature distribution, formation lithology, porosity, and water content. Among them, the thermal properties of rock mass mainly include the thermal conductivity, specific heat, thermal diffusion rate and radioactive heat generation rate of rocks. In this paper, the data on thermophysical parameters taken from [28] and given in tab. 1 were used. Studies have shown that granite and sandstone have better heat transfer performance [29].

The study of deep geothermal reservoirs in this paper is mainly carried out on typical geothermal reservoirs composed of rock-soil masses and groundwater systems. Other types of geothermal reservoirs are not involved here. In undeveloped deep geothermal reservoirs, most of the parts with fault structures removed are low permeability dense rock mass, which makes it difficult to apply geothermal energy. In the development of geothermal reservoirs, reservoir reconstruction methods are often used to treat low permeability tight rocks. The body undergoes transformation, as shown in fig. 1 for the engineering fracture system. At present, the main reservoir modification methods are thermal excitation, hydraulic excitation and chemical excitation [29]. In the process of geothermal reservoir research, except for the aforementioned thermal physical properties, the difference of rock mass scale (such as pore size) has a great influence on the thermal physical properties of geothermal reservoirs, and it is an important parameter to judge the thermal conductivity of the reservoir.

**Table 1. Thermophysical properties of common reservoir rock materials [28]**

| Rock mass | $c$ [Jkg$^{-1}$°C$^{-1}$] | $\lambda$ [Wm$^{-1}$°C$^{-1}$] |
|---|---|---|
| Granite | 794 | 2.721 |
| Limestone | 920 | 2.010 |
| Sandstone | 878 | 2.596 |

### *Analysis of thermal conductivity characteristics during thermal storage development*

The heat and mass transfer process is an important process for the application of geothermal reservoirs, and the thermal conductivity of the thermal storage is often affected by its occurrence environment. Impurities such as cements and interstitials in the rock medium will

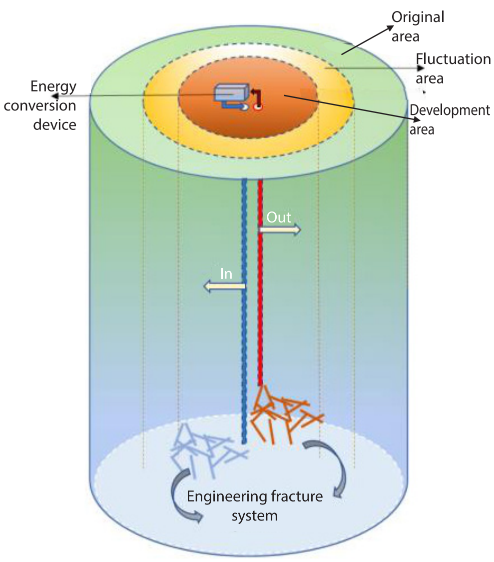


**Figure 1. Physical model of dynamic characteristics of deep thermal reservoir during exploitation**

also affect the thermal conductivity of the reservoir. As shown in fig. 1, the porosity of the thermal storage near the heat extraction well after the transformation becomes larger, the connectivity becomes better or the heat exchange area is increased, and the heat conduction effect becomes better. The rock formation at the infinity of the heat extraction well has not changed. Affected by the rapid loss of heat near the heating well and the influence of heat transfer at infinity, the boundary between the vicinity of the heating well and the infinity presents a fluctuating state, and the heat conduction effect is unclear.

According to the different thermal conductivity characteristics of different regions in the development process of geothermal reservoirs, the geothermal reservoir during the development process is divided into primitive areas at infinity, the development area near the thermal wells and the fluctuation area between the two.

## Description and characterization method of deep geothermal reservoir based on REV

*The REV description method for porous media*

Porous media is a space occupied by multi-phase materials, and it is also a combination of multi-phase materials coexisting. It is generally composed of a solid framework and fluid inside the pores. In the process of porous media research, methods such as volume averaging and homogenization are often used to select representative units for coarsening research. When studying the heat-related issues of porous media, the composition of the solid framework of the porous media, the form of fluid existence and the presence or absence of phase change, the size of the pores*, etc.* will affect the results of the study. Therefore, the selection of the characterization unit should be considered more. Figure 2 shows the relationship between the size of the average volume and the porosity. It can be seen that the key points for determining the characterizing unit body are [30]:

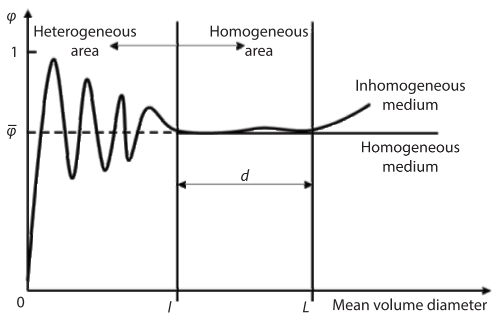


**Figure 2. The relationship between average volume size and porosity**

- This REV should be a small range around Point P, which is much smaller than the size of the entire fluid region.
- The REV should be much larger than a single void space so that it can contain enough pores.
- In REV, the variation of its basic parameters with spatial co-ordinates is small and the average value is close to the true value.

### *The REV description method for deep thermal storage porous media*

Deep geothermal reservoirs occur in high temperature and high pressure surrounding rocks, with water and steam circulating in their pores, and are a typical porous medium. The rock mass is generally an unsaturated multi-phase system, and the media in the pores are mainly dissolved particles (impurities), water and air. In the process of geothermal reservoir development, water injection causes the temperature of the reservoir in the development interval to drop sharply, the rock mass structure changes and phase transitions occur, and the thermal properties of the rock mass will also be affected. As shown in fig. 3, deep magma-type geothermal reservoirs are mainly composed of low permeability rock masses with small pore scales and fractures. The pore structure of porous media can describe its micro-structure more closely. Based on the coupled heat and moisture transfer model of porous media [31] and the basic theory of heat transfer, this paper establishes a simplified model and a fine model of the porous media pore structure of deep geothermal reservoirs.

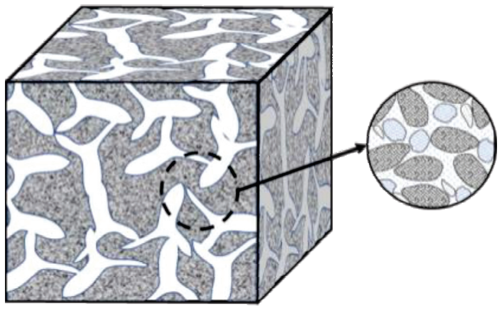

**Figure 3. Real rock mass REV structure (granite)**

### *Related parameters of thermal storage porous media*

For the analysis methods in figs. 2 and 3, for geothermal reservoir porous media to characterize the unit body, some related parameters (such as porosity*, etc.*) need to be clearly defined:

– Pore structure description model based on REV

The pore structure description model based on REV is shown in fig. 4. It includes: solid framework, $l_r$, rock impurities, $l_z$, liquids, $l_w$, gases, $l_g$, pores, $x$, and characterization units, $l$.

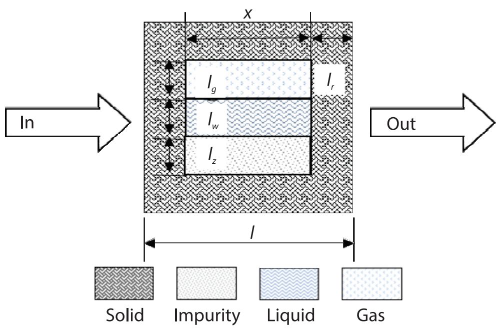


**Figure 4. Pore structure description model based on REV**

– Basic description parameters
  – Porosity refers to the ratio of the total volume of tiny pores in the skeleton of a porous medium rock mass to the total volume of the rock mass:

$$\varphi = \frac{V_k}{V} \tag{1}$$

where $\varphi$ is the porosity of the rock mass, $V_k$ – the total volume of pores, $V$ – the total volume of the porous medium of the rock mass. When the characterizing unit body is 2-D, and l the unit length, there are $x = \varphi^{1/2}$:

  – Pore impurity ratio refers to the proportion of impurities such as cements and interstitials in the rock mass medium in the pores of the rock mass medium, and its expression it:

$$m = \frac{V_z}{V_k} \tag{2}$$

where m is the porosity of the rock mass, $V_z$ – the total volume of pores, $V_k$ – the total volume of the porous medium of the rock mass. When the characterizing unit body is 2-D, and $l$ – the unit length: $l_z = (\varphi m)^{1/2}$.

– The pore water content refers to the proportion of the liquid volume in the pore volume in the characterizing unit of the porous medium of the rock mass:

$$\beta = \frac{V_w}{V_k} \tag{3}$$

where $\beta$ is the pore water content, $V_w$ – the liquid volume, $V_k$ – the total pore volume. When the characterizing unit body is 2-D, and $l$ – the unit length: $l_w = (\beta m)^{1/2}$.

## Thermal conductivity analysis model of porous thermal storage structure

The porous media structure of thermal storage is affected by the high temperature and high pressure environment and the uncertain structure, which has the characteristics of complexity, difficulty in precise exploration and estimation. At present, field experiments and heat and mass exchange mechanism research are also in a bottleneck due to lack of information. According to the characteristics of thermal storage, this paper proposes a REV-based thermal conductivity analysis model of geothermal porous media: simplified model and refined model.

### *Porous structure simplified heat conduction model*

In magma-type geothermal reservoirs, pore-type porous media dominated by fractures with smaller pore sizes are the most common. The pore-type porous media is divided into two types: hollow skeleton and solid particles. The hollow skeleton structure is the intermediate circulating pore medium (water, air, and impurities), and the solid particle structure is the solid skeleton surrounded by the porous medium:

– Simplified analysis model of hollow skeleton

The so-called hollow skeleton simplified analysis model is composed of solid skeleton around and simplified as an equivalent single fluid inside, as shown in fig. 5. The equivalent single fluid of this model can be an equivalent representation of one fluid or several fluids.

– Simplified unit of solid particles

The so-called simplified analysis model of solid particles, that is, there is an equivalent single fluid around it, and a solid skeleton inside, as shown in fig. 6.

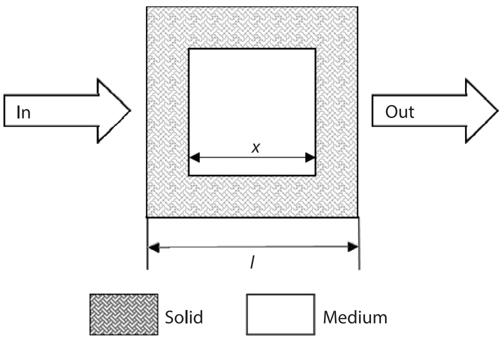


**Figure 5. REV simplified hollow skeleton model of pore structure**

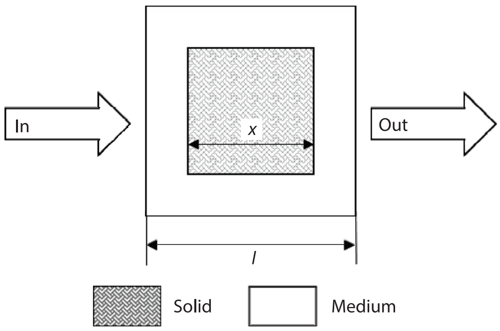


**Figure 6. REV simplified model of pore structure solid particles**

*Pore structure fine thermal conductivity model*

In the simplified analysis models shown in figs. 5 and 6, the fluid is simplified as an equivalent single fluid. The actual fluid can be multi-phase and multicomponent, with a small number of impurities*, etc.*, which need to be corrected. After correction, a fine characterization model is obtained: a hollow skeleton fine characterization model and a solid particle fine characterization model:

– Fine representation model of hollow skeleton

The composition and phase of the fluid in the pores are different at different mining intervals and at different moments. Based on figs. 4 and 5, a fine characterization model of the hollow skeleton is proposed, as shown in fig. 7.

– Fine representation model of solid particles

The composition and phase of the fluid in the pores are different at different mining intervals and at different moments. Based on figs. 4 and 6, a fine characterization model of solid particles is proposed, as shown in fig. 8.

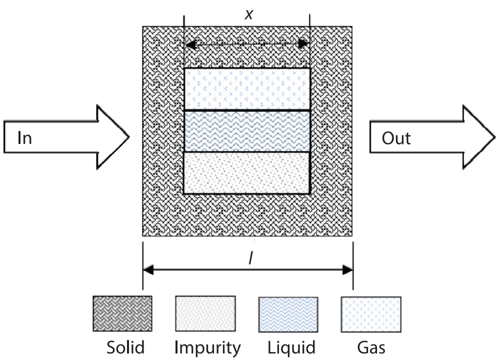


**Figure 7. The pore structure hollow skeleton REV fine characterization model**

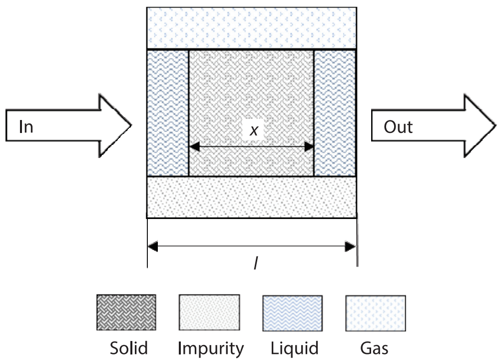


**Figure 8. The REV model for fine characterization of pore structure solid particles**

## Analysis of thermal conductivity based on simplified and refined analysis model

In practical applications, due to the structural characteristics of hollow skeleton type primitives and solid particle type primitives, the proportions of the two in the development zone, the fluctuation zone and the primitive zone are very different. The former mainly exists in the undeveloped original zone, while the latter mainly exists in the engineering fracture system in the hot mining area.

*Thermal conductivity process analysis of simplified model*

– Simplified model of hollow skeleton REV

For the model shown in fig. 5, in the heat conduction analysis, for the vertical channel direction, the model is represented as a form in which an equivalent single fluid is connected in series with the solid framework and then in parallel with the solid framework.

The equivalent thermal conductivity, $\lambda_c$, of a single fluid in series with the solid framework is:

$$\frac{1}{\lambda_c} = \frac{1-\sqrt{\varphi}}{\lambda_r} + \frac{\sqrt{\varphi}}{\lambda_f} \tag{4}$$

That is, the thermal conductivity of the simplified model of hollow skeleton REV $\lambda_x$ is:

$$\lambda_x = \left(1-\sqrt{\varphi}\right)\lambda_r + \sqrt{\varphi}\lambda_c \tag{5}$$

Substituting eq. (4) into eq. (5):

$$\lambda_x = \frac{\left(1-\sqrt{\varphi}+\varphi\right)\lambda_r\lambda_f + \left(1-\sqrt{\varphi}\right)\sqrt{\varphi}\lambda_r^2}{\sqrt{\varphi}\lambda_r + \left(1-\sqrt{\varphi}\right)\lambda_f} \tag{6}$$

where $\lambda_r$ and $\lambda_f$ [Wm$^{-1}$K$^{-1}$] are the thermal conductivity of the solid skeleton of the rock mass and the pore fluid, respectively, $\varphi$ is the porosity:

– Simplified model of solid particle REV

For the model shown in fig. 6, in the heat conduction analysis, the model is expressed as a form in which the equivalent single fluid is connected in series with the solid framework and then in parallel with the equivalent single fluid.

The equivalent single fluid and solid framework series thermal conductivity, $\lambda_c$ is:

$$\lambda_s = \left(1-\sqrt{1-\varphi}\right)\lambda_f + \sqrt{1-\varphi}\lambda_c \tag{7}$$

That is, the thermal conductivity of solid particle REV simplified model $\lambda_s$ is:

$$\frac{1}{\lambda_c} = \frac{1-\sqrt{1-\varphi}}{\lambda_f} + \frac{\sqrt{1-\varphi}}{\lambda_r} \tag{8}$$

Substituting eq. (7) into eq. (8), there are:

$$\lambda_s = \frac{\left(2-\sqrt{1-\varphi}-\varphi\right)\lambda_r\lambda_f + \left(1-\sqrt{1-\varphi}\right)\sqrt{1-\varphi}\lambda_f^2}{\sqrt{1-\varphi}\lambda_f + \left(1-\sqrt{1-\varphi}\right)\lambda_r} \tag{9}$$

*Analysis of the heat conduction process of the fine model*

When conducting the thermal analysis of the fine model of the models in figs. 7 and 8, the internal components of the pores can be finely characterized as impurities, liquid media, and gaseous media for correction:

– Analysis of the heat conduction process of the hollow skeleton fine model

In the fine analysis of the hollow skeleton element, the internal medium of the pore contains impurities, liquid medium, and solid medium. When analyzing the model in fig. 7, the model is represented as a form in which impurities, liquid media and gaseous media are connected in parallel with the solid framework first and then connected in series with the solid framework.

That is, the thermal conductivity of the hollow frame REV fine model $\lambda_{jx}$ is:

$$\lambda_{jx} = \frac{\left(1-\sqrt{\varphi}+\varphi\right)\lambda_r\lambda_z\lambda_l\lambda_g + \left(1-\sqrt{\varphi}\right)\lambda_r^2\left[\sqrt{\varphi m}\lambda_l\lambda_g + \sqrt{\varphi\beta}\lambda_z\lambda_g + \left(\sqrt{\varphi}-\sqrt{\varphi m}-\sqrt{\varphi\beta}\right)\lambda_z\lambda_l\right]}{\left(1-\sqrt{\varphi}\right)\lambda_z\lambda_l\lambda_g + \sqrt{\varphi m}\lambda_r\lambda_l\lambda_g + \sqrt{\varphi\beta}\lambda_r\lambda_z\lambda_g + \left(\sqrt{\varphi}-\sqrt{\varphi m}-\sqrt{\varphi\beta}\right)\lambda_r\lambda_z\lambda_l} \tag{10}$$

where $\lambda_r$, $\lambda_z$, $\lambda_l$, and $\lambda_g$ [Wm$^{-1}$K$^{-1}$)] are the thermal conductivity of the rock-solid framework, rock impurities, liquid medium, and gas medium, respectively, $\varphi$ – the porosity, $m$ – the impurity in the pores rate, and $\beta$ – the pore water content.

– Analysis of the heat conduction process of the solid particle fine model

During the fine analysis of solid particles, the components in the pores surround the solid framework, the rock impurities are deposited at the bottom of the model, the gas medium is suspended on the upper part of the model, and the middle is filled with liquid medium. For the model in fig. 8, in thermal conductivity analysis, the model is expressed as the liquid medium and solid skeleton in series' first and then in parallel with gas medium and rock mass impurities.

That is, the thermal conductivity of the solid particle REV fine model $\lambda_{js}$ is:

$$\lambda_{js} = \frac{\sqrt{1-\varphi}\lambda_l \lambda_r}{\sqrt{1-\varphi}\lambda_l + \sqrt{\beta\varphi}\lambda_r} + \sqrt{\varphi m}\lambda_z + \left(\sqrt{\varphi} - \sqrt{\varphi m} - \sqrt{\beta\varphi}\right)\lambda_g \tag{11}$$

## Analysis of dynamic heat conduction in thermal storage mining process

For a certain macroscopic interval, it can be formed by the coexistence and coupling of hollow skeleton and solid particles, and it is also a description model of regular arrangement of primitives and from local to system. The specific analysis model is shown in fig. 9.

For the model shown in fig. 9, in the actual thermal storage process, the original interval REV can use a simplified model, but the fluctuation and production interval must use a fine model.

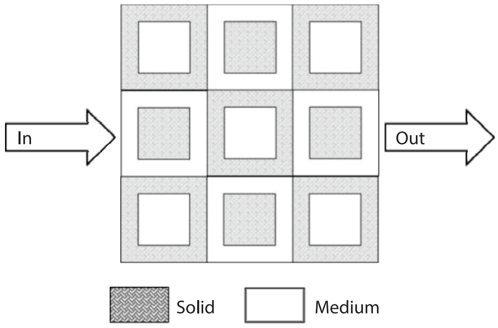


**Figure 9. Analysis model of heat transfer in macroscopic interval of heat storage**

### *Macroscopic thermal model analysis*

As far as fig. 9 is concerned, in the heat conduction analysis, according to the different heat conduction paths, the thermal storage macro-interval heat conduction analysis model can be expressed as: series-parallel model, fig. 10, and parallel-series model, fig. 11.

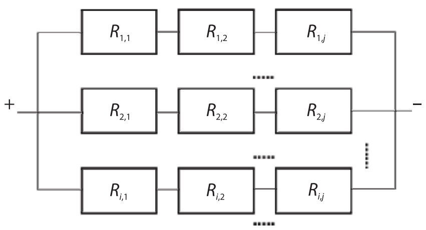


**Figure 10. Series-parallel model analysis**

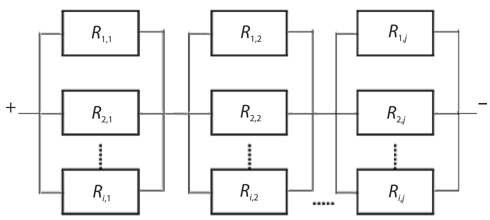


**Figure 11. Parallel-series model analysis**

### *Macroscopic heat conduction process analysis*

– Analysis of heat conduction process of series-parallel model

For fig. 10, the series-parallel model is to first connect the $j$-column thermal resistance in series, treat it as a whole, and then connect the $i$-row thermal resistance in parallel. The thermal conductivity of the series-parallel simplified model $\lambda_1$ is:

$$\lambda_1 = \frac{1}{i}\sum_{j-1}^{i} \frac{\lambda_{ss}\lambda_{xx}}{\lambda_{xx}\left(1-\gamma_j\right) + \lambda_{ss}\gamma_j} \tag{12}$$

where $\lambda_{ss}$ [Wm$^{-1}$K$^{-1}$] is the thermal conductivity coefficient of the solid particle characterizing the unit body model, $\lambda_{xx}$ [Wm$^{-1}$K$^{-1}$] – the thermal conductivity coefficient of the porous hollow skeleton characterizing the unit body model, $\gamma$ [%] – the channel composition coefficient: hollow frame the proportion of the characterization unit in a row (column) of the porous media characterization unit, $i$ – the number of rows, and $j$ – the number of columns.

– Analysis of heat conduction process of parallel-series model

For fig. 11, the parallel-series model is to first connect the $i$-row thermal resistance in parallel, treat it as a whole, and then connect the $j$-column thermal resistance in series. The thermal conductivity of the parallel-series simplified model $\lambda_2$ is:

$$\frac{1}{\lambda_2}=\frac{1}{j}\sum_{i=1}^{i}\frac{1}{\lambda_{ss}\left(1-\gamma_j\right)+\lambda_{xx}\gamma_j} \tag{13}$$

– Analysis of heat conduction process in practical application

In the actual heat storage, the hollow skeleton and solid particle elements exist simultaneously and are coupled with each other. The primitive areas are mostly tight rock formations, with hollow skeleton elementary structures occupying a larger portion and porosity smaller. In the engineering fracture system of the development zone, most of the fractures are solid particle element fine structures, and the fine structure of the hollow skeleton element of the rock mass between the fractures accounts for more, and the porosity or heat exchange area is increased. The fluctuation interval has the characteristics of both the original area and the development area. The fluctuation interval has the characteristics of both the original area and the development area. The fine structure of the hollow skeleton characterizing the unit body and the fine structure of the solid particle characterizing the unit body are coupled, and the original area and the development area are jointly considered in the analysis of the heat conduction process.

## Model verification and numerical analysis

Granite is a kind of granular crystalline rock, dense and hard. As a typical material for magmatic heat storage, granite generally dislocation and extension of the existing fracture surfaces of the reservoir by controlling the pressure of injected water, thereby forming an effective heat exchange area and used for reservoir reconstruction [32]. The pore size of granite is small and can be studied microscopically, which is suitable for model verification and numerical analysis of the pore structure of porous media in this paper.

### *Model validation*

Chen [33] used a thermal constant analyzer to obtain the change law of the thermal conductivity of granite conventional samples and dry samples at 25-150 °C through high temperature oil bath tests. The result shows that the conclusion obtained by the thermal constant analyzer is close to the actual situation, which can provide a reference for similar experiments. Select the thermal conductivity test value of this experimental BS15 sample at 120 °C to verify the model built in this article when the porosity is 0.07, the pore impurity rate is 0.3, and the pore water content is 0.3, to judge the correctness of the new model (the porosity of granite is generally between 0.04% and 10.71%).

It can be seen from tab. 2 that the thermal conductivity of the hollow skeleton and solid particle fine models are less than 15% from the experimental results, and the deviations between the two macroscopic models and the experimental results are less than 2%, and the models are close to reality.

**Table 2. Experimental test and model comparison**

| Project | Experiment | Fine model of hollow skeleton | Solid particle fine model | C-B | B-C |
|---|---|---|---|---|---|
| Thermal conductivity [Wm$^{-1}$K$^{-1}$] | 2.8 | 2.49 | 2.85 | 2.75 | 2.76 |
| Relative deviation [%] | – | 11 | –1.8 | 1.8 | 1.4 |

Note: The C-B is the thermal conductivity of the series-parallel model, and B-C is the thermal conductivity of the parallel-series model.

### *Basic parameter selection*

In this paper, granite is selected as the porous medium framework for simulation analysis, the pore fluid is water and air, and the pore impurities are quartzite (quartzite in granite internal impurities accounted for a large proportion of the composition) for numerical calculation, and the thermal conductivity and the influence of various parameters (porosity, pore impurity, pore water content, channel composition coefficient) are analyzed. Related parameters are shown in tab. 3.

**Table 3. Thermal conductivity of medium [28]**

| Medium | Thermal conductivity [Wm$^{-1}$K$^{-1}$] |
|---|---|
| Granite | 2.721 |
| Equivalent single fluid | 2.527 |
| Water | 0.599 |
| Air | 0.023 |
| Quartzite | 7.600 |

### *Analysis of the influence of porosity change on thermal conductivity*

According to the aforementioned thermal conductivity calculation equation and physical parameters, the thermal conductivity of the simplified thermal conductivity model, the fine thermal conductivity model and the macroscopic model are numerically calculated. The thermal conductivity of the hollow framework and solid particles are shown in fig. 12.

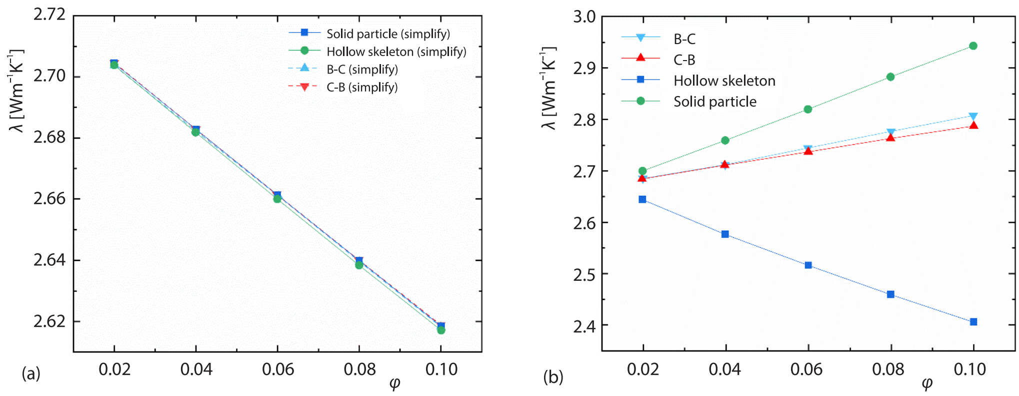


**Figure 12. Effect of porosity on thermal conductivity; (a) C-B (simplify) is the thermal conductivity of the series-parallel simplified model, and B-C (simplify) is the thermal conductivity of the parallel-series simplified model and (b) C-B is the thermal conductivity of the series-parallel fine model, and B-C is the thermal conductivity of the parallel-series fine model**

It can be seen from fig. 12(a) that when the pore impurity content and pore water content are constant, as the porosity increases, the thermal conductivity of the simplified hollow skeleton model, solid particles, series-parallel macroscopic, and parallel-series macroscopic thermal conductivity models are all shows a decreasing trend. Among them, the thermal conductivity of the simplified hollow skeleton model has the greatest change, which decreases from 2.7-2.61 W/mK.

It can be seen from fig. 12(b) that when the pore impurity content and pore water content are constant, with the increase of porosity, the thermal conductivity of the fine model of the hollow skeleton shows a decreasing trend, from 2.64-2.4 W/mK. The thermal conductivity of solid, series-parallel macroscopic, and parallel-series macroscopic fine thermal conductivity models all showed an upward trend with the increase of porosity, and the solid fine model had an obvious upward trend, with thermal conductivity increasing from 2.7-2.94 W/mK.

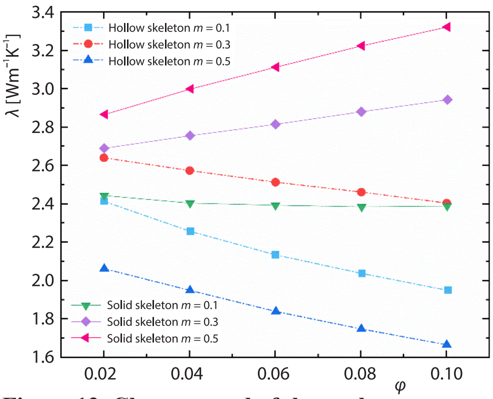


**Figure 13. Change trend of thermal conductivity at different time *m***

### *Analysis of the influence of the change of pore impurity rate on the thermal conductivity*

According to eqs. (10) and (11), when the porosity impurity content is 0.1, 0.3, and 0.5, the thermal conductivity varies with porosity as shown in fig. 13. When the pore water content is constant, the thermal conductivity of the hollow framework fine model decreases with the increase of the porosity, and first increases and then decreases with the increase of the pore impurity. The thermal conductivity of the fine solid particle model increases with the increase of porosity. When the porosity is constant, the thermal conductivity increases with the increase of the impurity content, and the growth rate decreases with the increase of the porosity.

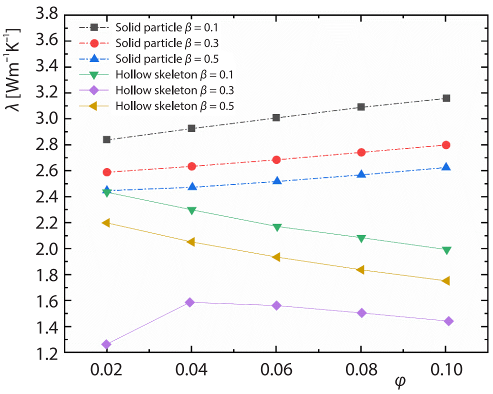


**Figure 14. Change trend of thermal conductivity at different time *β***

### *Analysis of the influence of the change of pore water content on the thermal conductivity*

According to es. (10) and (11), when the pore water content is 0.1, 0.3, and 0.5, respectively, the change of thermal conductivity with porosity is shown in fig. 14. The thermal conductivity of the fine hollow skeleton model decreases with the increase of porosity when the impurity content is constant. The thermal conductivity of the fine solid particle model increases with the increase of porosity. When the porosity is constant, the thermal conductivity of the fine hollow skeleton model decreases first and then increases with the increase of pore water content. The thermal conductivity of the fine solid particle model decreases with the increase of pore water content.

*Analysis of factors affecting thermal conductivity of macroscopic model*

According to eqs. (12) and (13), when the pore impurity content is 0.1, 0.3, 0.5, and the pore water content is 0.1, 0.3, 0.5, the thermal conductivity varies with porosity as shown in figs. 15(a)-15(c) as shown. It can be seen from fig. 15 that when the pore impurity content and pore water content are constant, the thermal conductivity of the macroscopic series-parallel model and the macroscopic parallel-series model both increase with the increase of porosity. It can be seen from fig. 15(a) that when the porosity and pore water content are constant, the thermal conductivity of the macroscopic series-parallel model increases first and then decreases with the increase of the pore impurity. The thermal conductivity of the macroscopic parallel-series model increases with the increase of the pore impurity content, and the growth rate decreases with the increase of the porosity. It can be seen from fig. 15(b) that when the porosity and pore impurity content are constant, the thermal conductivity of the macroscopic series-parallel model decreases and then rises with the increase of the pore water content. The thermal conductivity of the macroscopic parallel-series model shows a decreasing trend with the increase of pore water content, and the decreasing rate shows a decreasing trend with the increase of porosity. It can be seen from fig. 15(c) that when the porosity, pore impurity ratio, and pore water content are constant, the thermal conductivity of the macro series-parallel model and the macro parallel-series model both decrease with the increase of the channel composition coefficient.

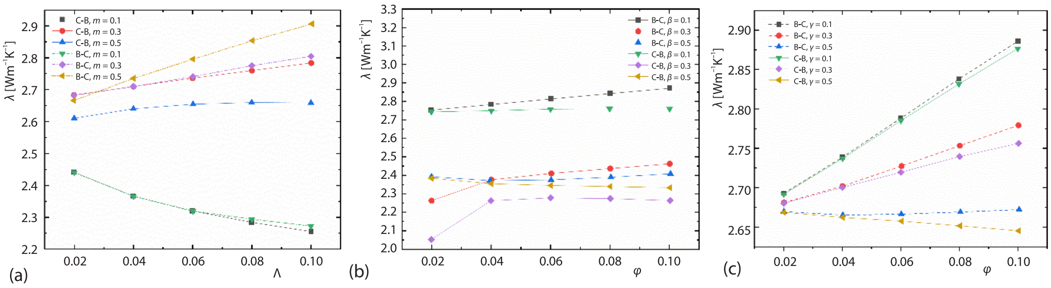


**Figure 15. Change trend of thermal conductivity of macroscopic model**

## Conclusion

The study of heat and mass transfer process in porous media of geothermal reservoirs considers both theory and engineering practice. Based on the REV description method, this paper studies the microscopic thermal conductivity model of thermal storage porous media, and the following conclusions are obtained are as follows.

- According to the different thermal conductivity characteristics during the development of magmatic geothermal reservoirs, they are divided into: the original area without disturbance at infinity, the development area near the heat extraction well, and the fluctuating area affected by the combined action of the two.
- According to the porous media characterization unit (REV) description and characterization method. The characterization and analysis of deep thermal reservoir are carried out, and the related description parameters of geothermal reservoir are given (porosity, pore impurity content and pore moisture content).
- Based on the REV description and analysis method, the thermal conductivity analysis model of the deep thermal storage pore structure is established: simplified thermal conductivity model and fine thermal conductivity model.

- According to the established model, taking granite as an example, numerical calculation is carried out to analyze the influence of porosity, pore impurity content, pore water content, and channel composition coefficient on the thermal conductivity of geothermal reservoirs. The main performance of the simplified thermal conductivity model is that the thermal conductivity decreases with the increase of porosity, and the change rate of thermal conductivity decreases with the increase of porosity.

The model built in this paper is not only suitable for the study of heat and mass transfer in the development of geothermal reservoirs, but also has certain reference and reference significance for the study of other porous media. At the same time, the research conclusions have guiding significance for the development and utilization of heat storage in daily life production.

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## Nomenclature

$l$ – characterizes the cell length
$m$ – impurity content of rock mass
$V$ – total volume of porous media
$V_k$ – pore volume
$V_w$ – liquid volume
$V_z$ – total volume of impurities

*Greek symbols*

$\beta$ – pore water content
$\gamma$ – channel composition factor, [Wm$^{-1}$K$^{-1}$]
$\lambda_1$ – thermal conductivity of series-parallel simplified model, [Wm$^{-1}$K$^{-1}$]
$\lambda_2$ – thermal conductivity of parallel - series simplified model, [Wm$^{-1}$K$^{-1}$]
$\lambda_c$ – series thermal conductivity, [Wm$^{-1}$K$^{-1}$]
$\lambda_f$ – thermal conductivity of the pore fluid, respectively, [Wm$^{-1}$K$^{-1}$]
$\lambda_g$ – thermal conductivity of gaseous media, [Wm$^{-1}$K$^{-1}$]
$\lambda_l$ – thermal conductivity of liquid media, [Wm$^{-1}$K$^{-1}$]
$\lambda_{js}$ – solid particle REV fine model thermal conductivity, [Wm$^{-1}$K$^{-1}$]
$\lambda_{jx}$ – thermal conductivity of hollow skeleton REV fine model, [Wm$^{-1}$K$^{-1}$]
$\lambda_r$ – thermal conductivity of the solid skeleton of the rock mass, [Wm$^{-1}$K$^{-1}$]
$\lambda_{ss}$ – solid particles represent the thermal conductivity of the element model, [Wm$^{-1}$K$^{-1}$]
$\lambda_x$ – thermal conductivity of hollow skeleton REV simplified model, [Wm$^{-1}$K$^{-1}$]
$\lambda_{xx}$ – porous hollow skeleton characterizes the thermal conductivity of the element model, [Wm$^{-1}$K$^{-1}$]
$\lambda_z$ – thermal conductivity of impurities in rock mass, [Wm$^{-1}$K$^{-1}$]
$\varphi$ – rock porosity, [%]

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