Research Article

Prediction of Thermal Conductivity of a Rock Wool Board by Computer X-Ray Tomography Technique Scanning and Random Generation-Growth Model

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Thermal conductivity of rock wool boards was investigated in this study. Although distribution of fibers in a realistic rock wool board is unclear, it can be simulated by computer X-ray tomography technique (CT) followed by rearrangement through the random generation-growth (RGG) model. An ideal CT-RGG structure model of rock wool boards (CT-random generation-growth model) was established by simplifying material properties based on the mesostructure parameters of the RGG model. Thermal conductivity of rock wool boards with different apparent densities and fiber diameters was studied, and the CT-RGG model was analyzed by explicit jump (EJ) diffusion equations solved by the fast Fourier transform method. We found that thermal conductivity of a single rock wool fiber can be successfully determined. Simulation and measurement results show that thermal conductivity increases consistently with the increase of apparent density and fiber diameter, particularly when the apparent density of rock wool board is greater than 140 kg m\(^{-3}\). Compared with the existing theoretical models, the proposed method does not depend on the empirical parameters; therefore, it is useful in designing and optimizing the thermal conductivity of rock wool boards.

1. Introduction

Porous fibrous materials have many vital applications in insulation and fire protection of constructions, shipbuilding, agriculture, and urban constructions [1, 2]. Rock wool board is a porous, fibrous material that makes basalt and diabase as the main raw materials and the resin binder and water repellent as auxiliary materials, which is subjected to high-temperature melting, blowing, and compressing [3, 4]. Because of its unique advantages, including light weight, nontoxic gas combustion, and advanced construction technology, rock wool board is widely employed in insulation systems for enclosure structures, such as walls, roofs, and pipes [5, 6]. Therefore, it is necessary to study their effective thermal properties.

Dry rock wool boards are two-phase materials that include air and fibers as gas and solid materials, respectively. Rock wool fiber is connected by lap joints, and the internal pores are interconnected [7]. The heat transfer methods of rock wool board porous material mainly include heat conduction, heat convection, and heat radiation [8]. Heat convection includes forced convection and natural convection, wherein the former is caused by an external force, and the latter can be ignored when external pressure is less than 105 N m\(^{-2}\), temperature is less than 1000 K, thickness is less than 5 cm, and porosity is below 95% [9]. Heat radiation is a result of photon conduction and is related to temperature and wavelength [10]. Heat conduction is the exchange and transfer of energy owing to the collision of particles in the composites after a contact with the heat source [11]. Depending on the environment in which a rock wool board is used, heat conduction is the main heat transfer method. Thermal conduction is the most important physical indicator that characterizes the thermal conduction of a material [12]. The factors affecting the thermal conductivity of a rock wool board include apparent density, alignment direction, porosity, and pore distribution [13]. Measuring thermal conductivity of a rock wool board is moderately simple; however, as many factors affect thermal conductivity, it is
difficult to determine a relationship between each factor and thermal conductivity. On the contrary, thermal conductivity of a single rock wool fiber is more difficult to measure, mainly performed using $3\omega$ and T-type methods, and the operation is complicated. Thermal conductivity of single carbon fiber was reported in the existing studies [14, 15].

However, traditional test methods cannot determine thermal conductivity of single fiber. At present, the fractal dimension method, lattice Boltzmann method (LBM), and 3D modeling method can be employed to establish models for calculating thermal conductivity of porous fibrous materials, using a computer. Some studies have introduced horizontal and vertical local fractal dimension theory and established a model appropriate for studying thermal conductivity of composite materials, which is used to predict thermal conductivity of ordered and disordered arrangement of fibers [16, 17]. Furthermore, some studies proposed a random generation-growth algorithm by LBM for reproducing two-dimensional (2D) random microstructure of fibrous materials [18]. In addition, the effects of fiber orientation angle and volume fraction on the effective thermal conductivity were investigated. It was found that thermal conductivity increases with the increase of fiber length and porosity [19]. The 3D theoretical model was employed to study fibrous microstructure networks of low-density wood-based fiberboard by X-ray microtomography to extract morphological data of real networks, fiber density, and orientation influence on local thermal conductivity [20]. Although there are some studies on thermodynamic properties of porous materials [21], the relationships between apparent density, fiber diameter of rock wool fibers, and thermal conductivity were not examined.

In this study, several images obtained by CT microtomography were imported into GeoDict software (Math2Market GmbH, www.geodict.com) to build random generation-growth (RGG) model of rock wool board. GeoDict software is highly reliable in exploring the structure and physical properties of porous materials. Gervais et al. introduced binderless monodisperse fiberglass model by X-ray microtomography images imported from GeoDict and predicted the permeability and collection efficiency values. An excellent agreement was found between the experimental results and simulated permeability values [22]. In the following sections, we introduce the explicit jump (EJ) diffusion equations for calculating thermal conductivity of rock wool board based on the CT-RGG model (CT-random generation-growth model). Subsequently, we present the results of mesoscopic simulations of rock wool board and discuss the influence of apparent density and fiber diameter on thermal conductivity. The simulated results were validated with the available experimental data.

2. Experimental Procedure and Numerical Simulations

2.1. Materials. Rock wool board with basalt and diabase as main components has an apparent density of 120–170 kg m$^{-3}$ (Heli Co., Ltd., Shaanxi, China), as shown in Figure 1. It was prepared via successive high-temperature melting, high-speed spraying, and compressing. The detailed composition of the rock wool is listed in Table 1, and Wt in the table means weight.

2.2. Measurement of Thermal Conductivity. The rock wool board was cut into cubes of 30 cm × 30 cm × 3 cm, and the samples were placed in a constant temperature blast drying oven (202–2, Shuangbiao Co., Ltd., China) with a temperature of 105°C before measurement. When the quality of rock wool board became constant, it was quickly taken out and sealed with a polystyrene film and then cooled down to room temperature. The samples were placed in a thermal conductivity measuring apparatus (DC-0515, ShunYu Co., Ltd., China) to measure thermal conductivity, as shown in Figure 2. The temperature of heating plate of the instrument was set to 35°C, the temperature of the cold plate was set to 15°C, and the measurement time was 150 min (includes preheating time of 30 min).

2.3. Rock Wool Board Was Scanned by CT. Based on the medical CT technology, high-precision industrial and nano-CT-tomography technologies have been developed. Advances in new technologies have provided new ways to
identify and test fiber materials of several micrometer diameters [23].

In this study, Phoenix Nanometer CT (Phoenix nanotom m CT, Zeiss, Germany) with a resolution of 0.1 μm was employed, and the detection accuracy was 200 nm. The samples were scanned with a 180 kV/15 W high power nanofocus X-ray tube. The sample with a size of 2 mm × 2 mm × 2 mm was selected and scanned along the depth by Nanometer CT. Each tomographic image was spaced 1.65 μm apart, and the final 1210 images were selected, respectively. The obtained CT images were binarized, noise-reduced, and contrast-converted for importing into the GeoDict software to reconstruct the RGG model of rock wool boards.

2.4. Random Generation-Growth Model of Rock Wool Board. The CT images were imported using the import module to construct the RGG model of rock wool board with the size of the scanned sample. Subsequently, the mesostructure parameters of rock wool board, including the fiber direction, apparent density, and fiber diameter, were obtained. An ideal CT-RGG structure model of rock wool board (see Figure 4) was established by simplifying the material properties based on the obtained parameters. Moreover, the factors that had less influence on the thermal conductivity were ignored, and these factors are the nonuniformity of the crimp and cross section density of the rock wool fibers, the size and content of the shot, and the binder content. The specific simplification conditions were as follows:

(i) The curl and cross section changes of rock wool fibers were ignored (the fibers were equivalent to straight rods with equal cross sections and a certain preferential orientation).

(ii) Fiber slag balls and binders could not be accurately described in the model and were considered as part of the rock wool fibers.

(iii) The fibers were allowed to overlap, and even the overlapping portion was considered fiber.

This process saved memory when handling the computational domain in addition to attaining reasonable computational time because of software requirements and computer hardware limitations.

2.5. Calculating Thermal Conductivity. GeoDict software relies on a fast solver to calculate the thermal conductivity of composite materials. In addition, GeoDict uses harmonic averaging and the fast Fourier transform and introduces the jumps across the material interfaces as additional variables to solve the stationary heat equation with periodic boundary conditions in geometrically complex porous fibrous materials with a high contrast in the thermal conductivities of the individual phases [24]. Compared with the classical finite-element or finite-volume methods, the EJ diffusion equations provide a highly efficient and automated method to compute thermal conductivity based on large images on the state-of-the-art desktop computers without a need for any further processing or additional mesh generation [25, 26]. Compared with the LBM, the EJ equation method has the advantage of requiring less memory [25]. In this study, we used the EJ diffusion equation method to calculate and predict the thermal conductivity of rock wool boards.

Heat transfer in board purely due to diffusion is described by

$$\nabla \cdot (k \nabla T) = \nabla \cdot Q$$

where $T$ is the temperature, $k(\vec{x})$ is the local conductivity at $\vec{x} = (x_1, x_2, x_3)$, $\Omega$ is the rectangular parallelepiped, $Q$
represents the heat sources or sinks, and \( \nabla \cdot \) is the divergence operator \( \partial / \partial x_1, \partial / \partial x_2, \partial / \partial x_3 \).

Equation (1) is an auxiliary differential equation with periodic boundary conditions, which can be solved by the next analysis:

\[
\begin{align*}
\frac{d}{dx} \left( k \left( \frac{dT}{dx} + 1 \right) \right) &= 0, \quad x \in (0, 1), \\
T(0) &= T(1), \\
k(0) \frac{dT}{dx}(0) &= k(1) \frac{dT}{dx}(1) + (k(1) - k(0)).
\end{align*}
\]

We assume that the rock wool board comprises air and fiber with conductivities \( k_1 \) and \( k_2 \), respectively, where the number of jumps is two (\( x_1 = a \) and \( x_2 = b \)).

\[
k(x) = \begin{cases} 
  k_1, & x \in [0, a], \\
  k_2, & x \in (a, b), \\
  k_1, & x \in [b, 1].
\end{cases}
\]

The solution of (1) with this \( k \) is a piecewise linear function:

\[
T(x) = \begin{cases} 
  \lambda_0 + \lambda_1 x, & x \in [0, a], \\
  \lambda_0 + \lambda_1 a + \lambda_2 (x - a), & x \in (a, b), \\
  \lambda_0 + \lambda_1 (x - 1), & x \in [b, 1].
\end{cases}
\]

The values \( \lambda_0, \lambda_1, \) and \( \lambda_2 \) can be determined using the three additional conditions at the material interfaces:

\[
\begin{align*}
\lambda_0 &= 0.5\lambda_1 (b - 1)^2 - 0.5\lambda_2 (b - a)^2 - \lambda_1 (b - a)^2 - 0.5\lambda_2 a^2, \\
\lambda_1 &= \left( \frac{b - a}(b - a - 1k_2) - (b - a)k_1, \\
\lambda_2 &= \frac{b - a - 1}(b - a - 1k_2) - (b - a)k_1.
\end{align*}
\]

The effective thermal conductivity coefficient of rock wool board \( k^* \) is found as follows:

\[
k^* = k_1 (\lambda_1 + 1) (1 + a - b) + k_2 (b - a) (\lambda_2 + 1).
\]

3. Results and Discussion

3.1. Thermal Conductivity of a Single Rock Wool Fiber.

The measured thermal conductivity of a rock wool board with an apparent density of 140 kg m\(^{-3}\) using a heat flow meter method was 0.0381 W/(m·K) [27]. When the assumed thermal conductivity of a single rock wool fiber is 1.25 W/(m·K), the estimated thermal conductivity of the rock wool board by the CT-RGG model and EJ equation method is likely to be 0.0382 W/(m·K). In addition, the relative standard deviation between the calculated value and measured result is 0.2410%. Therefore, thermal conductivity of the single rock wool fiber is found to be 1.25 W/(m·K). Rock wool fiber is composed of single fibers. The diameter distribution of rock wool fibers is shown in Table 2.

It can be seen from the table that the diameter of rock wool single fiber is distributed in the range of 0.75 to 21.0 \( \mu \)m. It is calculated that when the diameter of the single fiber is greater than 14.25 \( \mu \)m, the content is 6.58%. When the diameter of single fiber is greater than 13.5 \( \mu \)m, the content is 12.2%. Therefore, it can be approximated that the diameter of the single fiber obtained by the analysis is between 0.75 \( \mu \)m and 13.5 \( \mu \)m. The thermal conductivity of single fiber is calculated as shown in Table 3.

In Table 3, GeoDict software was used to calculate the thermal conductivity of different single fiber and rock wool boards of different random seeds. The relative standard deviation of each dataset in the software-calculated values does not exceed 3%; calculation results are less discrete. When the relative standard deviation of the calculated value and the measured value is less than 3%, the calculated value is considered consistent with the measured value. The thermal conductivity of rock wool single fiber is judged to be correct according to the relative standard deviation of calculated value and measured value, and adjusted by dichotomy. When the thermal conductivity of single rock wool is 1.25 W/(Km), the average value of the rock wool board model calculation results is 0.0381 W/(Km), and the relative standard deviation between the calculated and measured values is 0.2410%. It can be considered that the thermal conductivity of rock wool single fiber is 1.25 W/(Km).

Moreover, the main raw materials of rock wool board are similar to artificial diabase, both of which are high-temperature melting and extremely fast cooling materials belonging to vitreous structures [28]. Therefore, we may consider the thermal conductivity of a single rock wool fiber to be identical to that of an artificial diabase glass (artificial diabase glass is a vitreous structure, which is high-temperature melting and high-speed cooling material, and its thermal conductivity is 1.25 W/(m·K)). The thermal conductivity of artificial diabase is 1.25 W/(m·K), which is consistent with the simulation results, and this confirms the reliability of simulations by the GeoDict software [29].

3.2. Fiber Diameter Effect on the Thermal Conductivity of a Rock Wool Board. By establishing a CT-RGG model of rock wool board, the mesoscopic parameters of the fiber were obtained. This rock wool board uses a binder, which is a phenolic resin. Figure 5 shows the fiber diameter distribution of the rock wool board. The diameter distribution is a Gaussian distribution, concentrated in the range of 0.75 to 21 \( \mu \)m, which is in line with the actual production [30]. When the fiber diameter is greater than 14.25 \( \mu \)m and less than 3.5 \( \mu \)m, it accounted for 6.58 and 0.44% of the total distribution probability, respectively. When the fiber diameter of rock wool board is between 3 and 13.5 \( \mu \)m, it accounts for 92.98% of the total distribution probability. The maximum distribution probability is probably around 10 \( \mu \)m. The apparent density of the rock wool board was 140 kg m\(^{-3}\).
Figure 6 shows the relationship between the fiber diameter and the thermal conductivity when the apparent density is $140 \text{ kg m}^{-3}$. The fiber diameter distribution is a Gaussian distribution with fiber average diameters of $3$–$10.5 \mu m$ and a relative standard deviation of $2.4\%$. The calculated thermal conductivity of rock wool board by the EJ equations increases with the increase of fiber diameter. In addition, the maximum and minimum values are $0.03807$ and $0.03487 \text{ W/(m·K)}$, respectively. Furthermore, the difference between the two is $0.0032 \text{ W/(m·K)}$, and hence the influence of fiber diameter on the thermal conductivity cannot be ignored. When the fiber diameter is between $3$ and $5 \mu m$, thermal conductivity increases faster; however, when the fiber diameter is greater than $5 \mu m$, thermal conductivity increases at a slower rate. When the fiber diameter is between $10$ and $10.5 \mu m$, thermal conductivity barely increases and tends to be stable. When the fiber diameter of a rock wool board increases, the pore size increases under the same porosity (see Figure 7), and the interconnected pores have a shorter heat transfer path, resulting in a higher thermal conductivity [31]. Therefore, pore structure of porous fibrous materials dominates the thermal conductivity.

### 3.3. Apparent Density Effect on the Thermal Conductivity of a Rock Wool Board

Figure 8 shows the relationship between the apparent density ($100$–$200 \text{ kg m}^{-3}$) and thermal conductivity calculated by the EJ equation method where the fiber diameter distribution is a Gaussian distribution with an average of $3–10.5 \mu m$ and a relative standard deviation of $2.4\%$. The calculated thermal conductivity increases with the increase of apparent density. In addition, the maximum and minimum values are $0.0363$ and $0.0381 \text{ W/(m·K)}$, respectively. Furthermore, the difference between the two is $0.0058 \text{ W/(m·K)}$, and hence the influence of apparent density on the thermal conductivity cannot be ignored. When the apparent density is $100 \text{ kg m}^{-3}$, thermal conductivity increases faster; however, when the apparent density is greater than $200 \text{ kg m}^{-3}$, thermal conductivity increases at a slower rate. When the apparent density is between $100$ and $200 \text{ kg m}^{-3}$, thermal conductivity barely increases and tends to be stable. When the apparent density of a rock wool board increases, the pore size increases under the same porosity (see Figure 7), and the interconnected pores have a shorter heat transfer path, resulting in a higher thermal conductivity [31]. Therefore, pore structure of porous fibrous materials dominates the thermal conductivity.
Averagediameter of 10.5 μm and a relative standard deviation of 2.4%. Therefore, there is a linear positive correlation between the thermal conductivity and apparent density of the rock wool board. For every 10 kg·m⁻³ increase in the apparent density, the thermal conductivity increases approximately by 0.00946004 W/(m·K). The calculated thermal conductivity has minimum and maximum values of 0.03436 and 0.04382 W/(m·K), respectively. Additionally, the maximum value exceeds the requirement of 0.04 W/(m·K) according to GB/T 25975–2013, where rock wool boards are used as insulation materials [32]. This might be because when the apparent density of a rock wool board increases with the same diameter, the void fraction reduces (see Figure 9). Thermal conductivity of the solid phase is approximately 1.25 W/(m·K), which is greater than that of the air (0.026 W/(m·K)), resulting in an increase in the thermal conductivity of the entire porous material [33]. At this point, the thermal conductivity is essentially determined by the material properties.

3.4. Comprehensive Effect of Apparent Density and Fiber Diameter of a Rock Wool Board on the Thermal Conductivity. Eighty-eight CT-RGG models of rock wool boards were studied to investigate the effects of apparent density and fiber diameter on the thermal conductivity, where the apparent density changed between 100 and 200 kg·m⁻³, and fiber diameter varied from 3 to 10.5 μm.

Figure 10 shows that the higher the temperature color, the higher the thermal conductivity. Moreover, the effect of apparent density is more sensitive than fiber diameter, which was confirmed in other studies [34]. In China, the thermal conductivity of rock wool boards to be used in insulation materials is required to be within 0.04 W/(m·K); therefore, thermal conductivity should be controlled by adjusting the apparent density and fiber diameter. For instance, when the fiber diameter is 3 μm, thermal conductivity does not exceed 0.4 W/(m·K) with an apparent density of 200 kg·m⁻³. In addition, when the fiber diameter is between 4 and 5 μm, the apparent density should be constrained to be less than 180 kg·m⁻³. Furthermore, when the fiber diameter is in the range of 6 to 10.5 μm, the apparent density should be constrained to be less than 160 kg·m⁻³. As long as the production process allows, the fiber diameter and apparent density of a rock wool board should be as small as possible. Consequently, producing rock wool boards with apparent densities greater than 180 kg·m⁻³ is not recommended. This is useful for design and optimization of rock wool board production and does not depend upon empirical parameters, which have to be determined case by case.

3.5. Comparing Experimental and Simulation Results. Figure 11 shows a comparison of the experimental results and calculated values using the CT-RGG model and EJ diffusion equation method for thermal conductivity of a rock wool board, with the apparent density between 120 and 170 kg·m⁻³ and fiber diameter between 3 and 10.5 μm.

The measured thermal conductivity of rock wool board fluctuates significantly. When apparent density varies between 110 and 140 kg·m⁻³, the simulated thermal...
conductivity tends to be underestimated and is lower than the experimental result; however, the difference between the two decreases. The reason is that the apparent density of rock wool board is small, the porosity and pore sizes are large, and natural convection in the plate is evident. However, in the software simulation, only the influence of heat conduction is considered, and the thermal convection is ignored; therefore, the measured result was larger than the calculated value. When apparent density changes from 140 to 180 kg m\(^{-3}\), thermal conductivity of the rock wool board is within the range of calculated values; however, there is a certain difference between the obtained results. This may be because slag balls and binder existed in fibers, which were simplified into fibers in the CT-RGG models. Moreover, with the increase of apparent density, the porosity and pore size in the board gradually decrease, then the natural convection in the board has a small or no effect on the thermal conductivity, and measured and calculated values become very close to each other. In summary, the optimal simulated thermal conductivity of rock wool board porous material is in a reasonable agreement with the measured one, whereas the apparent density is greater than 140 kg m\(^{-3}\). As an insulation material in a building, the apparent density of rock wool boards is in the range of 120–160 kg m\(^{-3}\). When the apparent density is extremely small, the mechanical properties of a rock wool board will be inadequate. When the apparent density is extremely large, the rock wool board easily disengages from the wall surface due to excessive gravity.

### 4. Conclusions

The following conclusions can be drawn from this study:

1. The fiber distribution of actual rock wool boards is unclear; however, it can be simulated using CT followed by rearrangement through the random generation-growth (RGG) model. Through this model, the geometry of a rock wool board can be intuitively displayed. With an apparent density of...
140 kg m$^{-3}$ and a fiber diameter of 10.5 μm, the highest distribution probability was obtained.

(2) It is difficult to measure and calculate the thermal conductivity of a single fiber. In this study, thermal conductivity of a single rock wool fiber can be reversed by repeatedly calculating the EJ diffusion equation. Finally, thermal conductivity of a single fiber was found to be 1.25 W/(m·K), which was consistent with the experimental results.

(3) Thermal conductivity of rock wool boards can be predicted by varying the apparent density and fiber diameter. The thermal conductivity of a rock wool board increases with the increase of apparent density and fiber diameter. In addition, the difference is that the former is positively correlated and the latter gradually tends to be stable.

(4) The simulated thermal conductivity increased with the increase in apparent density and fiber diameter. In addition, the results obtained using the proposed method agreed well with the available experimental results, particularly for apparent densities greater than 140 kg m$^{-3}$.

Data Availability

The data required to reproduce these findings are available from the corresponding author upon request.

Additional Points

Highlights. (1) Structure of rock wool board can be simulated by computer X-ray tomography technique scanning and the random generation-growth model. (2) Thermal conductivity of a single fiber can be reversed by repeatedly calculating the EJ diffusion equation. (3) Thermal conductivity can be predicted by changing apparent density and fiber diameter of rock wool board. (4) For an optimal design, apparent density of a rock wool board should be greater than 140 kg m$^{-3}$.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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