International Journal of Heat and Mass Transfer 125 (2018) 387–399

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A model for the effective thermal conductivity of moist porous building materials based on fractal theory

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ARTICLE INFO

Article history:
Received 6 November 2017
Received in revised form 4 March 2018
Accepted 14 April 2018

Keywords:
Model
Thermal conductivity
Moist porous building materials
Fractal

ABSTRACT

An accurate estimation of building material thermal conductivity is crucial for the modeling of heat transfer processes and the calculation of building energy consumption. The effect of moisture content on the thermal conductivity of the material is usually neglected in most currently used calculation methods. These methods cannot represent the interior multi-phase heat transfer process. In this paper, the coexisting solid-liquid-gas thermal conductivity physical model was proposed. Taking into account the pore structure characteristics of building materials, a coexisting tri-phase thermal conductivity calculation model based on capillary structure was established using fractal theory. The quantitative influence relationship of the parameters, such as porosity, pore diameter distribution, moisture content and fractal structure, on the thermal conductivity of moist porous materials was analyzed. The results provide a theoretical basis for the thermal conductivity correction of moist building materials.

1. Introduction

The thermal conductivity of building materials is one of the most important parameters for heat transfer performance. In actual use, there is a certain moisture content in porous building materials. Moreover, the heat transfer performance will change when the building material contains moisture [1–3]. Currently, the physical parameters of porous building materials are often approximated as constant values in the calculation method and computational modeling of heat and cold load. Meanwhile, the influence of moisture content on thermal conductivity is ignored. This will cause errors in the calculation of heat transfer of the envelope and building energy consumption. Therefore, it is necessary to study the quantitative relationship between the moisture content and the porous building materials' thermal conductivity.

The effective thermal conductivity of the porous building material is obtained by converting multiple heat transfer modes (heat conduction, convection, radiation) inside the material into an equivalent heat transfer. The moisture content affects the building material thermal conductivity mainly through the heat conduction between the moisture, the material's solid skeleton and the air in the pores [4,5]. Therefore, the thermal conductivity of porous building materials is closely related to the moisture content and geometric structure of the materials.

Fractal dimensionality was introduced by Yao and Pitchumani [6,7] in an analysis of the effective thermal conductivity of porous fiber composite materials. The effective thermal conductivity calculation model of bi-phase timber using the method of series parallel thermal conductivity was developed by Li et al. [8]. According to the principle of thermoelectric analogy, the calculation model of the soil effective thermal conductivity based on fractal theory was developed by Chen and Shi [9,10]. The model expressed the effective thermal conductivity as a function relating the thermal conductivity coefficient, solid particle and pore scale and fractal dimensionality. However, the thermal conductivities of the internal gas and liquid in the model were not treated separately. Based on the principle of thermoelectric analogy and statistical self-similarity method, a dimensionless calculation model of the effective thermal conductivity of saturated and unsaturated porous media was obtained by Kou et al. [11] without the use of any empirical constants in the model.

Yu and Cheng [12] established an effective thermal conductivity calculation model of a bi-dispersed porous material (particle chain and cluster renewal) based on the fractal theory. The model involved the tortuous fractal dimensionality of a particle chain, the pore area fractal dimensionality of cluster renewal, porosity, the size ratio between solid and liquid, and the solid-liquid thermal

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.063
0017-9310/

conductivity ratio [13]. This model provided a good reference for the analysis of the thermal conductivity process of porous materials with a large number of capillary tubes.

Ma et al. [14,15] were the first to propose an analytical model for the effective thermal conductivity of three-phase/unsaturated porous media based on the thermal-electrical analogy technique and exact self-similar fractal geometry, and their model is expressed as a function of the porosity (related to the stage of Sierpinski carpet), ratio of areas, ratio of component thermal conductivities, and water saturation. On this basis, the effective thermal conductivity calculation model of the bi-phase porous media with n-stage Sierpinski carpet structure was established by Feng [16]. The effective thermal conductivity of porous media can be expressed as a function of porosity, area ratio, microstructure size, composition ratio of thermal conductivity and water saturation. Based on the Sierpinski carpet fractal structure, Li et al. [17] used the series and parallel structures to describe the physical structure of moist porous materials and obtained a multi-stage tri-phase calculation model of effective thermal conductivity of porous material. Based on the multi-stage Sierpinski carpet structure, the fractal structure of the tri-phase state was constructed, and the effective thermal conductivity model was derived [18]. On the basis of Sierpinski carpet structure, a mixed fractal unit model with different fractal dimensionality was established by Pia and Sanna [19–21]. The mixed fractal unit model was used to extend the application range of the Sierpinski carpet in porous media.

Analyses of the effective thermal conductivity coefficient of bi-phase or tri-phase porous media based on the fractal theory mostly apply the aforementioned traditional regular structures or use a combination of special fractal structures; the latter approach has enabled further progress in the calculation of the effective thermal conductivity coefficient of porous media. However, the effect of the pore size and distribution of porous material on the material's thermal conductivity is not taken into consideration in these studies.

Heat transfer in a porous medium is closely related to the medium's internal geometrical structure, and the complex structural characteristics of internal porous media can be effectively described using fractal theory [22]. However, there is a wide variety of porous materials with distinct internal structures, and some simulations of the internal structure of an actual material using ideal fractal models will still differ from reality. Therefore, a fractal geometric structure that is conducive to the calculation of the effective thermal conductivity coefficient of porous media was constructed based on the parameters such as the porosity, pore diameter distribution characteristics and fractal dimension.

The internal microstructure, pore size and distribution characteristics, and moisture content of porous building materials have different influences on the thermal conductivity coefficient. Empirical relationships between the thermal conductivity and moisture content of porous building materials obtained via experimental analysis have significant limitations [23,24]. Because they neglect the internal absorbed moisture and condensed moisture of materials and only consider the heat transfer effect of a material's solid skeleton and moist air, existing theoretical analyses of the thermal conductivity of porous building materials cannot accurately represent the interior multi-phase heat transfer process, resulting in large errors in the thermal conductivity coefficient calculations [25]. Therefore, an accurate determination of the quantitative relationship between the thermal conductivity and parameters, such as the moisture content, porosity, pore size and distribution of the material, is key for accurately predicting the thermal conductivity of moist porous building materials.

The aim of this paper is to reveal the quantitative relationship between the moisture content and building material thermal conductivity and to provide the correction method for the thermal conductivity of moist porous building materials. Taking into account the pore structure characteristics of porous building materials, the calculation model of thermal conductivity of tri-phase coexisting porous materials based on a capillary structure was established by fractal theory. The calculation model was validated by experiment. Using this calculation model, the influence of the relevant parameters, such as porosity, pore diameter distribution, moisture content and fractal structure, on the thermal conductivity of moist porous materials was analyzed and evaluated quantitatively. Detailed discussions and analyses are presented in the following sections.

2. Theoretical modeling

According to the analysis of moisture condition in porous building materials, it is found that in addition to the gaseous moisture in the material, liquid moisture such as the moisture in the adsorption and condensed states is present as well. Therefore, derivation of the thermal conductivity physical model of the coexisting solid-liquid-gas is the basis for the analysis of the heat conduction process of the moist porous building materials. At the same time, an accurate description of the spatial distribution of the solid skeleton and liquid moisture and moist air is crucial for the analysis of the heat conduction process.

Based on the microthermal conductivity of solid-liquid-gas coexistence, the principle of thermoelectric analogy can be used, in addition the internal structure characteristic of porous building materials is described by fractal theory. The effects of the fractions of the space occupied by solid, liquid, and gas space and the spatial distribution on the internal thermal conductivity of porous building materials were analyzed, and then the calculation model for the thermal conductivity of moist porous building materials was obtained.

2.1. Thermal conductivity physical model of liquid-gas space replacement in the material

Based on the structural characteristics of the pore tortuous connections of porous building materials, such as normal concrete, and the transfer characteristics of moisture in the material interior, it is believed that porous building materials are connected by pores of different sizes and that the porous structure constitutes capillary bundles of a certain tortuosity. A simplified model of the porous structure of porous building materials is shown in Fig. 1(a). In the cross-section perpendicular to the vertical thermal flow direction, the pore sizes are randomly distributed within some size range. In the longitudinal section along the thermal flow, the pore spaces are connected to form capillary channels, and many capillary channels are arranged in parallel.

Analysis of the moisture conditions of porous building materials finds that due to the presence of moist air during the transmission process of porous building materials, some volume of absorbed water will form on the surface of the solid skeleton as a result of the absorptive action of water molecules on the surface. In addition, the heat-moisture coupled transmission process may produce condensed water, and the conductivity coefficient of liquid water is much greater than that of moist air. Currently, theoretical analyses of the thermal conductivity of porous building materials only consider the thermal conductivity of the solid skeleton and moist air; such analyses cannot truly represent the multi-phase conductivity process of the building material interior, which will give rise to large errors in the calculation of the thermal conductivity coefficient of the material.

Therefore, for porous building materials containing moist air, a liquid-gas space replacement is formed based on the moisture