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Effect of moisture migration and phase change on effective thermal conductivity of porous building materials

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ABSTRACT

In this paper, a new method for precise evaluation of the effective thermal conductivity (ETC) caused by moisture transfer inside porous building materials was proposed. Moreover, the mathematical models for coupled heat and moisture transfer without and with moisture phase change were established. Based on the interactions among the moisture phase change, temperature field, and moisture field inside the porous materials, a loop iteration calculation method was proposed to solve for the heat flux caused by moisture migration and phase change. By combining the heat flux with the classical evaporation and condensation theory, the additional thermal conductivities (ATCs) caused by the moisture migration and phase change were obtained. In order to obtain the quantitative relationships between the main factors and ATC caused by moisture transfer, different temperature and humidity boundary conditions were used to analyze the ATC. The results show that the ATC caused by moisture migration increases when the temperature difference decreases and the water vapor pressure difference between the indoor and outdoor air increases. The ATC is greatly influenced by outdoor air temperature fluctuations, while the influence of water vapor pressure fluctuations is relatively small. The value for the ATC caused by moisture phase change is mainly determined by the temperature gradient.

1. Introduction

Porous building materials, such as ordinary concrete, aerated concrete, and insulation materials, are widely used in building structures. The thermal conductivity of porous building materials is one of the most important thermal parameters in cooling and heating load and energy consumption calculations for buildings. Because of the effects of moisture absorption and transfer, there is moisture content inside most porous building materials [1,2]. The thermal performance will change when moisture is present [3,4]. Therefore, research on the quantitative relationships among the moisture content, moisture migration, and the effective thermal conductivity (ETC) of porous building materials is significant for energy efficiency analysis and load calculations for buildings [5]. The ETC of a porous material is obtained by converting a variety of heat transfer methods (e.g., heat conduction, heat convection, radiation heat transfer, heat transfer caused by moisture migration, and phase change inside the material) into equivalent heat conduction [6,7].

Depending on the state of the moisture inside the porous materials, including static moisture distribution and moisture transfer, the mechanisms that influence internal heat transfer performance are different. Static moisture mainly affects the thermal performance of porous material through heat conduction among the moisture, solid skeleton, and gases inside the material [8], while migration moisture mainly leads to variation of material enthalpy through the moisture transfer process. The current research on the influence of moisture content on the ETC of porous building materials is mostly based on moisture in the static state [9,10]. Many experiments and theoretical models have analyzed the ETCs of porous building materials with static moisture [11–13]. However, a perfect calculation method for the ETC caused by moisture transfer inside porous building materials is still lacking [14].

de Vries [15] converted the heat transfer caused by moisture diffusion into equivalent heat conduction and then obtained a simple calculation model for the additional thermal conductivities (ATC) caused by the water vapor diffusion. Krischer et al. [16] improved the de Vries model. The de Vries and Krischer models only considered the heat transfer caused by water vapor diffusion,

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which did not take into account the influence of liquid water transfer. Ochs et al. [17] established an ETC calculation model that takes into account the heat conduction of the static moisture content, the skeleton, and the vapor–gas mixture inside porous materials. In this model, an additional item is added to the calculation of the ATC caused by moisture diffusion, which is based on the de Vries and Krischer models [15,16].

When testing the ETC of moist porous materials, the temperature gradient causes redistribution of the enclosed moisture, which will cause a significant difference between the apparent and the actual thermal conductivity. Becker et al. [18] suggested a procedure for estimating the dependence of the actual thermal conductivity on the moisture content via the apparent heat conductivity and the calculated moisture phase change. However, this method cannot distinguish between the influences of static moisture and migration moisture on heat transfer. Considering moisture redistribution and latent heat due to moisture phase change during a test of the ETC of a moist building material, Campanale et al. [19] presented a modified formula for ETC to solve for the influence of the errors caused by moisture phase change and redistribution, based on the Whitaker's model [20] for coupled heat and moisture transfer. However, this modified model of ETC considers the total influence of moisture phase change and redistribution. Therefore, it is only suitable for quasi-steady or steady state heat and moisture transfer conditions.

The current research related to moisture transfer in buildings is mainly focused on the influence of moisture transfer on the heat transfer of envelopes and the building load. However, these research results can help us to analyze the influence of moisture transfer on the ETCs of porous building materials. Belarbia et al. [21] proposed a modified two-dimensional Luikov model [22] for evaluating the non-isothermal moisture migration in porous building materials under different hot and humid conditions. Liu et al. [23] developed a coupled heat and moisture transfer transient model in which relative humidity and temperature gradients were chosen as the driving potentials. By employing the developed model, the internal surface temperatures of walls made of different materials were evaluated under constant and variable boundary conditions. The results show that the effect of moisture transfer on the wall internal surface temperature is significant.

Budaiwi et al. [24] studied the adsorption and condensation moisture inside walls when moisture condensation occurs. The adsorption moisture and condensation moisture are determined with the isothermal absorption curve and the moisture equilibrium method, respectively. Wyrwał et al. [25] described spatially steady-state distribution of accumulated moisture in a porous wall. Closed-form analytical expressions for the temperature, condensation rate, and moisture content were obtained. Leskovšek et al. [26] presented a transient model for heat and mass transfer, including the sorption and condensation processes. The saturation concentration of the water vapor was determined using the saturation-pressure equation recommended by Ochs et al. [17]. The calculations for the evaporation and condensation of the moisture in the above models are essentially simplified calculation methods based on the macroscopic moisture diffusion theory.

Based on the Philip and de Vries theory [27], Mendes et al. [28] analyzed the effects of moisture on conduction loads under varying boundary conditions. The results show that ignoring moisture may lead to overestimating conduction peak loads up to 210% and underestimating the yearly integrated heat flux up to 59%. On the basis of preliminary research [23], Wang et al. [29] believed that the night ventilation rate negatively correlates with the sensible heat load and positively correlates with the latent heat load because of the increased amount of moisture that is absorbed or desorbed at the interior wall surface. Liu et al. [30,31] developed a coupled heat and moisture transfer model, which was used to calculate cooling and heating transmission loads. It was found that peak cooling and heating loads are overestimated by 2.1–3.9% and 4.2–10.1%, in the hot summer and cold winter zone of China, respectively, if the effect of moisture transfer on the heat transfer of external walls is ignored. Heat transfer in porous building material is affected not only by the static moisture distribution but also by moisture transfer. In these studies, the effects of static and migration moisture on heat transfer and building loads were not distinguished.

The objective of this paper is to propose a calculation method for the correct evaluation of ETC and to improve a relevance theory for ETC due to moisture transfer of moist porous building materials. A coupled heat and moisture transfer mathematical model is established by the analysis of the heat and moisture transfer mechanism of porous material, and water vapor pressure and temperature gradients are chosen as driving potentials. The moisture and heat generation rates of the moisture phase change are introduced into the coupled heat and moisture transfer governing equations with moisture phase change as the heat and moisture sources, respectively. Based on the interactions among the moisture phase change, temperature field, and moisture field inside porous materials, the ATC caused by moisture migration and phase change can be obtained by solving for the heat flux caused by moisture migration and phase change, combined with the classical evaporation and condensation theory.

2. Theoretical model

There are two scenarios with respect to the effect of moisture transfer on heat transfer inside porous materials. The first is that there is no moisture phase change inside porous materials, and the moisture only affects the heat transfer in the form of sensible heat. The second is that the moisture phase change occurs and is affected by sensible and latent heat. For these two scenarios, based on analysis of the coupled heat and moisture transfer mechanisms, a one-dimensional mathematical model for coupled heat and moisture transfer with and without moisture phase transformation in porous materials is established in this paper. Based on the model, the heat transfer caused by moisture transfer is equivalent to the heat conduction, and, therefore, the ATC caused by moisture transfer can be obtained.

To simplify the complex calculation process, the assumptions listed below are taken into account for the mathematical model.

(1) The porous material is homogenous.
(2) A local thermal equilibrium exists among the solid, liquid, and gas phases of the porous material.
(3) A local moisture equilibrium exists among the adsorption, liquid, and gas moisture inside the porous material.
(4) The air and water vapor are an ideal gas.
(5) A pressure equilibrium exists between the liquid and gas phases.

2.1. Governing equations without moisture phase change

2.1.1. Moisture transfer

In porous materials, moisture transfer includes liquid moisture and gas moisture transfer, and the moisture equilibrium equation is as follows:

$$\frac{\partial w}{\partial t} + \frac{\partial}{\partial x}(J_v + J_l) = 0 \quad (1)$$

where w is the moisture content per unit volume, kg/m^3, J_l is the liquid water flux, kg/(m^2·s), and J_v is the water vapor flux, kg/(m^2·s).

When there is no moisture phase change in the porous material, the variation of the moisture content can be determined based on