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The effect of heat and moisture coupling migration of ground structure without damp-proof course on the indoor floor surface temperature and humidity: Experimental study

Yingying Wang*, Chao Jiang, Yanfeng Liu, Dengjia Wang, Jiaping Liu

School of Environmental and Municipal Engineering, Xi'an University of Architecture and Technology, 13 Yanta Road, Xi'an 710055, China

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ABSTRACT

The heat and moisture states of building floors without impermeable boundary construction, which affect the indoor thermal and moist environment, are determined by the heat and moisture distribution features and coupled transfer process of the under-soil and groundwater level. Previous studies based mainly on mathematical models only considered heat transfer or simplified the boundary conditions as adiabatic and impermeable, which resulted in limitations in application, specifically greater errors in shallow groundwater areas. In this paper, a scale model experiment that combined the floor, soil and groundwater was conducted to study the affected degree of the thermal and wet conditions of the floor in terms of the combined effect of soil heat and moisture transfer and indoor thermal and moist environment. The results showed that under the influence of the latent heat of vaporization, groundwater increases the floor temperature in the short term, and under the influence of water vapor pressure, groundwater decreases the relative humidity of the floor in the short term. The influence range of underground moisture source, analysis of building energy consumption effected by underground moisture source, process of ground surface hot and humid states reaching equilibrium, were discussed by numerical calculations.

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1. Introduction

In hot and humid regions, many building floors do not have a damp-proof course. With the influence of various factors such as climate and underground hydrology, soil heat and moisture migration are particularly active in these cases. The wet component of soil can easily reach the floor when no moisture barrier layer is present. The continuous evaporation of the wet component from the floor surface decreases the temperature of the floor surface, and the lower surface temperature enables the indoor air to easily condense at the surface easily. This characteristics results in the widespread phenomenon of moisture accumulation in the basement surface of urban buildings and village buildings. The phenomenon of serious moisture accumulation causes damp floors [1], bacterial growth [2], shortened building material life [3] and other issues and affects the temperature and humidity of the floor surface, thereby affecting human thermal comfort [4] and building energy consumption [5], which are closely related to the indoor thermal and moist environment. Existing models of heat and moisture transfer in building envelopes are not yet mature and simplified and are rarely applied in practical engineering. Therefore, calculation of building energy consumption in practical engineering often ignores the influence of wet components. In the study of heat and moisture transfer in the envelope structure, researchers generally use theoretical models. During the process, too many model conditions are simplified to accurately reflect the physical structure and the process of heat and moisture transfer. Moreover, studies based on theoretical models generally focus on the walls, while relatively little research has been published on soil heat and moisture transfer, which are mostly concentrated on the ground source heat pumps, agriculture, forestry and other fields. Therefore, when addressing building energy consumption, it is important to accurately reflect the process of heat and moisture transfer in soil and to account for the changes in the heat and moisture state of floors without using a moisture-proof layer.

The existing building energy consumption models are often based on pure heat transfer theory or dynamic heat transfer calculations, such as DOE-2, EnergyPlus, and TRNSYS [6]. These software do not account for the influence of the moisture content of the building envelope on the building load; therefore, the accuracy of the building energy consumption is greatly decreased in hot and humid regions. To simplify the tedious calculation process, some scholars

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* Corresponding author.
E-mail address: 1274296191@qq.com (Y. Wang).

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have ignored the influence of wet components in the establishment of mathematical models. The limitations of previous research on the unsteady heat transfer of the envelope were analyzed by Yimin Xiao [7], and a Z-transfer function method was proposed to calculate the unstable heat transfer through the envelope of an underground caver. However, this model neglected the heat transfer caused by moisture transfer through the envelope. On the premise of ignoring the influence of wet components, Yanping Yuan [8] studied the steady-periodic heat transfer of an attached underground engineering envelope. The interzone temperature profile estimation (ITPE) technology could provide rapid and accurate means to calculate the heat transfer. To reduce building energy consumption, it is necessary to consider the impact of the wet component from the exterior space and building envelope on building energy consumption in practical engineering. By studying the transmission mechanism of the wet component in the envelope structure, the heat transfer coefficient can be adjusted or relevant measures can be taken in building construction.

The research of coupled heat and moisture transfer in the envelope structure is a branch of research on heat and mass transfer in porous media, which has a long research history. After nearly one hundred years, the research has developed a strict theoretical system, including energy and liquid diffusion theory, capillary flow theory and evaporation condensation theory, which has also been used to explore heat and moisture transfer in building envelopes. The earliest theory of porous medium coupled heat and moisture transfer was proposed by J.R. Philip and D.A. de Vries [9]. They analyzed the effect of temperature on soil moisture migration and found that the wet component exists in two forms (gas and liquid phase) in soil moisture transport, and the motion of the two-phase flow is driven by the temperature and humidity gradients. They developed a single thermal driving mechanism and a double moisture driving mechanism and established a mathematical model of soil heat and moisture coupling transfer, which has been cited by many scholars to solve their problems. Luikov [10] proposed that heat transfer depends not only on heat conduction but also on the distribution of wet components in the building envelope and that mass transfer depends not only on moisture diffusion but also on thermal diffusion, which means that heat transfer and wet transmission interact and influence each other. Based on the temperature and volume moisture contents as the driving potential, a two-parameter model of coupled heat and mass transfer in porous media was established, which laid the theoretical foundation of coupled heat and mass transfer. However, this model did not include explicit expressions of the coefficients and often assumed them as constant or determined by experimental tests, which presented obstacles to the wide application of the model. Several hydro-thermal coupled numerical models have since been proposed with different forms of driving force for moisture migration. I. Budaiwi [11] established a mathematical model to describe the internal temperature and humidity of the multilayer wall structure with air humidity and temperature as the driving forces. Mendes [12,13] proposed a model of heat and moisture transfer in multilayer walls with the temperature gradient and humidity capacity gradient as the driving forces. Based on the temperature and water vapor density, a coupled heat and moisture transfer model was established by Belarbi [14] and Menghao Qin [15,16]. Qinru [17] used the Poiseuille law to approximately describe air infiltration in a porous enclosure and established a coupled heat, air and moisture transfer model of building envelopes based on the driving forces of temperature, capillary pressure and air pressure. Whitaker [18] considered the multiple transmission mechanisms of moisture, heat and energy in porous media using classical transport theory and space average law to select the representative elementary volume (REV). The representative volume element method (or REV method) overcomes the difficulty of simulating anisotropic porous media and is widely used by researchers. Fitsum Tariku [19] and Mohammed Yacine [20] established a mathematical model of coupled heat, moisture and air in porous media. The accuracy of the model was confirmed by comparing the calculated results with experimental data, numerical data and other analytical solutions. The model can predict the temperature and humidity distribution inside building envelopes. Although the theoretical models of these studies include the wet component in the heat transfer model, these models are mostly applied for heat and moisture transfer of the walls in building energy consumption calculations. In contrast, the heat and moisture transfer processes of the soil and floor are usually ignored or treated as wall treatments. The outer heat and moisture boundary of the building floor without a moisture-proof layer is soil. The outer boundary of the wall is the outdoor atmosphere. In view of the different boundary conditions, the heat and moisture transfer mechanisms are different. Therefore, the mechanism of heat and moisture transfer of the wall is difficult to apply directly to the soil and floor.

Most of the research results on heat and moisture transfer in soil are focused on three categories. The first category is the effect of soil moisture and heat transfer on the heat transfer efficiency of the ground source heat pump. Xinguo Li [21] presented an inner heat source model of an underground heat exchanger based on heat and mass transfer theory in soil. In addition, analyses were conducted on the influences of different soil properties and operation modes on the underground temperature field around a single U-vertical underground heat exchanger. Jianzhi Dong [22] Zhao [23] performed an experimental study to investigate the thermal performance of saturated soil around a coaxial ground coupled heat exchanger. Wang et al. [24–26] conducted a preliminary study on heat and moisture transfer in soil under the conditions of high-temperature thermal storage and investigated the occurrence of the moisture and peak temperature during the process. Mathematical models of heat and moisture transfer in the soil around the buried pipe are usually simplified as one-dimensional heat and moisture transfer in the horizontal direction. However, when analyzing the effect of soil moisture and heat transfer on the floor, the influence of vertical gravity on the driving force cannot be ignored. The driving force is determined by analyzing the synergistic and inhibitory relationship between the vapor pressure, capillary force, gravity and other wet transfer forces in the gas–liquid combined wet phase. Therefore, there are some limitations to the application and extension of mathematical models that do not consider gravity. The second category is to study the effects of soil water evaporation and frozen soil on vegetation. A model was established by V.Z. Antonopoulos [27] to describe the soil water movement and the mass transport and transformation of nitrogen in the soil. The model was applied to predict the soil temperature and water content under a crop of ryegrass. To analyze the effects of soil moisture and temperature on crops, Liu Bingcheng [28] referenced to the Phillip and de Vries soil heat and moisture coupled transport model and then used Whitaker multiphase system transmission theory and the method of volume averaging to analyze the heat and moisture transfer of wet layered soil under a natural environment. Harlan [29] correlated the water transport mechanisms in partially frozen soil with the water transport mechanisms in unsaturated soil and built a hydrodynamic model coupled to heat-fluid transport in porous media. Wu et al. [30] established a macrokinetic model of ice crystal growth, which was used to quantify the processes of nucleation and growth coupled with heat transfer and fluid flow in fully saturated soil. These studies provide insight into the process to estimate thermal-moisture dynamics. These studies, however, were performed mainly for unfrozen soil or saturated freezing soil and the extended evaporation phase was generally ignored. These established mathematical models consider three phase states of the wet component and complex outdoor environ-

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