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Development of a moisture transfer calculation method of hygroscopic material plate in buildings

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ABSTRACT

Hygroscopic material could be used to moderate the indoor humidity fluctuation and reduce heating and cooling energy consumption. In order to calculate the moisture transfer between the wall hygroscopic material plate and the indoor air quickly and accurately, a simple moisture transfer calculation method coupling moisture transfer function and Fourier transform is proposed and developed. This paper further presents the analytical verification and experimental validation of this method. The analytical verification shows that the average relative error between the model prediction and analytical results under the periodic sinusoidal and rectangular variations of indoor air humidity are 0.2% and 5.2% respectively. An experiment test rig was established to measure the moisture sorption of hygroscopic material plate taking silicate calcium plate as a sample. The chamber climate was controlled as expected and two typical real office climates with different moisture load schedule were simulated. Compared with the experimental measurements, the average relative errors of the moisture flux between the model prediction and the measurement are 10.7% for Case 1 and 12.1% for Case 2 respectively. The proposed method has also been validated by published experiment measurements and shows a good accuracy as well as high computationally efficiency. This simple method can be easily applied on moisture sorption calculation of hygroscopic materials.

1. Introduction

The energy crisis has become a serious problem as the consumption rates of energy resources is largely exceeding energy renew rate. Inefficient energy consumption will not only hinder the development of global economy, but also cause various environmental issues. Building energy consumption accounts for 30% and 40% of the total energy consumption in China [1] and in the whole world [2]. More than half of this part energy is particularly consumed to maintain the indoor thermal and moisture comfort. Thus, reducing building energy consumption is an effective path to solve the problem of energy crisis and environmental pollution.

There are many techniques and measures for building energy conservation. Some researchers are engaged in enhancing the wall insulation [3,4], improving the energy efficiency of HVAC system [5] and utilizing low-grade or renewable energy resources etc. [6]. Some researchers make efforts to investigate the application of passive energy conservation including passive solar house [7], phase change material wall [8] and passive energy-saving natural ventilation [9] etc. Many passive approaches are mainly focused on reducing the heat gain/loss through the building envelope.

As the same as indoor air temperature, indoor air humidity also plays an important role on indoor air quality [10], human comfort [11] and durability of building envelope [12]. Besides the indoor air quality, it also has a significant influence on building loads and building energy consumption. Bailey et al. [13] simulated the dynamic latent heat storage effects of building construction and furnishing. The results indicate that moisture storage acts to increase cooling loads and cooling energy.

Excessively low or high humidity are not good for living and working. In recent years, hygroscopic materials are used to moderate the indoor humidity fluctuations and reduce the peak indoor relative humidity [14]. Hygroscopic material acts as the skin of wall with the function of breathing. When the relative humidity increases, hygroscopic material draws in the water vapour from indoor air to depress the growth rate of indoor humidity. On the contrary, when the relative humidity falls, it breaths out the water vapour to hold the indoor humidity. For example, in domestic buildings, hygroscopic material absorbs moisture during the occupied time (e.g. sleeping night) and release moisture during the unoccupied time (e.g. working daytime).

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Nomenclature

a_m	Vapour diffusivity (m^2/s)
A	Material exposed area (m^2)
d	Penetration depth (m)
h_m	Mass transfer coefficient (kg/Pa·m^2·s)
H	High L Low
L_m	Material thickness (m)
m	Material mass (kg)
P_a	Indoor air partial vapour pressure (Pa)
P_{sat}	Vapour pressure at saturation (Pa)
P_v	Partial vapour pressure (Pa)
q_m	Vapour flux {kg/(m^2·s)}
s	Laplace transform variable
t	Time (s)
u	Real part of the complex
v	Imaginary part of the complex
x	Spatial coordinate (m)

Greek letters

α	Proportional coefficient
ζ	Moisture capacity (kg/m3)
δp	Vapour permeability for partial vapour pressure {(kg/m·s·Pa)}
τ	Time period (s)
ω	Angular frequency (rad/s)
φn	Phase (rad)

Subscripts

amp	Amplitude
mean	Mean
exp	Experiment
sim	Simulation

During the unoccupied time, hygroscopic material can be dried by ventilation which makes it ready for the next cycle. Osanyintola et al. [15] investigated the application of hygroscopic materials in a building with well-controlled HVAC systems. The results show that it may be possible to reduce heating and cooling energy consumption by up to 5% and 30% respectively.

The moisture transportation in building wall is one of the most important constitute in building hygrothermal simulation. The mechanism of moisture transfer in hygroscopic material has been studied in terms of theory, experiment and numerical simulation over the past decades. Moisture transfer in hygroscopic material is a complex process and will be influenced by various factors. Some are the material properties including moisture capacity and water vapour permeability. Some are geometrical shapes including the exposed area and active thickness. Based on experimental investigation and theoretical assumption, many advanced moisture transfer models have been developed, such as effective capacitance (EC) model [16], effective moisture penetration depth (EMPD) model [17,18], combined heat and moisture transfer (HAMT) model) [19] etc. Compared to the lumped parameter model (EMPD model) and the empirical model (EC model), the physical model (HAMT model) has a better accuracy and can quantitatively evaluate the moisture exchange between hygroscopic material and indoor air [20].

There are many computational methods proposed to solve the governing differential equation derived from the physical model of moisture transfer in building hygroscopic materials. Typical methods are finite difference method [21], finite control volume method [22] and MultiTri-Diagonal-Matrix Algorithm (MTDMA) method [23] etc. These methods use numerical iteration to solve the governing equations which is time-consuming especially for obtaining the quasi-steady-state solution of the periodic moisture transfer problem. Sometimes it is hard to find reliable answers. Chen [24,25] presented a transfer function model of moisture transfer in hygroscopic materials with a simple solution and satisfactory accuracy. Besides, he also presented the frequency domain calculation method and the frequency domain characteristics validation of moisture transfer in hygroscopic materials. However, for solving the moisture transfer function, it needs to find the poles of hyperbolic s-transfer functions and compute their residues. In this calculation process, it tends to miss roots, particularly in the case where two adjacent roots are close together [26]. On the other hand,

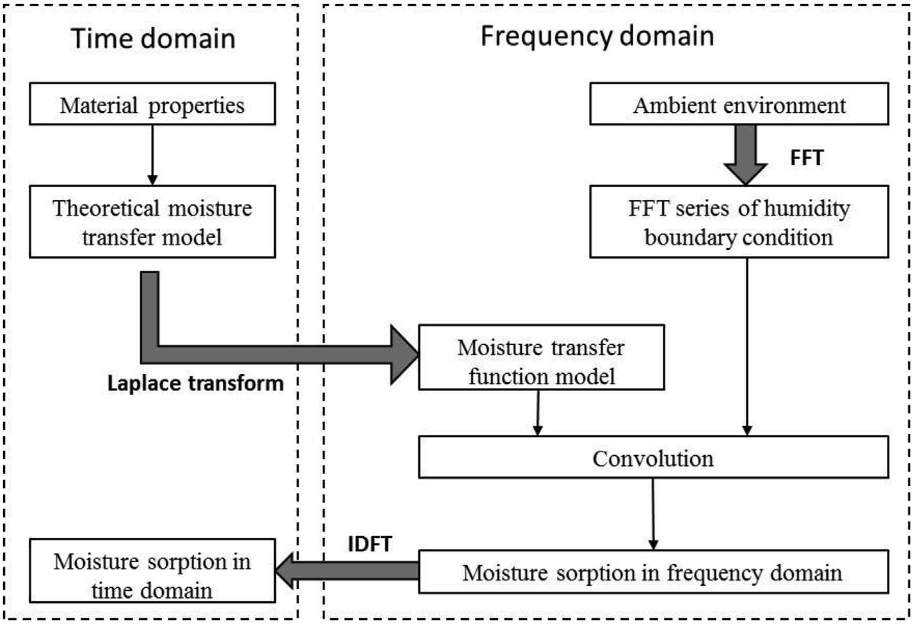

Fig. 1. Flow chart of the moisture transfer calculation of hygroscopic material plate.