Effect of Uncertainty in the Hygrothermal Properties on Hygrothermal Modeling

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Abstract Building envelopes are subject to the transient climate conditions. Moisture transfer which is coupled with heat transfer is an important issue in the field of building science. The moisture transfer and accumulation within building envelopes can lead to poor thermal performance, metal corrosion, wood decay, structure deterioration, microbial and mold growth. It is of great significance to investigate the hygrothermal behavior of building envelopes to improve the building energy efficiency, service life of buildings and indoor comfort. Though a lot of works have been done on the hygrothermal behavior of building materials, the experimental investigation is relatively lack. The hygrothermal properties of commonly used building materials which are the foundation of hygrothermal modeling often show a great uncertainty in the existing literatures. It may lead to significant discrepancy in the numerical results. In this paper, the local sensitivity analysis (LSA) method is used to investigate the effect of the uncertainty in hygrothermal properties, including the thermal conductivity, sorption isotherm, water vapor permeability and liquid water permeability, on the hygrothermal modeling. The results show that the uncertainty in the sorption isothermal and vapor permeability can lead to pretty high discrepancy in the distribution of the moisture content. The uncertainty in the sorption isothermal and vapor permeability causes relatively high error in temperature. These two properties must be determined accurately. The error caused by the uncertainty in liquid water permeability is limited since the relative humidity of the outdoor atmosphere is usually lower than 95% under which the capillary conduction is extremely weak.

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1 Introduction

Building envelopes are exposed to random climate conditions on the external surface. Moisture transfer within building envelopes is an important issue in building science. On the one hand, moisture transfer and accumulation within building envelopes can lead to poor thermal performance because of the reduction in the thermal insulation value of building components. On the other hand, high moisture level can cause metal corrosion, wood decay and structure deterioration which limit the service life of buildings. Besides, high moisture level within building components can result in microbial and mold growth which may have a detrimental effect on the health of the occupants. Thus, it is of great significance to investigate the hygrothermal behavior of building envelopes to improve the building energy efficiency, service life of buildings and indoor comfort.

Over the past half-century, a lot of researches have been done on the hygrothermal behavior of building materials. They can be classified into two categories: numerical modeling and experiment investigation. Numerical modeling is an efficient and fast way to predict the hygrothermal behavior of building envelopes. Over the past decades, significant advances have been made in mathematical methods to predict the hygrothermal behavior of building materials and components [1–6]. Compared with numerical modeling, experiment investigation is expensive and time-consuming. However, experiment investigation of the hygrothermal behaviors of building materials is necessary in order to gain hygrothermal properties and validate the developed model. In the recent past, many works focused on the hygrothermal properties investigation [7–11]. And a lot of benchmark experiments have developed data sets to validate mathematical models for coupled heat and moisture transport [12–15].

The hygrothermal models are applied in many aspects of building engineering such as durability investigation [16–18], energy performance study [19–23] and mold growth control [24–26] in buildings since lots of achievements have been obtained on investigation of the hygrothermal behavior of building materials. Whatever aspect is applied, hygrothermal models need proper input data. Though extensive databases of hygrothermal properties are documented in literatures [7–10], the properties often show a great uncertainty. The numerical results of a hygrothermal modeling may exist significant discrepancy due to the uncertainty of the hygrothermal properties.

The objective of this paper is to investigate the effect of uncertainty of hygrothermal properties on hygrothermal modeling under natural climate. The effect of changes in hygrothermal properties (thermal conductivity, sorption isothermal, water vapor permeability and liquid water permeability) on numerical results is studied.

2 Hygrothermal Model

The hygrothermal model can be deduced based on the principle of mass and energy conservation. The governing equations can be written as follows [6]:

$$\xi \frac{\partial \varphi}{\partial t} = \nabla\left(\left(\delta_{\mathrm{p}}\varphi \frac{\mathrm{d}P_{\mathrm{s}}}{\mathrm{d}T} + K_{\mathrm{l}}\rho_{\mathrm{l}}R_{\mathrm{D}}\ln(\varphi)\right)\nabla T + \left(\delta_{\mathrm{p}}P_{\mathrm{s}} + K_{\mathrm{l}}\rho_{\mathrm{l}}R_{\mathrm{D}}\frac{T}{\varphi}\right)\nabla\varphi\right) \tag{1}$$

$$\left(\rho_{\mathrm{m}}c_{\mathrm{p,\,m}} + \omega c_{\mathrm{p,l}}\right)\frac{\partial T}{\partial t} = \nabla\left(\left(\lambda + h_{\mathrm{lv}}\delta_{\mathrm{p}}\varphi\frac{\mathrm{d}P_{\mathrm{s}}}{\mathrm{d}T}\right)\nabla T + h_{\mathrm{lv}}\delta_{\mathrm{p}}P_{\mathrm{s}}\nabla\varphi\right) \tag{2}$$

where ξ (J/m^3) is sorption capacity, φ is relative humidity, t (s) is the time, δ_{p} (s) is the vapor permeability, P_{s} (Pa) is the saturated vapor pressure, K_{l} (s) is the liquid water permeability, ρ_{l} (kg/m^3) is the density of water, R_{D} (J/kg K) is the gas constant of water vapor, T (K) is temperature, ρ_{m} (kg/m^3) is the density of the dry material, $c_{\mathrm{p,\,m}}$ (J/kg K) is the specific capacity of the dry material, ω (kg/m^3) is the moisture content, $c_{\mathrm{p,\,l}}$ (kg/m^3) is the specific heat of water, λ (W/m K) is the thermal conductivity, and h_{lv} (J/kg) is the latent heat of evaporation.

3 Hygrothermal Property Parametric Analysis

The hygrothermal properties are important input variables of the hygrothernal model. The output of hygrothermal modeling may heavily depend on the input variables. It is of great significance to investigate the uncertainty of the hygrothermal properties on the wall hygrothermal variation.

3.1 Parametric Analysis Method

The parametric analysis is performed by using local sensitivity analysis (LSA) method which studies the changes of model response by varying single parameter per time, whereas the others are maintained constant. Consequently, a HAM model output is obtained with respect to a specific hygrothermal property. The distribution of temperature and moisture content within an external wall has great impacts on the hygrothermal performance, efficiency and durability of buildings. Thus, the temperature and moisture content within an external wall are used to evaluate the effect of uncertainty of hygrothermal properties on hygrothermal modeling. The parametric analysis is concentrated on hygrothermal properties, including the thermal conductivity, sorption isothermal, water vapor permeability and liquid water permeability.

3.2 Configuration of Exterior Wall

Nanchang (hot-humid climate) is selected as a study city. The configuration of the typical wall is 20 mm cement plaster + 240 mm aerated concrete brick + 20 mm lime plaster (from the exterior to the interior). The properties of materials are given in Table 1.

3.3 Climate Conditions

The outdoor conditions are taken from typical meteorological year data [27]. The indoor conditions are set as 26 °C and 60% relative humidity according to the design code for heating, ventilation and air-conditioning of civil buildings [28].

4 Results and Discussion

The effect of changes in hygrothermal properties of the aerated concrete brick (AC) on the numerical results is presented and analyzed since the aerated concrete brick is the main component of the external wall.

The effect of changes in thermal conductivity of the aerated concrete brick on the average moisture content and temperature in the aerated concrete brick is presented in Fig. 1. As can be seen in Fig. 1a, the maximum errors for the average moisture content which is caused by increasing or decreasing the thermal conductivity by 50% range from 0.36 to 1.40%. The maximum error for the temperature is between 2.66 and 5.32%, and the mean error ranges from 1.16 to 1.61%. It also can be seen from Fig. 1b that the larger the thermal conductivity is, the severer the fluctuation of temperature is.

The effect of changes in sorption isothermal of the aerated concrete brick on the average moisture content and temperature in the aerated concrete brick is presented in Fig. 2. As can be seen in Fig. 2a, the mean errors for the average moisture content which is caused by increasing or decreasing the sorption isothermal by 50% range from 48.77 to 52.14%. It indicates that the uncertainty in the sorption isothermal has a significant effect on the distribution of moisture content. The maximum error for the temperature is between 1.80 and 4.48%, and the mean error ranges from 0.25 to 0.37%.

The effect of changes in vapor permeability of the aerated concrete brick on the average moisture content and temperature in the aerated concrete brick is presented in Fig. 3. The maximum errors for the average moisture content range from 5.13 to 16.32%, and the mean error ranges from 2.95 to 12.44%. The maximum error for the temperature is between 1.56 and 5.47%, and the mean error ranges from 0.31 to 1.08%.

Table 1 Properties of wall components [8]

Component	ρ_m (kg/m^3)	$c_{p,m}$ (J/kg K)	δ_p (10^{-12}s)	ω (kg/m^3)	λ (W/m K)	D_w (m^2/s)
Cement plaster	1807	840	54.67	$\frac{\varphi}{-0.022\varphi^2+0.025\varphi+0.0001}$	$0.854 + 0.0045\omega$	$1.4 \times 10^{-9} \exp(0.027\omega)$
Aerated concrete brick	615	950	34.7	$\frac{\varphi}{-0.1196\varphi^2+0.1226\varphi+0.0011}$	$0.177 + 0.00098\omega$	$9.2 \times 10^{-11} \exp(0.0215\omega)$
Lime plaster	1500	840	13.57	$\frac{\varphi}{-0.052\varphi^2+0.052\varphi+0.005}$	$0.526 + 0.0031\omega$	$2.7 \times 10^{-9} \exp(0.0204\omega)$

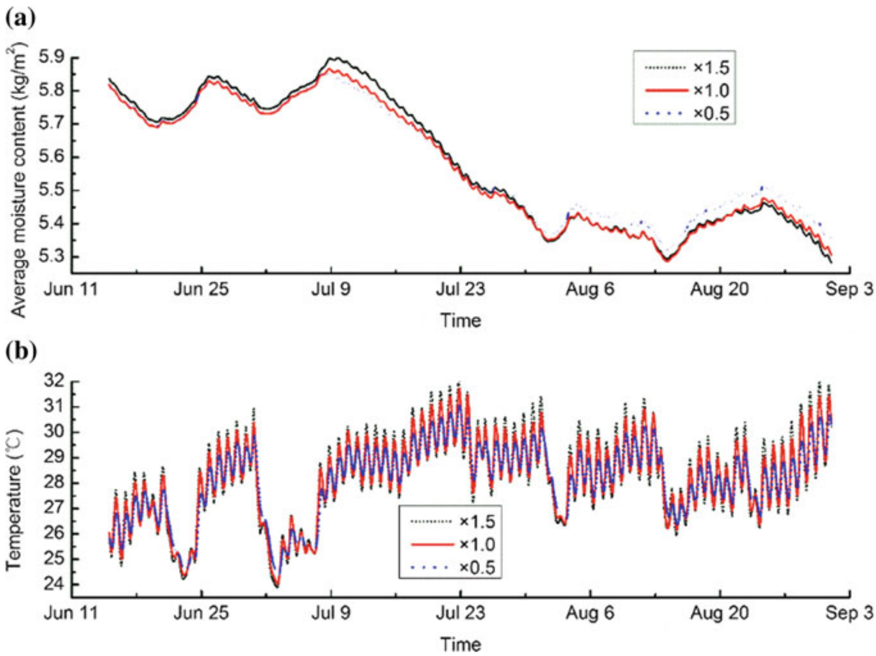

Fig. 1 Effect of changes in thermal conductivity of the aerated concrete brick on the average moisture content and temperature at the middle of the aerated concrete brick

The effect of changes in liquid water permeability of the aerated concrete brick on the average moisture content and temperature in the aerated concrete brick is presented in Fig. 4. The maximum error for the average moisture content is within 0.79%, and the mean error for the temperature remains 0.17–0.32%. It indicates that the uncertainty in liquid water permeability has a very tiny effect on the hygrothermal modeling. The main reason is that the relative humidity of environments is usually low than 95% under which the capillary conduction is extremely weak.

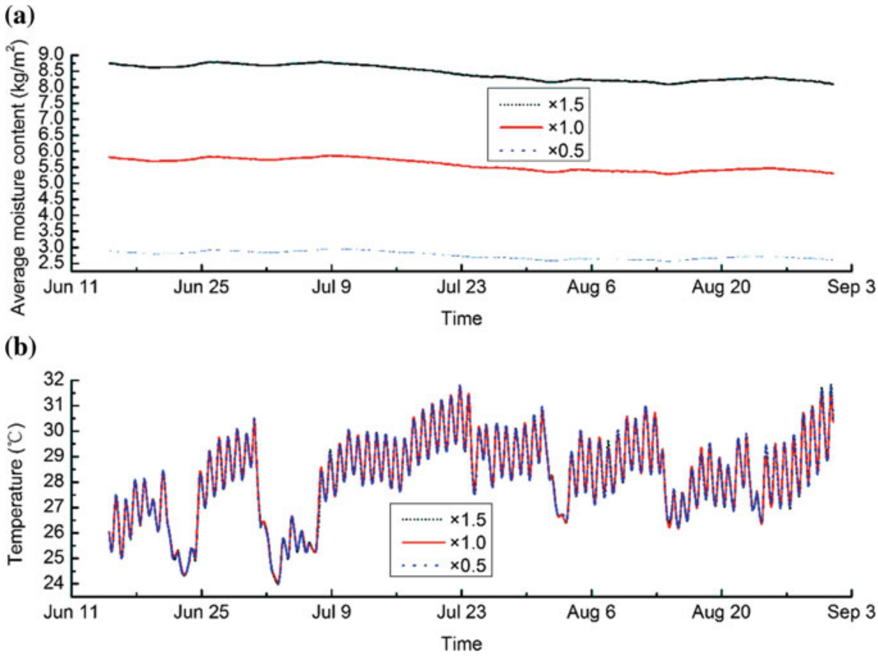

Fig. 2 Effect of changes in sorption isothermal of the aerated concrete brick on the average moisture content and temperature at the middle of the aerated concrete brick

5 Conclusions

The effect of uncertainty of hygrothermal properties, including the thermal conductivity, sorption isothermal, water vapor permeability and liquid water permeability, on hygrothermal modeling is studied under natural climate for typical wall which is commonly used in Nanchang (hot-humid climate), China. The results show that

(1) The effect of uncertainty in sorption isothermal on the distribution of moisture content in wall is tremendous. And the effect of uncertainty in vapor permeability on the distribution of moisture content in wall is also obvious. Thus, these two properties must be determined accurately.
(2) The uncertainty in the sorption isothermal and vapor permeability leads to relatively high error in temperature.
(3) The error caused by the uncertainty in liquid water permeability is limited because the relative humidity of environments is usually low than 95% under which the capillary conduction is extremely weak.

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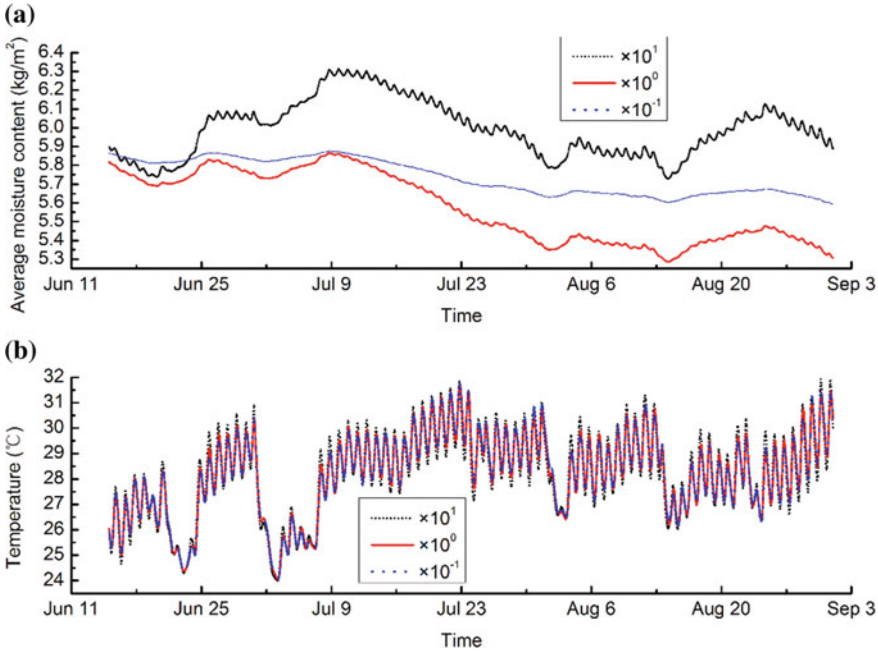

Fig. 3 Effect of changes in vapor permeability of the aerated concrete brick on the average moisture content and temperature at the middle of the aerated concrete brick

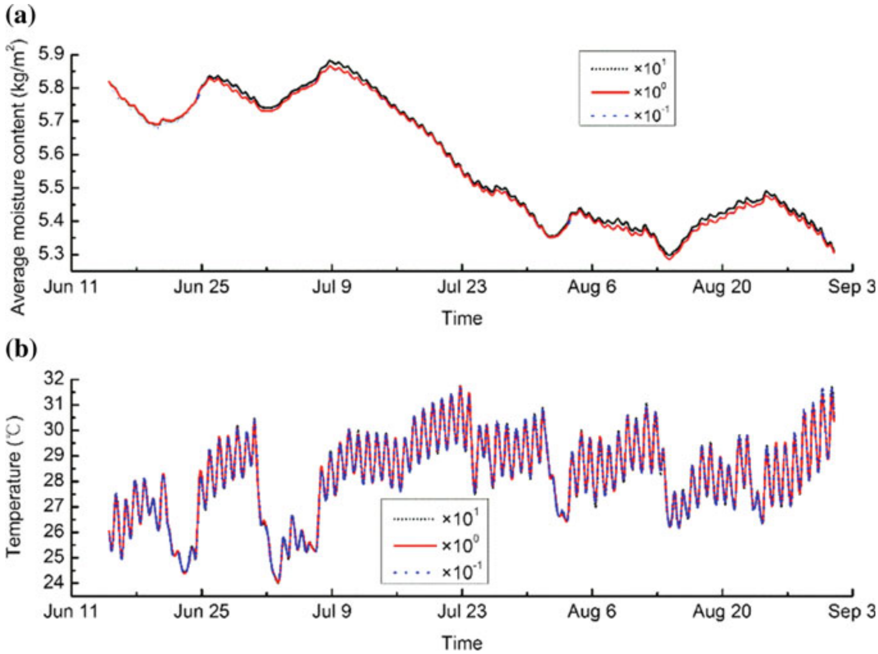

Fig. 4 Effect of changes in liquid water permeability of the aerated concrete brick on the average moisture content and temperature at the middle of the aerated concrete brick

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