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Numerical investigation for thermal performance of exterior walls of residential buildings with moisture transfer in hot summer and cold winter zone of China

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ABSTRACT

The building envelopes are exposed to the hot-humid climate with high humidity in hot summer and cold winter zone (HSCW) of China. The moisture transfer may severely influence the conduction loads through exterior walls. In this paper, a coupled heat and moisture transfer model is developed and validated to investigate the thermal performance of exterior walls. The conduction loads through a typical exterior wall are used to evaluate the effect of moisture transfer on the thermal performance of exterior walls in HSCW zone of China. The results show that the peak cooling and heating loads are overestimated by 2.1–3.9% and 4.2–10.1%, respectively, when ignoring moisture transfer. In cooling season, the sum of the latent load accounts for 14.3–52.2% of the sum of the total load and the yearly latent load accounts for 4.9–6.1% of the yearly total load when considering moisture transfer. The total cooling, heating and the yearly load are underestimated by 9.9–34.4%, 1.7–4.0%, and 5.2–6.8%, respectively, when ignoring moisture transfer. The results indicate that ignoring moisture transfer causes significant discrepancy in predicting the conduction loads. A detailed model considering moisture transfer in building envelope is essential to accurately evaluate the building energy performance in HSCW zone of China.

1. Introduction

In hot-humid climate regions, building thermal performance is much influenced by the moisture transfer and storage within porous building envelopes. The hot summer and cold winter zone of China is a typical hot-humid climatic region, which has over 40% of the total population of China and shares 48% of China's gross domestic product [1]. With the opening-up of China, this region is experiencing an unprecedented development in economy and significant improvements in living standards. The building industry in this region is undergoing a rapid boom. Both new buildings and existing buildings without heating and cooling facilities installed in the past are equipped with heating and air-conditioning systems to meet the thermal comfort requirements of occupants. This leads to the great increase of building energy consumption in this region.

In order to optimize the design of envelopes and heating and air-conditioning systems for improving building energy efficiency, some energy simulation programs, such as DeST, eQUEST are often used to evaluate the energy and thermal performance of buildings in the HSCW zone of China [2,3]. Porous bricks and concrete are commonly used as building envelopes in this region. The building envelopes are exposed to the hot-humid climate with intense temperature change and high humidity. The monthly average relative humidity in this region is considerably high ranging from 75% to 80% all year round [4]. The heat transfer through the building envelopes accompanies with the moisture transfer and storage. The models embedded in these energy simulation programs to calculate the conduction heat through building envelopes are commonly the transient heat transfer models (TH) without taking into account the effect of moisture transfer in porous envelopes [2,3]. This may lower the validity and reliability of energy performance evaluation and optimal design, and thus lead to the reduction of energy efficiency of the building systems in this region.

Many studies have been carried out to investigate the hygrothermal transfer phenomena in porous materials. Most of these

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Nomenclature

c_p	specific heat of material (J/kg K)
D_w	moisture diffusivity (m^2/s)
g	moisture flow (kg/m^2 s)
g_v	vapor diffusion flux (kg/m^2 s)
g_l	liquid flux (kg/m^2 s)
h	surface heat transfer coefficient (W/m^2 K)
h_c	convection heat transfer coefficient (W/m^2 K)
h_l	enthalpy of liquid water (J/kg)
h_v	enthalpy of water vapor (J/kg)
h_{lv}	latent heat of evaporation (J/kg)
I	solar radiation (W/m^2)
K_l	liquid water permeability (s)
M_w	molecular weight of water molecular (kg/mol)
N_c	total number of cooling days (d)
N_h	total number of heating days (d)
p_c	capillary pressure (Pa)
p_v	partial water vapor pressure (Pa)
P_s	saturated water vapor pressure (Pa)
q	heat flow (W/m^2)
Q	total heat flow (W/m^2)
R	universal gas constant (J/mol K)
R_D	gas constant of water vapor (J/kg K)
t	time (s)
T	temperature (K)
x	space coordinate (m)

Greek symbols

α	solar absorptivity of exterior surface
β_p	surface vapor transfer coefficient (kg/(Pam^2 s))
δ_p	water vapor permeability (s)
λ	thermal conductivity (W/m K)
ξ	sorption capacity (kg/m^3)
ρ	density of material (kg/m^3)
φ	relative humidity
ω	moisture content (kg/m^3)

Subscripts

c	cooling
e	exterior side of wall
h	heating
i	interior side of wall
l	liquid/latent load
m	dry material
n	normal direction
s	saturated state/sensible load
surf	surface
t	total load
v	vapor

hygrothermal models' development were based on the work by Phillip and De Veries [5] and Luikov [6] who developed transient models that used moisture content as the driving potential for moisture transport. Due to the discontinuity of moisture content in the interface surfaces of two different materials, some scholars tried to modify the models using other continuity driving potential instead of moisture content. I.Budaiwi [7] used the air humidity ratio as the driving potential. However, the model considered only vapor transfer, and the capillary liquid water transfer at high moisture level was not considered. R. Belabi [8] and M. Qin [9] used water vapor content to instead of moisture content as the driving potential. The shortcoming of their model was that it was difficult to obtain the phase conversion factor and thermogradient coefficient. Kuenzel [10] used relative humidity as the driving potential, and the moisture storage function in hygroscopic region and capillary water region become consistent through Kelvin's formula. A commercial program (WUFI) has been developed based on Kuenzel's model. After several decades' development, the hygrothermal models were applied in many aspects of building engineering such as durability investigation [11–18] and energy performance study of buildings [19–24].

F. Kong's [21] investigation showed that the maximum of conduction load of wall in the first year was about 13.6% higher than that of the 10th year due to the high initial moisture content in the concrete wall. N. Mendes's [22] investigation showed that ignoring the influence of moisture may overestimate conduction peak load by up to 210% and underestimate the yearly integrated heat flux by up to 59%. R.M. Barbosa's [23] research showed that disregarding the influence of moisture may oversize the HVAC system by 13% and underestimate the cooling energy consumption by 4%. H.J. Moon's [24] investigation showed that the energy consumption is 4.4% higher when moisture was taken into consideration. In order to acquire a better knowledge of whole-building heat, air and moisture balance and its effects on the indoor environment, on energy consumption and on envelope's durability, a project, IEA Annex 41 Whole Building Heat, Air and Moisture Response, was carried out (2003–2007) [25].

Though the moisture transfer and storage in the building envelopes is common [26] and a lot of research works have been carried out internationally, only few studies have been carried out on the hygrothermal transfer in the building envelopes specific to China [21,26,27]. The effect of moisture transfer on the thermal performance of building envelopes has not been investigated yet for the HSCW zone of China. The buildings are subjected to the hot-humid climate with high temperature and humidity in this region. The moisture effect on the thermal load of building envelopes may be significant [21–24]. To accurately evaluate the building energy performance in this region, the effect of moisture transfer and storage on the thermal performance of building envelopes should be included.

The objective of this paper is to investigate the effect of moisture transfer on the thermal performance of building envelopes in the HSCW zone of China. In this paper, a coupled heat and moisture transfer model (CHM) is developed to calculate conduction loads through building envelopes. It is solved by using a finite-element based computational tool called COMSOL Multiphysics, and validated by comparing with the benchmark test of EN 15026 [28] and the benchmarks of the HAMSTAD project [29]. Then, the proposed model is applied to investigate the effect of moisture transfer on thermal performance of exterior walls of residential buildings in the HSCW zone of China. The conduction loads through an exterior wall is used as an index to evaluate the effect of moisture transfer within exterior walls on the thermal performance of exterior wall. The detailed climatic sub-zones (A, B, C) and typical city corresponding to each climatic sub-zone in the HSCW zone of China are given in Table 1 according to HDD18 and CDD26. Three cities, Chengdu (30.67°N, 104.02°E), Changsha (28.22°N, 112.92°E), and Shaoguan (24.68°N, 113.60°E), are selected as the investigation cities.

2. Coupled heat and moisture transfer model for an exterior wall

2.1. Governing equations

2.1.1. Mass transfer

In building components, the moisture can be present in three phases: vapor, liquid and solid (ice). The effects associated with phase change, liquid to ice, are neglected in the present model,