Effect of Moisture Transfer on Thermal Performance of Exterior Walls in Hot and Humid Region of China

Lu Bai, Jingchao Xie, Yaping Cui, Jiaping Liu and Ying Ji

Abstract Moisture transfer in building envelopes can affect the internal surface temperature of the envelopes and the air-conditioning energy consumption. Therefore, this study aims to evaluate the effect of moisture transfer on thermal performance of exterior walls. In this study, a coupled heat and moisture transfer model was proposed. With the measured continuous outdoor climate parameters for four hot and humid regions including Haikou, Qionghai, Xiamen, and Guangdong, this model assessed the impact of moisture transfer on the inner surface temperature, the peak cooling loads, and the heat from walls. The results showed that the fluctuation range of the internal surface temperature decreased when moisture transfer is considered. The peak cooling loads were overestimated when moisture transfer is ignored. Besides, the total heat from walls was underestimated by around 4% in the cooling seasons. This study could provide basis for future studies on moisture transfer characteristics in coastal and island areas.

Keywords Moisture transfer · Thermal performance · Hot and humid region · Exterior wall

1 Introduction

Moisture transfer in building envelopes affects the heat gain of the room in summer. Normally, cooling load is calculated only considering heat transfer while moisture

L. Bai · J. Xie (✉) · Y. Cui · J. Liu · Y. Ji
Key Laboratory of Green Built Environment and Energy Efficient Technology, Beijing University of Technology, Beijing, China
e-mail: xiejc@bjut.edu.cn

L. Bai
e-mail: bailu1266@163.com

Y. Cui
e-mail: 15650752008@163.com

J. Liu
e-mail: liujp@bjut.edu.cn

Z. Wang et al. (eds.), *Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019)*, Environmental Science and Engineering, https://doi.org/10.1007/978-981-13-9528-4_6

transfer within walls is neglected. In fact, the interaction between moisture transfer and the heat transfer should not be neglected, especially in the outdoor environment with high humidity.

Many studies have been performed about the moisture transfer in building envelopes. Talukdar [1] established a material heat and moisture transfer model and validated the model in the wind tunnel. Qin [2] presented a model for predicting heat and moisture transfer of the whole building. The results showed that hygroscopic materials cloud improve to the building thermal design. Kong [3] analyzed the moisture transferring performance of enclosures on building initial stage in severe cold area and studied the coupling transfer of heat and moisture in building envelopes. Liu [4] evaluated the effect of moisture transfer on the thermal performance of exterior walls in hot summer and cold winter zone of China. Wang [5] studied the influence of moisture transfer on the internal wall surface temperature. The internal surface temperature of walls made of different materials was evaluated under the constant and variable boundary conditions. Though a lot of research works have been done wildly, few studies are conducted in hot and humid regions including Hainan Island and southeast coast of China, where the effect of moisture transfer on thermal performance of exterior walls has not been clear.

In this paper, a numerical model considering the coupled heat and moisture transfer was built. The model was verified and employed to assess the impact of moisture transfer on the inner surface temperature of walls, the peak cooling loads, and the heat from the exterior wall. The effect of moisture transfer on thermal performance of exterior walls was analyzed, and differences in four hot and humid regions were obtained.

2 Methods

2.1 Coupled Heat and Moisture Transfer Model for an Exterior Wall

The total moisture transfer consists of vapor flux and liquid diffusion flux within building envelopes. The main gradients for both temperature and relative humidity are on the *x*-axis direction, so the 1-D modeling hypothesis is used in this paper. The moisture transfer equations are given below.

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

where w is the moisture content, J_v is the vapor diffusion flux, and J_l is the liquid flux. The vapor diffusion flux is described by Fick's law:

$$J_v = -\delta \frac{\partial P_v}{\partial x} \tag{2}$$

where δ is the vapor permeability and P_v is the vapor pressure. The relative humidity is continuous at the interface of different materials owing different moisture storage properties. For convenience of calculations, relative humidity is chosen as the driving potential of moisture transfer. The water vapor pressure can be expressed as:

$$P_v = \varphi P_s \tag{3}$$

where φ is the relative humidity. P_s is the saturated water vapor pressure. The liquid diffusion flux is described by Darcy's law:

$$J_l = -K_l \frac{\partial P_l}{\partial x} \tag{4}$$

where K_l is the liquid water permeability and P_l is the capillary pressure. The capillary pressure can be expressed as a function of temperature and relative humidity by Kelvin's formula:

$$P_l = \rho_l R_v T \ \ln(\varphi) \tag{5}$$

where ρ_l is the density of liquid water and R_v is gas constant of water vapor. So the moisture transfer equations, Eq. (1), can be transformed using relative humidity and temperature as the driving potential as:

$$\xi \frac{\partial \varphi}{\partial t} = -\frac{\partial}{\partial x}\left(D_\varphi \frac{\partial \varphi}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_T \frac{\partial T}{\partial x}\right) \tag{6}$$

$$D_\varphi = \delta P_s + (K_l R \rho_l \frac{T}{\varphi}) \tag{7}$$

$$D_T = \delta \varphi \frac{\partial P_s}{\partial T} + K_l R \rho_l \ln \varphi \tag{8}$$

where ξ is the sorption capacity of the porous material, D_φ is the mass transport coefficient associated with a relative humidity gradient, and D_T is the mass transport coefficient associated with a temperature gradient.

Phase change of moisture happens in heat transfer process of building envelopes. Therefore, the coupled relationship of moisture transfer should be considered and heat transfer. The energy conservation equation within building envelopes can be given by:

$$(\rho_s c) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\alpha_T \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(\alpha_\varphi \frac{\partial \varphi}{\partial x}\right) \tag{9}$$

$$\alpha_T = \lambda + L(T) \varphi \delta \frac{dP_s}{dT} \tag{10}$$

$$\alpha_\varphi = L(T) \delta P_s \tag{11}$$

where ρ_s is the density of the material, c is the specific capacity of the dry material, λ is the thermal conductivity, $L(T)$ is the heat of vaporization, α_T is the heat transport coefficient associated with a temperature gradient, and α_φ is the heat transport coefficient associated with a relative humidity gradient.

For the internal surface ($x = 0$):

$$-\left(D_\varphi \frac{\partial \varphi}{\partial x}\right) - \left(D_T \frac{\partial T}{\partial x}\right)\Bigg|_{x=0} = h_{mi}\left(\rho_{v,x=0} - \rho_{v,i}\right) \tag{12}$$

$$-\alpha_T \frac{\partial T}{\partial x} - \alpha_\varphi \frac{\partial \varphi}{\partial x}\Bigg|_{x=0} = h_{ci}(T_{x=0} - T_i) + L(T)h_{mi}(\rho_{v,x=0} - \rho_{v,i}) \tag{13}$$

For the external surface ($x = l$):

$$-\left(D_\varphi \frac{\partial \varphi}{\partial x}\right) - \left(D_T \frac{\partial T}{\partial x}\right)\Bigg|_{x=l} = h_{me}(\rho_{v,x=l} - \rho_{v,e}) \tag{14}$$

$$-\alpha_T \frac{\partial T}{\partial x} - \alpha_\varphi \frac{\partial \varphi}{\partial x}\Bigg|_{x=l} = h_{ce}(T_{x=l} - T_e) + L(T)h_{me}(\rho_{v,x=l} - \rho_{v,e}) + \psi I \tag{15}$$

where h_m is the convective mass transfer coefficient, h_c is the surface convective heat transfer coefficient, ρ_v is the density of water vapor, I is the solar radiation, and ψ is the solar absorptivity of exterior surface of exterior wall.

2.2 Validation of the Numerical Model

The presented coupled transient heat and mass transfer model is validated by comparing with the benchmarks of the HAMSTAD project. This case is a drying process of 200-mm-thick wall which is exposed in an initial condition with a temperature of 20 °C and a relative humidity of 95% relative humidity. The detailed description of this case is given in the literature [6]. As shown in Fig. 1, the moisture distributions in wall are evaluated using the moisture transfer model presented in this paper, which shows a good agreement with the result of the benchmarks case. The average deviation is 2.2%.

2.3 Information of the Studied Building

To evaluate the impact of moisture transfer on the thermal performance of exterior walls, the typical structure of the exterior wall is used as the studied wall, which is commonly used in the southeast coast. The exterior wall consists of the concrete layer with a thickness of 240 mm in the middle of the wall and cement plaster layers with a

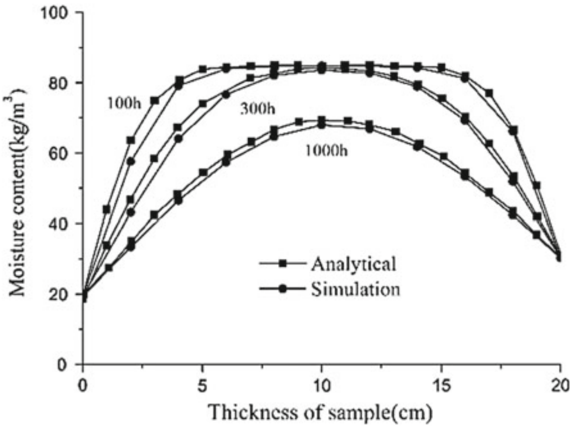

Fig. 1 Moisture profiles of the structure at 100, 300, and 1000 h

thickness of 20 mm on both sides. Thermal properties of the material are given in the literature [7]. Outdoor climate parameters for four different hot and humid regions are used as the external boundary condition from 22 June to 23 September. The set points of temperature and relative humidity are 26 °C and 60%. RH for the room is used as the internal boundary. One is traditional heat transfer model (model A) of the wall; the other is coupled heat and moisture transfer model presented in this paper (model B).

2.4 Calculation of the Peak Cooling Load

Moisture transfer within building envelopes not only affects their internal surface temperature, but also enhances the latent load. The cooling load of walls can be calculated as follows:

$$q_{s,c} = h_i(T_{surf,i} - T_i) \tag{16}$$

$$q_{l,c} = h_{mi}(\rho_{v,x=0} - \rho_{v,0}) \tag{17}$$

$$q_{t,c} = q_{s,c} + q_{l,c} \tag{18}$$

where $q_{s,c}$ is the instantaneous sensible load, $q_{l,c}$ is the instantaneous latent load, and $q_{t,c}$ is the instantaneous total load.

2.5 Calculation of the Heat from Walls

The simulation results are hourly cooling loads. Therefore, during the studied period of time, the heat from the exterior wall is defined as the accumulation of cooling load over time. The heat from the exterior wall can be calculated as follows:

$$Q_{\text{s,c}} = \sum_{i=1}^{N_{\text{c}}} (3600 q_{\text{s,c}}) \tag{19}$$

$$Q_{\text{l,c}} = \sum_{i=1}^{N_{\text{c}}} (3600 q_{\text{l,c}}) \tag{20}$$

$$Q_{\text{t,c}} = Q_{\text{s,c}} + Q_{\text{l,c}} \tag{21}$$

where, $Q_{\text{s,c}}$ is the sensible heat from the exterior wall, $Q_{\text{l,c}}$ is the latent heat from the exterior wall, $Q_{\text{t,c}}$ is the total heat from the exterior wall, and N_{c} is the total hours.

3 Results and Discussion

To evaluate the impact of moisture transfer on the thermal performance of exterior walls, the result calculated using model A is compared with that calculated using model B presented in this paper, including the inner surface temperatures of walls, the peak cooling loads of walls, and the heat from walls.

The inner surface temperatures of walls in four hot and humid regions are shown by the box plot in Fig. 2. The fluctuation of the inner surface temperature calculated considering moisture transfer is much smaller than that without considering moisture transfer, because the moisture exchange exists at the interface between the indoor

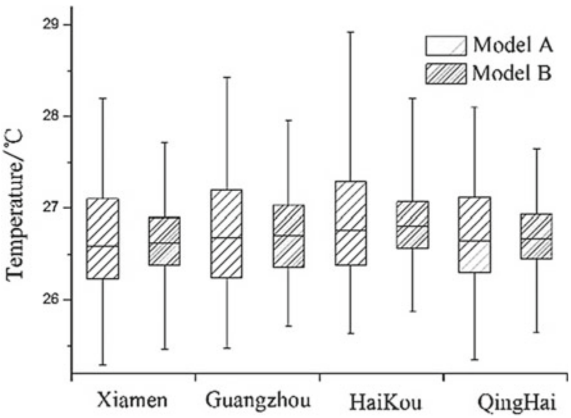

Fig. 2 Inner surface temperatures of walls

air and internal surface. When the moisture content of the inner surface is higher than that of the indoor air, the moisture-desorption absorbs heat, which leads to the surface temperature reeducation. Therefore, moisture absorption–desorption at the interface of building envelopes affects the surface temperature. In the four hot and humid regions, the average temperature calculated by the two models during the period is very close, which indicates that the change of the fluctuation for the surface temperature is obvious while the change of the mean value is small after considering the moisture transfer.

To evaluate the difference of the influence among the four regions, the variance of eight sets of temperature data is shown in Fig. 3. In Haikou, the variance of the inner surface temperature data is 0.35 when ignoring moisture transfer and becomes 0.14 when considering moisture transfer. The decrease of variance is most significant in Haikou (60%), followed by Qionghai (59%), Xiamen (54%), and Guangdong (51%).

The peak cooling loads of walls calculated by the two models in four regions are shown in Fig. 4. The peak cooling loads are overestimated when ignoring moisture

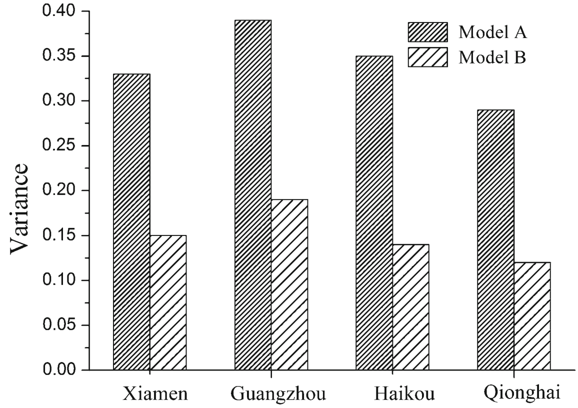

Fig. 3 Variance of the internal surface temperature

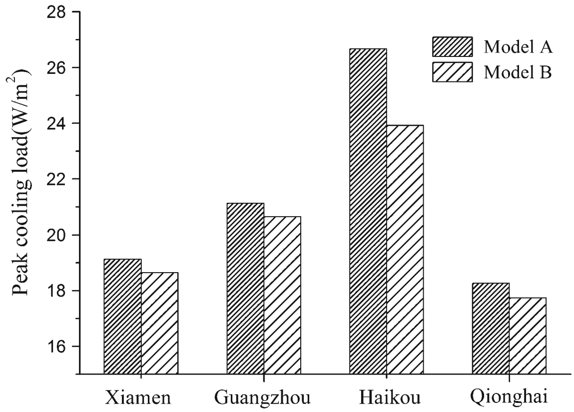

Fig. 4 Peak cooling load

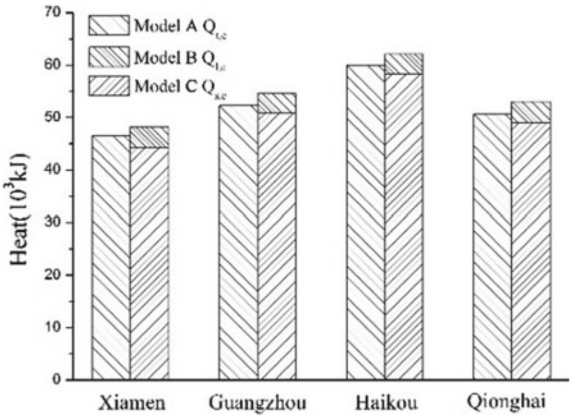

Fig. 5 Heat from walls

transfer. This overestimate was also most significant in Haikou with an increase of 10 and 2.5% in the other places. This comes from the significance cooling effect of the moisture on the surface temperature when inner surface temperature is high.

As shown in Fig. 5, although moisture transfer reduces the peak cooling loads in the cooling seasons, the total heat from walls increases, which is due to enhancement of the latent heat. The sensible heat from walls decreases when considering moisture transfer, but the total heat from walls is higher than that without considering moisture transfer. This difference was most significant in Qinghai (4.5%), similar to that of Guangdong, Xiamen, and Haikou, with an increase of about 3.7%. Research findings in this study evaluate the effect of moisture transfer on thermal performance of exterior walls under the steady internal boundary condition; however, the internal boundary condition is often dynamic. This issue needs to be considered in future studies.

4 Conclusion

A coupled heat and moisture transfer model was proposed in this study. And the accuracy of the model was verified in the benchmark test. With the measured continuous outdoor climate parameters for four hot and humid regions, this model was further employed to assess the impact of moisture transfer on thermal performance of exterior walls.

(1) The trend of the inner surface temperature which times calculated using model A and model B is basically the same. Due to the absorption and desorption materials adsorb or desorb moisture and moisture transfer, the fluctuation range of the internal surface temperature of walls decreased when considering moisture transfer. This decrease was most significant in Haikou.

(2) In the four regions studied in China, the peak cooling loads were overestimated when ignoring moisture transfer. This overestimate was most significant in Haikou by 10%, and by 2.5% in the other places, which may lead to unreasonable equipment selection and system design of air-conditioning system.
(3) The total heat from walls calculated in the cooling seasons was 4.6–3.5% higher when considering moisture transfer. Therefore, the total heat from walls is underestimated, which may cause the deviation of the building energy consumption between the calculated value and the real value.

The results indicated that the wall in Hainan Island was more affected by moisture transfer than the mainland, which could provide preliminary basis for future studies on moisture transfer characteristics of building walls in coastal and island areas.

Acknowledgements The project is supported by National Key R&D Program of China, Technical System and Key Technology Development of Nearly Zero Energy Building (Number 2017YFC0702600), National Natural Science Foundation of China (Major Program, Number 51590912). The Basic Research Fund Project of Beijing University of Technology (No. 004000546318525)

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