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Simulation research on the condensation characteristics of thermal insulation walls with a vapour barrier

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Abstract

The condensation problem of thermal insulation walls is becoming increasingly serious. The problem not only affects the performance of the thermal insulation layer and durability of the envelope structure but also increases the risk of mildew. To explore the condensation characteristics of thermal insulation walls and the anti-condensation effect of the vapour barrier in hot and humid areas in China, a coupled heat and moisture transfer model of a one-dimensional wall with temperature and relative humidity as the driving potential was established and verified. Taking the internal and external thermal insulation walls of EPS-Clay brick as an example, the relative humidity distribution of eight types of envelope structures with vapour barriers at three different interfaces or without vapour barriers was simulated. The results show that the best anti-condensation effect is provided by creating a vapour barrier outside of the wall (Interface 1 of internal and external thermal insulation walls). Therefore, in the high-humidity area represented by Guangzhou, the vapour barrier layer is recommended to be set at Interface 1.
Keywords: Condensation; internal and external thermal insulation; coupled heat and moisture transfer; vapour barrier.

Nomenclature

ξ	Slope of the moisture absorption curve	D_v	Penetration coefficient of water vapour (kg·Pa^{-1}·m^{-1}·s^{-1})
ρ	Density of materials (kg·m^{-3})	D_l	Penetration coefficient of liquid water (kg·Pa^{-1}·m^{-1}·s^{-1})
u	Balanced moisture content of materials (kg·kg^{-1})	P_l	Capillary pressure of liquid water (Pa)
J_v	Diffusion flux of water vapour (kg·m^{-2}·s^{-1})	$P_{v,s}$	Partial pressure of saturated vapour (Pa)
J_l	Diffusion flux of liquid water (kg·m^{-2}·s^{-1})	R_v	Gas constant of water vapour (J·kg^{-1}·K^{-1})
h_m	Mass transfer coefficient of water vapour (m·s^{-1})	C	Specific heat capacity of materials (J·kg^{-1}·K^{-1})
L	Latent heat of water vapour (J·kg^{-1})	λ	Thermal conductivity of materials (W·m^{-1}·K^{-1})
S	Heat source term (J·m^{-2}·s^{-1})	h	Heat transfer coefficient of wall surface (W·m^{-2}·K^{-1})

1. Introduction

In recent years, the energy consumption associated with the building envelope is an important factor with respect to the energy consumption of buildings. A thermal insulation layer and vapour barrier have often been considered to be installed to envelop the structures of existing buildings for building optimization in China [1-2]. Usually, the thermal insulation and vapour barrier arrangement system in North China is also used in South China [3-4]. This direct application does not consider the hot and humid

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climate in South China, which may cause moisture condensation and influence use [5].

The hot summer and warm winter (HSWW) zone is a typically hot and humid area. The relative humidity throughout the year is very high. Hot and humid air infiltration leads to moisture condensation at the surface or inside building envelopes, which has a negative influence on the indoor environment. Therefore, the condensation risk of walls in this area is much higher than that in other areas [3]. For the HSWW zone in particular, there is a lack of research on how to arrange the insulation layer, vapour barrier and base material to achieve the best anti-condensation effect and satisfy comfort requirements.

In this paper, a coupled heat and moisture transfer model of a one-dimensional wall with temperature and relative humidity as the driving potential is established and verified. Guangzhou is regarded as representative of the HSWW zone. 8 types of internal thermal insulation (ITI) and external thermal insulation (ETI) walls with vapour barriers at three different interfaces or without a vapour barrier are simulated and compared.

2. The coupled heat and moisture transfer model

2.1. Construction of the model

The moisture transfer equation can be expressed as follows.

$$\frac{\partial(\rho u)}{\partial t} = -\nabla(J_v + J_l) \tag{1}$$

According to the moisture absorption curve of the material, the following relation can be obtained.

$$\frac{\partial(\rho u)}{\partial t} = \rho\frac{\partial u}{\partial t} = \rho\frac{\partial u}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \rho\xi\frac{\partial \varphi}{\partial t} \tag{2}$$

According to Fick's law and Darcy's law:

$$J_v = -D_v\frac{\partial P_v}{\partial x} \tag{3}$$

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

The gradient of the partial pressure of water vapour can be transformed as follows:

$$\frac{\partial P_v}{\partial x} = \frac{\partial(\varphi P_{v,s})}{\partial x} = P_{v,s}\frac{\partial \varphi}{\partial x} + \varphi\frac{\partial P_{v,s}}{\partial T}\frac{\partial T}{\partial x} \tag{5}$$

According to the Kelvin relation [6], the capillary pressure P_l can be obtained as follows:

$$P_l = \rho_l R_v T \ln(\varphi) \tag{6}$$

According to Eqs. 6, 5 and 1, the moisture transfer equation of the wall can be obtained as follows:

$$\rho\xi\frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x}\left[\left(D_v P_{v,s} + D_l\rho_l R_v\frac{T}{\varphi}\right)\frac{\partial \varphi}{\partial x} + \left(D_v\varphi\frac{\partial P_{v,s}}{\partial T} + D_l\rho_l R_v\ln(\varphi)\right)\frac{\partial T}{\partial x}\right] \tag{7}$$

According to Fourier's law, the following heat transfer equation can be obtained.

$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + s \tag{8}$$

During heat and moisture transfer in the wall, the heat source is mainly the phase change heat of water.

$$s = -L\frac{\partial J_v}{\partial x} \tag{9}$$

According to Eqs. 3, 5, 8, and 9,

$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\left(\lambda + LD_v\varphi\frac{\partial P_{v,s}}{\partial T}\right)\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial x}\left(LD_v P_{v,s}\frac{\partial \varphi}{\partial x}\right) \tag{10}$$

According to Eqs. 7 and 10, the coupled heat and moisture transfer equation can be obtained.

$$\begin{cases} a_\varphi(\varphi,T)\dfrac{\partial\varphi}{\partial t}=\dfrac{\partial}{\partial x}\left[D_{\varphi\varphi}(\varphi,T)\dfrac{\partial\varphi}{\partial x}\right]+\dfrac{\partial}{\partial x}\left[D_{\varphi T}(\varphi,T)\dfrac{\partial T}{\partial x}\right] \\ a_T(T,\varphi)\dfrac{\partial T}{\partial t}=\dfrac{\partial}{\partial x}\left[D_{TT}(T,\varphi)\dfrac{\partial T}{\partial x}\right]+\dfrac{\partial}{\partial x}\left[D_{T\varphi}(T,\varphi)\dfrac{\partial\varphi}{\partial x}\right] \end{cases} \tag{11}$$

The empirical formula for the partial pressure $P_{v,s}$ of saturated water vapour is as follows:

$$P_{v,s}=610.5\exp\left(\frac{17.268t}{237.3+t}\right)=610.5\exp\left(\frac{17.268(T-273.15)}{T-35.85}\right) \tag{12}$$

The formula for calculating the gasification latent heat of water vapour is as follows [7]:

$$L=(2500-2.35t)\times10^3=(1858.9025-2.35T)\times10^3(\text{J/ kg}) \tag{13}$$

According to the BET equation, u can be calculated.

$$u=\frac{a\varphi}{(1+b\varphi)(1-c\varphi)}(kg/kg) \tag{14}$$

2.2. Validation of the model

Python language and the finite volume method was used for programming. To verify the accuracy of the model, the experimental data in [8] about spruce plywood are compared with numerical results. The program was run and the relative humidity simulation results were compared with experimental results at thicknesses of 9 mm and 18 mm as shown in Fig. 1. The experimental and simulated data showed that both are in good agreement, further proving the accuracy of the model and the program.

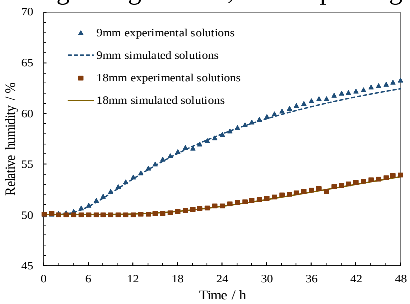


Fig. 1. Simulated and experimental solutions

Fig. 2. Map of five climatic zones in China

3. Methodology

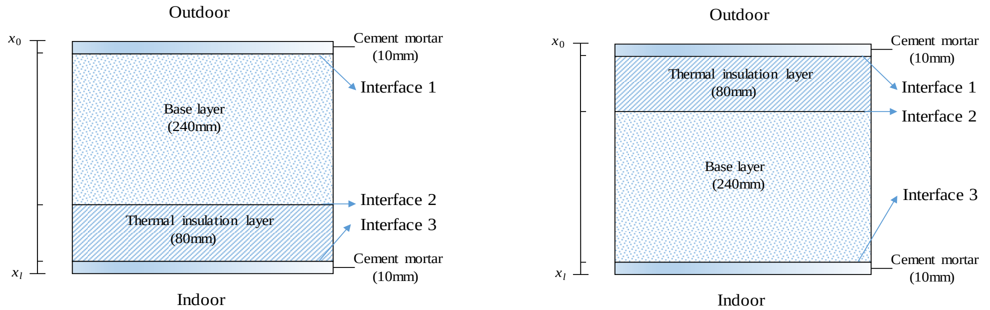
3.1. Outdoor and indoor boundary conditions

Climatic divisions for building design divide China into five zones. As shown in Fig. 2, Guangzhou typically belongs to the HSWW zone. Therefore, it was taken as the representative city, and the typical meteorological year parameters in Guangzhou were taken as the outdoor boundary conditions.

For many occasions, indoor environments with constant temperature and relative humidity must be maintained, such as in a laboratory, precision instrument production workshop, and hospital ward. Constant temperature and relative humidity were adopted as indoor boundary conditions. The temperature was held at 22 °C, and the relative humidity (*RH*) was held at 60%.

3.2. Numerical simulations

The insulation layer material is EPS. The base materials are clay brick. Cement mortar is used on both sides of the wall. As shown in Fig. 3, the thicknesses of the base layer, thermal insulation layer and cement mortar are 240 mm, 80 mm and 10 mm, respectively. The three interfaces in Fig. 3 are the locations of the vapour layer. Generally, the locations of the vapour barrier (VB) layer in Guangzhou are usually divided into the outer side of the wall (Interface 1), the interior side of the wall (Interface 3) and the interface between the base layer and the thermal insulation layer (Interface 2). 8 types of envelope structures with VB at 3 different interfaces or without a VB were simulated. A total of 16 groups of simulations were carried out with or without solar radiation.



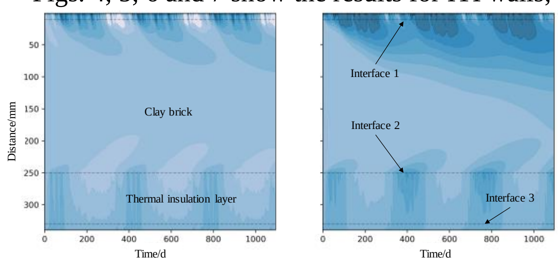
(a) ITI wall (b) ETI wall

Fig. 3. Overhead view of insulation walls

4. Methodology

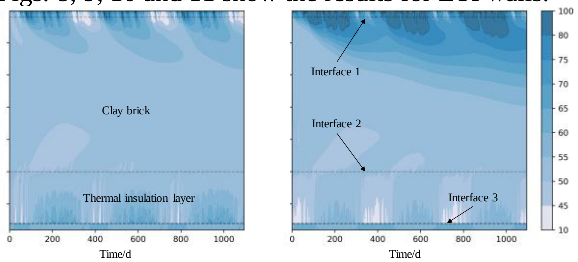
4.1. Internal thermal insulation walls

Figs. 4, 5, 6 and 7 show the results for ITI walls; Figs. 8, 9, 10 and 11 show the results for ETI walls.



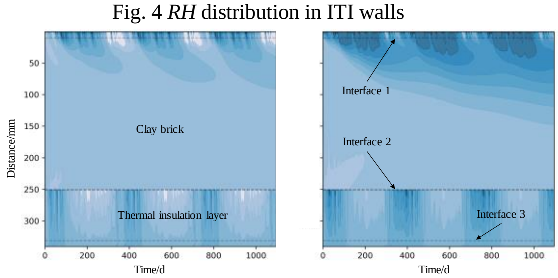
(a) With solar radiation (b) Without solar radiation

Fig. 4 *RH* distribution in ITI walls



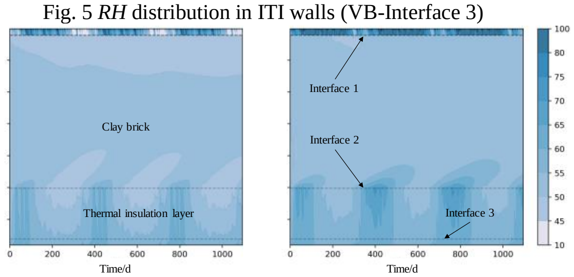
(a) With solar radiation (b) Without solar radiation

Fig. 5 *RH* distribution in ITI walls (VB-Interface 3)



(a) With solar radiation (b) Without solar radiation

Fig. 6 *RH* distribution in ITI walls (VB-Interface2)



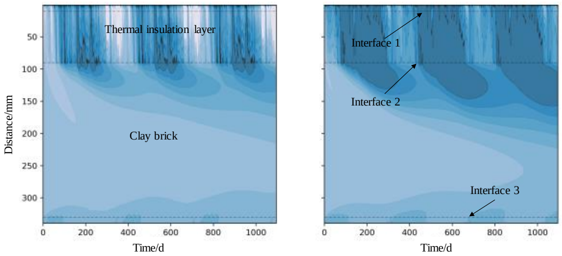
(a) With solar radiation (b) Without solar radiation

Fig. 7 *RH* distribution in ITI walls (VB-Interface1)

As shown in Fig. 5, after setting a VB layer at Interface 3, the slight moisture accumulation phenomenon at Interface 2 disappears because the VB blocks the water vapour from the interior to the outside. However, this measure cannot solve the problem of the condensation of moisture at Interface 1 at all in summer. The moisture accumulation of ITI walls under winter conditions is not significant, and condensation will not occur; thus, setting a VB layer at Interface 3 is not an effective method for preventing condensation.

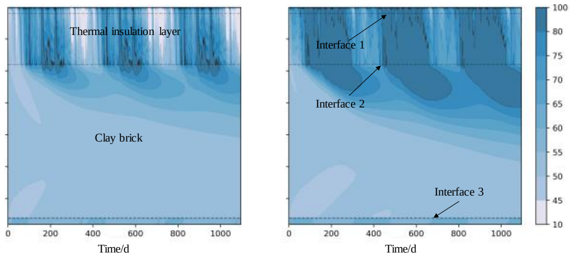
As shown in Fig. 6, similarly to setting a VB layer at Interface 3, setting a VB at Interface 2 does not weaken the condensation on the outer wall in summer. Furthermore, this measure makes the moisture accumulated at Interface 2 in winter more serious than that without a VB, and there is even slight condensation at Interface 2 in winter. The main reason for this phenomenon, as described in Section 4.1.1, is that the water vapour is transferred from indoors to outdoors in winter, and water vapour can be gathered at Interface 2 more easily because of the barrier of the VB layer. In general, it is not appropriate to set a VB between the thermal insulation layer and the base layer (Interface 2) for internal thermal insulation walls, which can not only alleviate the condensation phenomenon but also aggravate it.

As shown in Fig. 7, setting a VB at Interface 1 can effectively relieve the condensation on the outside of the wall, and moisture is completely obstructed in the cement mortar layer. Under the effects of solar radiation, the condensation in the cement mortar layer will be weakened, as shown in Fig. 7 (a). However, the phenomenon of moisture accumulation is the same as that shown in Fig. 4, which means this type of envelope structure configuration cannot solve the problem of moisture accumulation at Interface 2.



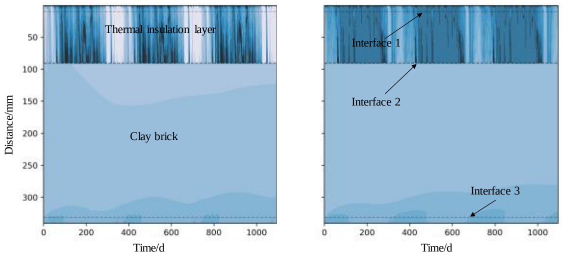
(a) With solar radiation (b) Without solar radiation

Fig. 8 *RH* distribution in ETI walls



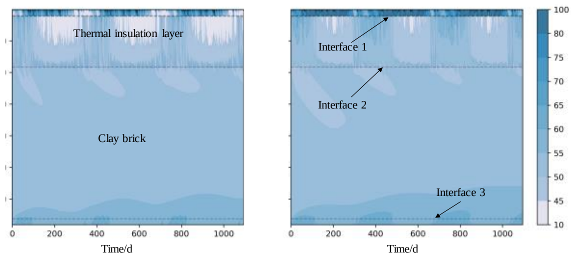
(a) With solar radiation (b) Without solar radiation

Fig. 9 *RH* distribution in ETI walls (VB-Interface 3)



(a) With solar radiation (b) Without solar radiation

Fig.10 *RH* distribution in ETI walls (VB-Interface 2)



(a) With solar radiation (b) Without solar radiation

Fig.11 *RH* distribution in ETI walls(VB-Interface 1)

4.2. External thermal insulation walls

Fig. 8 is the result of the 3-year simulation of ETI walls considering solar radiation or no solar radiation. The accumulation of moisture on the internal side of ITI walls in winter is more significant than that of ETI walls, and the condensation phenomenon on the external side of ETI walls in summer is more significant than that of ITI walls.

As shown in Fig. 9, after setting a VB layer at Interface 3, the slight moisture accumulation phenomenon at Interface 3 disappears, as observed for ITI walls. However, this measure cannot solve the problem of condensation of moisture at Interfaces 1 and 2 or at the cement mortar layer and thermal insulation layer in summer, similarly to ITI walls. Therefore, regardless of the wall type, it is inappropriate to set the VB on the indoor side (Interface 3). This method increases the cost of construction and does not prevent condensation.

As shown in Fig. 10, setting a VB at Interface 2 can significantly reduce the condensation phenomenon in the clay brick layer in summer, which can effectively stop the buildup of mildew in the clay brick layer. However, this measure does not alleviate the condensation phenomenon of thermal insulation layer; in fact, the condensation becomes more serious.

As shown in Fig. 11, installing the VB at Interface 1 can effectively relieve the condensation of the wall, and moisture is completely obstructed in the cement mortar layer, similarly to ITI walls. In addition, under the effects of solar radiation, the condensation in the cement mortar layer will be weakened, as shown in Fig. 11 (a), similarly to ITI walls. Therefore, this type of structure is beneficial to reducing the relative humidity inside the wall.

5. Conclusions

This paper focuses on the condensation characteristics of building envelopes that contain insulation layers and vapour barriers. According to numerical simulations and analysis, the condensation characteristics of thermal insulation walls are closely related to the construction arrangement of the insulation layer and the base material as well as climate parameters.

(1) In the HSWW zone, in summer, the outer side of walls easily produces dew, and the condensation of ETI walls is more significant than that of ITI walls. In winter, moisture accumulation tends to occur on the interior side of walls, and ITI walls (Interface 2) show more significant moisture accumulation than do ETI walls (Interface 3).

(2) Whether for ITI or ETI walls, it is most appropriate to set the vapour barrier layer at Interface 1, and it is not appropriate to set the vapour barrier on the indoor side (Interface 3), which increases the cost of construction and does not prevent condensation.

(3) Overall, the influence of solar radiation on the condensation characteristics of ETI walls is significant, and the effect on the condensation of ITI walls is limited.

Acknowledgements

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References

[1] Liang Fang, Nairen Diao, Zhukun Shao, Ke Zhu, Zhaohong Fang. A computationally efficient numerical model for heat transfer simulation of deep borehole heat exchangers. Energy Build. 2018;167:79-88.
[2] Yilin Li, Jo Darkwa, Georgios Kokogiannakis. Heat transfer analysis of an integrated double skin façade and phase change material blind system. Build. Environ. 2017;125:111-121.
[3] You S, Li W, Ye T, et al. Study on moisture condensation on the interior surface of buildings in high humidity climate. Build. Environ. 2017;125:39-48.
[4] Lihua Zhao, Zhongcheng Dong, et al. Study on moisture transfer of external thermal insulation wall. Journal of harbin university of civil engineering and architecture 2001;34(6):78-81.
[5] Moon H J, Ryu S H, Kim J T. The effect of moisture transportation on energy efficiency and IAQ in residential buildings. Energy Build. 75(2) (2014) 439–446.
[6] Künzel H M. Simultaneous heat and moisture transport in building components: one-and-two-dimensional calculation using simple parameters. Irb Verlag 1995.
[7] Mendes N, Philippi P C, Lamberts R. A new mathematical method to solve highly coupled equations of heat and mass transfer in porous media. International Journal of Heat & Mass Transfer 2002;45(3):509-518.
[8] Talukdar P, Olutmayin S O, Osanyintola O F, et al. An experimental data set for benchmarking 1-D, transient heat and moisture transfer models of hygroscopic building materials. Part I: Experimental facility and material property data. International Journal of Heat & Mass Transfer 2007;50(23):4527-4539.

Biography

Chengcheng Xu, born in 1994, Ph.D student in Southeast University, Nanjing, China. The main research area is the energy-saving technology of Chinese traditional dwellings.