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Evaluation of the impact of phase change humidity control material on energy performance of office buildings

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ABSTRACT
Phase change humidity control material (PCHCM) is a new kind of composite made of high performance PCM microcapsules and diatomite. The PCHCM composite can moderate the hygrothermal variations by absorbing or releasing both heat and moisture and significantly reduce the peak/valley values of indoor temperature and relative humidity. In this paper, a novel model is developed to evaluate the energy performance of office buildings with PCHCM. The model is validated by a series of experiments, and then applied to investigate the effect of PCHCM on energy consumption in different typical climates worldwide (i.e. Beijing, Paris, Atlanta, and Guangzhou). Results show that high values of energy efficiencies can be obtained in the climates which characterized by a wide amplitude of temperature and humidity difference all day along (Paris and Atlanta). Noteworthy, the highest potential energy saving rate could be up to 19.57% for the office building in Paris.

KEYWORDS
Phase change humidity control material, HAMT, Enthalpy method, Energy consumption

INTRODUCTION
Nowadays, increased energy demand has resulted in environmental issues worldwide (International Energy Agency, 2012). Building sector represents about 40% of global energy consumption and produces 30% of global greenhouse gas emissions annually (United Nations Environment Programme, 2009).The energy consumption of heating, ventilation and air-conditioning (HVAC) system accounts for 50% of building energy consumption in developed countries (Dincer, 1998). For this reason, it's essential to reduce the energy consumption of HVAC systems. The application of innovative building materials which can control the indoor hygrothermal condition at a relatively comfortable level is a promising way of energy saving.

The phase change materials (PCM) and porous hygroscopic materials are commonly used to moderate the indoor hygrothermal fluctuations (Barreneche et al. 2013; Evola et al. 2013; Andersen and Korsgaard, 1986; Toftum et al. 1998).However, those two kinds of material cannot simultaneously regulate the indoor temperature and humidity. Therefore, the phase change humidity control materials (PCHCM) that have the capability of both thermal and moisture buffering were prepared by our research group (Chen et al. 2015; Chen and Qin, 2016). The synthesis of novel phase change humidity control material (PCHCM) was achieved by using composite microencapsulated phase change material (MPCM) and diatomite. The PCHCM can moderate indoor air fluctuations of temperature and relative humidity by absorbing or releasing both heat and moisture.

Currently, the coupled heat and moisture transfer (HAMT) model proposed by Künzel (1995) is the most used and validated model to calculate the coupled heat and moisture transfer through porous building materials. On the other hand, the enthalpy method that can evaluate the general convection and diffusion phase change process was proposed by Voller et al (1987). However, very few models can be used to calculate the coupled heat, air and moisture transfer with phase change process.

The objectives of this study are: (1) to propose a novel mathematical model for calculating the coupled heat, air and moisture transfer with phase change process; (2) to analyse the energy saving effect of PCHCM in different climates.

METHODS

Methodology

The following equations are taken from HAMT model (Künzel, 1995). The heat balance of building envelops can be described in equation (1):

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{\omega}\frac{\partial T}{\partial x}\right) + h_{\mathrm{v}}\frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial(\varphi P_{\mathrm{sat}})}{\partial x}\right) \tag{1}$$

where H is the total enthalpy of material (kJ/kg), T is the temperature (°C), t is the time (s), x is the thicknes (m), k_{ω} is the heat conductivity coefficient (W/m·K), h_{v} is the vaporization enthalpy of water (kJ/kg), δ is the vapor diffusion coefficient in air (kg/(m·s·Pa)), μ is the resistance coefficient of moisture, φ is the relative humidity, P_{sat} is the partial pressure of saturated water vapor (Pa).

The capacity of heat storage can be expressed as:

$$\frac{\partial H}{\partial T} = c_{\mathrm{dry}}\rho_{\mathrm{dry}} + c_{\mathrm{p,vapor}}\omega \tag{2}$$

where c_{dry} is the specific heat capacity of dry materials (J/kg·K), ρ is the density of water (kg/m^3), $c_{\mathrm{p,vapor}}$ is the specific heat capacity of water vapor (J/kg·K), ω is the water content (kg/m^3).

Equation (3) describes the mass conservation of building envelops:

$$\frac{\partial \omega}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x}\left(D_{\omega}\frac{\partial \omega}{\partial \varphi}\frac{\partial \varphi}{\partial x}\right) + \frac{\delta}{\mu}\frac{\partial}{\partial x}\left(\varphi P_{\mathrm{sat}}\right) \tag{3}$$

According to the enthalpy method, the enthalpy H_{dry} can be expressed as:

$$H_{\mathrm{dry}} = c_{\mathrm{dry}}T + L_{\mathrm{heat}}f_{\mathrm{liq}} \tag{4}$$

where H_{dry} is the enthalpy of dry material (kJ/kg), L_{heat} is the latent enthalpy (J/kg), f_{liq} is the Liquid fraction.

The relationship between the specific heat capacity of dry material and temperature can be described by enthalpy method (Voller et al. 1987):

$$\rho_{\mathrm{dry}}c_{\mathrm{dry}}\frac{\partial T}{\partial t} = \rho_{\mathrm{dry}}\frac{\partial H_{\mathrm{dry}}}{\partial t} \tag{5}$$

The combined equation can be written by plugging the Eq. (2) and (4) into equation (1):

$$\rho_{\mathrm{dry}}\frac{\partial H_{\mathrm{dry}}}{\partial t} + \omega c_{\mathrm{p,vapor}}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{\omega}\frac{\partial T}{\partial x}\right) + h_{\mathrm{v}}\frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial(\varphi P_{\mathrm{sat}})}{\partial x}\right) \tag{6}$$

Combining with the moisture transfer Eq. (3), Eq. (6) and Eq. (3) are the whole heat and moisture governing equations of HAMT-Enthalpy (HAMT-E) model.

Validation

In order to verify the coupled HAMT-E model, a test facility with the PCHCM layer was built in Nanjing University.

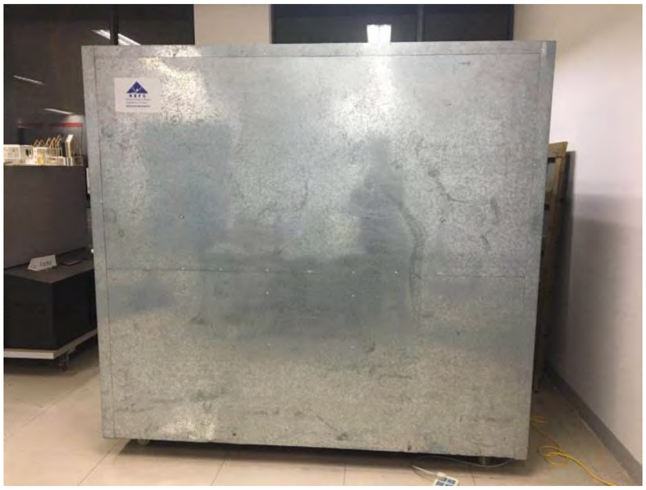
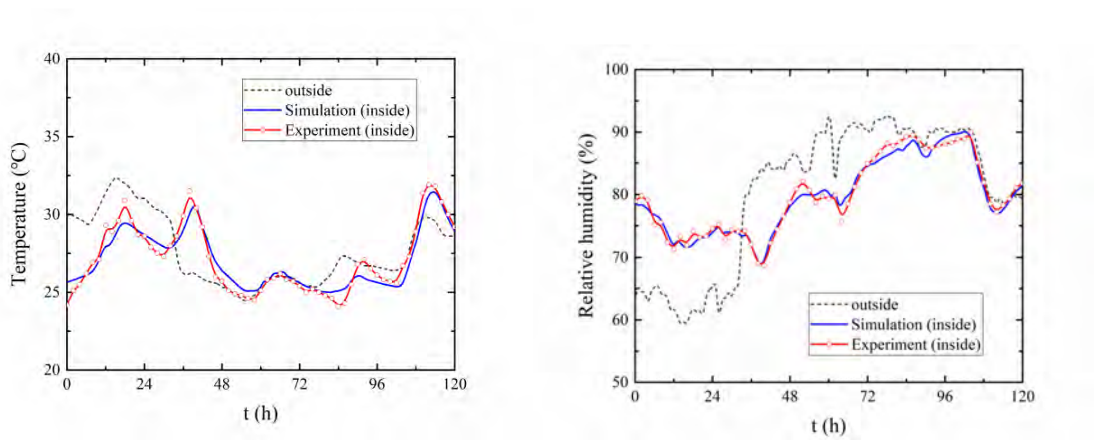


Figure 1. Experimental cabin

As show in Fig. 2, the internal dimensions of the experimental cabin are 3m (depth)×2m (width)×2m (height). The cabin are made of 30 mm-thick wood boards and covered with an insulating material (thermal/humidity) on its four external sides. The 1m (width)×1.2m (height) double-glazed window are equipped in the south wall. The interior floor is covered with a 2 mm-thick PCHCM layer. The phase change temperature range of PCM is 25~27 °C. The tests are performed with a constant air change rate (ACH) of 0.5 h^{-1}. The experiment were conducted from July 1th to July 10th, 2017.

The temperature and relative humidity were measured both in the inside and outside space of the experimental cabin. The comparison between the experimental and simulated results is shown in Fig. 2 and Fig. 3. It can be seen that the high coincide results can be obtained with the HAMT-E model both in thermal and humidity aspect.



a) b)

Figure 2. The comparison of simulated indoor temperature and relative humidity with the measured data

CASE STUDY

The validated HAMT-E model was applied to investigate the impact of PCHCM on building energy consumption under different climates. Four worldwide cities including Beijing, Paris, Altlanta and Guangzhou which characterized by typical urban climates were selected as boundary weather conditions for analysis. The BESTEST base case building (Fig. 3) from the IEA ECBCS Annex 21 was selected as the test office building (Zhang et al. 2017). The physical parameters of building envelopes are listed in Table 1. The simulation settings and boundary conditions can be seen in Table 2 as a office house.

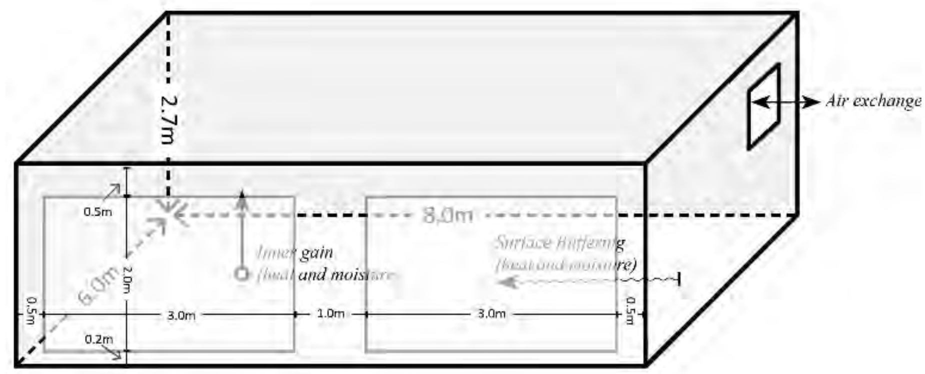


Figure 3. The BESTEST base case building adopted in application examples

Table 1. Physical parameters of different layers in building envelopes.

Construction	Material	d (m)	ρ (kg/m^3)	c_p (J/kg·K)	K (W/m·K)	U (W/m^2·K)
Wall (from outer layer to inner layer)	Wooden board	0.010	530	900	0.14	0.474
	Rock wool board	0.066	60	850	0.04	
	Concrete	0.1	1400	1000	0.51	
	PCHCM layer	0.02	650	975	0.85	
Roof (from outer layer to inner layer)	Cement panel	0.012	1130	840	0.255	0.307
	Rock wool board	0.122	60	850	0.04	
	PCHCM layer	0.02	650	975	0.85	
Floor (from outer layer to inner layer)	Thermal insulating layer	1	60	850	0.04	0.04
	PCHCM layer	0.02	650	975	0.85	
Window	Double glazing unit	-	-	-	-	1.99

Table 2. Simulation settings and boundary conditions.

Conditions	Office case		
Case ID	Reference	CaseA.1	CaseA.2
PCHCM area (m^2)	0	63.6	159.6
Heat power (W/m^2)	15 (occupied period)		
Moisture releasing rate (g/m^3 h)	6 (occupied period)		
Permissible room temperature range (°C)	18-26 (occupied period)		
Permissible max relative humidity (RH)	≤65% (occupied period)		
Air change rate (ACH)	0.5 (2ACH in unoccupied time)		
Air infiltration	No		
Occupied period (h)	09:00-17:00		
Unoccupied period	The rest of the day		

RESULTS

In a typical year, the energy consumption and efficiency of PCHCM applied in office building are compared (Table 3). The energy saving quantity and efficiency tend to rise with the increase of PCHCM's area. It illustrates that PCHCM could effectively moderate indoor hygrothermal environment; and a notable energy saving effect could be obtained.

Noteworthy, higher energy saving efficiency can be achieved in Paris and Atlanta, which have a temperate climate characterized by the wide amplitude of outdoor hygrothermal difference. Guangzhou has a hot and humid climate. It usually has a high temperature and relative humidity condition in the whole day. The high outdoor air temperature restrains the exothermic process of melting of the PCM. Similarly, the high outdoor relative humidity prevents the desorption process of diatomite. Therefore, the residual heat and moisture in PCHCM could not be efficiently discharged by the outside hygrothermal environment. As a result, the cooling loads of air conditioning system cannot be reduced by the efficiency of daily cyclic procedure of PCHCM.

The values of energy saving efficiency strictly follow the conclusions mentioned above. For instance, it can be seen that the utilization of PCHCM achieves the high values of energy saving efficiency in summer typical week. In Beijing, Paris, Atlanta and Guangzhou, the energy saving efficiencies are 10.22%, 19.57%, 17.82% and 8.76% in CaseA.2, respectively. Additionally, the highest values of energy saving efficiency can be obtained in Paris with wide hygrothermal difference and the lowest can be obtained in Guangzhou with narrow hygrothermal difference.

Table 3. Energy consumption and energy saving of different cities in office buildings (Beijing, Paris, Atlanta and Guangzhou).

City	Load and efficiency	Area of PCHCM		
		$0m^2$ (Reference)	$63.6m^2$ (Case A.1)	$159.6m^2$ (Case A.2)
Beijing	Total load ($kWh\ m^{-2}\ a^{-1}$)	78.52	75.41	70.49
	Sensible heat saving(%)	-	0.77	7.40
	Latent heat saving(%)	-	18.98	23.48
	Total energy saving (%)	-	3.96%	10.22%
Paris	Total load ($kWh\ m^{-2}\ a^{-1}$)	71.12	64.77	57.21
	Sensible heat saving(%)	-	0.87	8.82
	Latent heat saving(%)	-	38.13	58.51
	Total energy saving (%)	-	8.93%	19.57%
Atlanta	Total load ($kWh\ m^{-2}\ a^{-1}$)	71.13	67.52	58.45
	Sensible heat saving(%)	-	0.72	14.83
	Latent heat saving(%)	-	17.41	26.31
	Total energy saving (%)	-	5.07%	17.82%
Guangzhou	Total load ($kWh\ m^{-2}\ a^{-1}$)	104.57	102.09	95.41
	Sensible heat saving(%)	-	1.3	10.44
	Latent heat saving(%)	-	3.83	6.84
	Total energy saving (%)	-	2.37%	8.76%

CONCLUSIONS

This study intends to investigate the application of PCHCM in office buildings as a passive method to reduce energy consumption under different climate conditions. In this paper, a model for analyzing the energy consumption of the PCHCM is developed. The model is implemented in MATLAB-Simulink, and is validated by performing a series of experiments and validation tools. By using the model, the energy saving effect of PCHCM in office building is analyzed.

The research indicates that the application of PCHCM has the potential to reduce the energy consumption of office buildings. Overall, the PCHCM presents a melting point of 25~27 ℃, which achieves the energy reduction of sensible heat in a summer typical week. Additionally, the porous structure of PCHCM enables the energy reduction of latent heat in moisture buffering process. From the analysis of energy saving, the overall energy saving potential of Paris with temperate maritime climate is found to be the best while the potential of energy reduction is limited in Guangzhou (located in subtropical humid climate) with high temperature and humidity all day long. Above all, the numerical results indicate that PCHCM is suitable for the areas that simultaneously manifest a wide amplitude of hygrothermal (temperature and humidity) difference.

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