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Abstract

The synthesis of novel phase change humidity control material (PCHCM) was achieved by using composite microencapsulated phase change material (MPCM) and hygroscopic material. The PCHCM composite can moderate indoor hygrothermal fluctuations by absorbing or releasing both heat and moisture. The MPCM was synthesized by the microencapsulated phase change material (PCM) with SiO_2 shell. The diatomite was used as hygroscopic material.

The morphology of MPCM and PCHCM were measured by scanning electron microscopy (SEM). The thermal properties of the new composites were analyzed with differential scanning calorimetry (DSC). The thermal gravimetric analysis (TGA) was used to study the thermal stability. Both the moisture transfer coefficient and moisture buffer value (MBV) of the PCHCM were measured by two bottle method. The DSC results show that the super-cooling degrees of microcapsule and PCHCM are lower than pure PCM. Both the moisture transfer coefficients and the MBV of PCHCM are higher than pure hygroscopic materials.

The influence of PCHCM on indoor hygrothermal environment and building energy consumption was also studied. The results show that the PCHCM can effectively regulate the indoor temperature and relative humidity, thus own a potential energy saving rate of 18% for the test building in research. The overall hygrothermal performance of PCHCM is better than the simple combination of two separate layers of PCM and hygroscopic materials. The PCHCM could be used as an innovative passive material to improve the building energy efficiency.

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Keywords: Microencapsulated phase change material; Humidity control material; Building energy efficiency; Passive hygrothermal design

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1. Introduction

The global energy demand is increasing quickly due to fast economic development, especially in developing countries [1]. Buildings consume 45% of the world's total energy, and 40% of which is consumed by the heating, ventilation and air conditioning (HVAC) system [2,3,4]. There are normally two strategies to reduce building energy consumption [5,6]: one is active approach, for example, improving the efficiency of HVAC system, the other is passive approach, for example, using innovative passive materials to reduce the building demand for energy [7,8]. Motivated by a desire to provide comfortable indoor space and conserve energy in residential environment, researches have focused on the passive hygrothermal performance of materials which could provide indoor thermal and humid buffering capacity [9,10].

Currently, the phase change materials and porous hygroscopic materials are commonly used as passive energy-saving materials [11,12]. The phase change materials can absorb or release large amounts of thermal energy in its phase change process between liquid and solid, so it can stabilize the indoor temperature fluctuations and reduce the sensible load of the air conditioning system [13,14]. The hygroscopic materials can absorb and release water vapour with relative humidity fluctuations in living environment for its unique porous structure, so it can adjust indoor humidity and reduce indoor latent heat load during moisture buffering process [11,12].

This paper attempts to propose a phase change humidity control material (PCHCM) which has the functions of temperature regulation and humidity controlling, and its application effect on buildings also has been analysed.

Nomenclature

A	area of interior wall covered by PCHCM [m^2]
a	contact area for moisture absorption of the material in the air [m^2]
COP	coefficient of performance of air conditioning system [17]
c_H	specific heat capacity of air at 27°C [kJ/kg K]
c_L	specific heat capacity of air at 24°C [kJ/kg K]
d	thickness of PCHCM coating [m]
E	air conditioning load [kWh]
E_{PCM}	heat absorbed by PCM contained in PCHCM
E_S	sensible heat load [kWh]
E_L	latent heat load [kWh]
G	moisture uptake of the material [g]
h	latent heat of water vapour [kJ/kg]
h_{PCHCM}	latent heat of PCHCM [kJ/kg]
MBV	moisture transfer coefficient [kg/m·s]
q	internal heat load [W]
q'_m	evaporation in a unit time and a unit area [g]
q_m	moisture releasing rate [g/h]
RH	relative humidity [%]
SW_H	saturation water vapour concentration at 27°C [g/m^3]
SW_L	saturation water vapour concentration at 24°C [g/m^3]
V	volume of the room [m^3]
x	material thickness [m]
η	ratio of the enthalpy available between different temperatures by the total enthalpy
λ	moisture transfer coefficient [kg/m·s]
ρ_H	air density at 27°C [kg/m^3]
ρ_L	air density at 24°C [kg/m^3]
ρ_{PCHCM}	density of PCHCM [kg/m^3]

2. Characterization of the MPCM/diatomite components

Phase change humidity material (PCHCM) was synthesized by composite microencapsulated phase change material (MPCM) and diatomite. The MPCM was synthesized by sol-gel method with methyl triethoxysilane (MTES) as the precursor, the phase change material (PCM) which contain a mixture of capric acid was used as core, SiO_2 was used as shell [15] and diatomite was selected as porous hygroscopic material [16].

2.1. Morphology of the MPCM and diatomite

The microstructural morphology of MPCM and diatomite are shown in Fig. 1 by scanning electron microscopy (SEM, S-3400NII, Hitachi Inc., Japan).

It can be seen from Fig. 1a, MPCM exhibits a spherical microcapsule structure which between 60-80μm with a smooth spherical surface. The silica shell of the spherical microcapsules tightly encases the PCM in its inner space. When the temperature of PCM reaches the melting point, the silica shell could effectively prevent the leakage of PCM materials in liquid phase, which contribute to the purpose of environmental protection and re-use. It can be seen from Fig. 1b that diatomite exhibits a porous microstructure, and the strong moisture absorption property of diatomite is due to the large number of nanoscale microvoids on its surface。
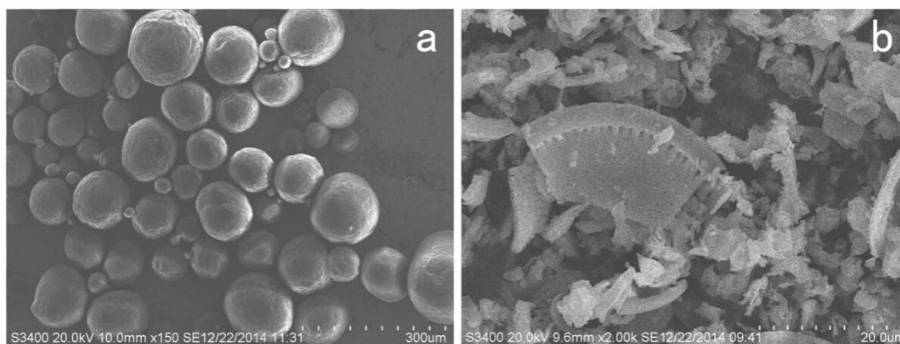

Fig. 1. SEM photographs of the MPCM (a), diatomite (b).

2.2. Thermal properties of the PCM, MPCM and PCHCM

Thermal properties analyses of PCM, MPCM and PCHCM were performed with a differential scanning calorimeter (Pyris 1 DSC, PerkinElmer). A constant stream of argon at a speed of 20 ml/min was used to heat and cool the experimental sample with a rate of 5 ℃/min. The accuracy of temperature measurement and enthalpy was ±2 ℃ and ±5%, respectively.

The DSC results of PCM, MPCM and PCHCM are shown in Fig. 2, Fig. 3 and Table 1. It can be seen from the table 1, comparing with the PCM, the MPCM and PCHCM have lower melting points, higher freezing points and lower super-cooling degrees. These characteristics enable them to release enthalpy of fusion at higher temperature, and absorb enthalpy of solidification at lower temperature.
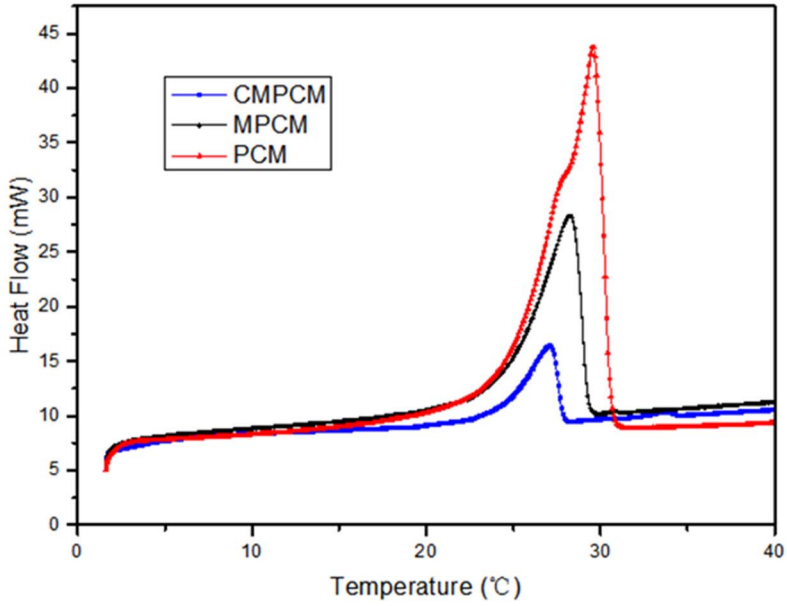
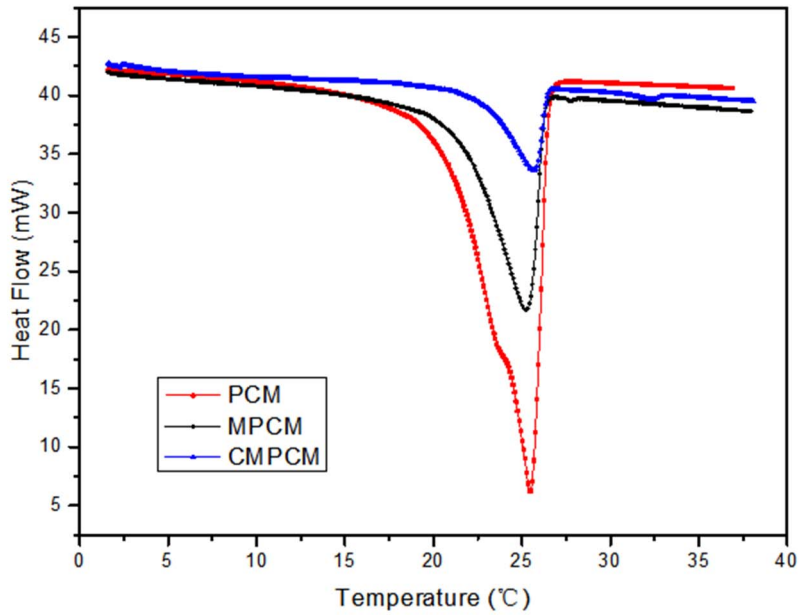Fig. 2. Melting DSC curve of PCM, MPCM and PCHCM

Fig. 3. Solidifying DSC curve of PCM, MPCM and PCHCM

Table 1. DSC data of the PCM, MPCM, PCHCM.

Sample name	Encapsulation ratio of the PCM (%)	Melting (5℃/min)	Solidifying (5℃/min)

		Temperature (℃)	Latent heat (kJ/kg)	Temperature (℃)	Latent heat (kJ/kg)
PCM	100.0	28.1	145.7	26.2	144.3
MPCM	63.4	27.2	94.4	26.7	89.6
PCHCM	12.9	27.0	19.0	26.7	18.4

As can be seen from Table 1, the lack of heat absorption process of diatomite contributes to the worst heat storage capacity of PCHCM among three samples, and the PCM content is proportional to the heat storage capacity of the MCPM and PCHCM.

2.3. Thermal stability of the PCM, MPCM and PCHCM

Thermal stability analyses of the PCM, MPCM and PCHCM were investigated with a thermogravimetric analyzer (Pyris 1 TGA, Perkin-Elmer). A constant stream of nitrogen at a speed of 20 ml/min was used to heat the experimental sample with a rate of 20 ℃/min. The temperature measurement range was controlled between 25 ℃-700 ℃.
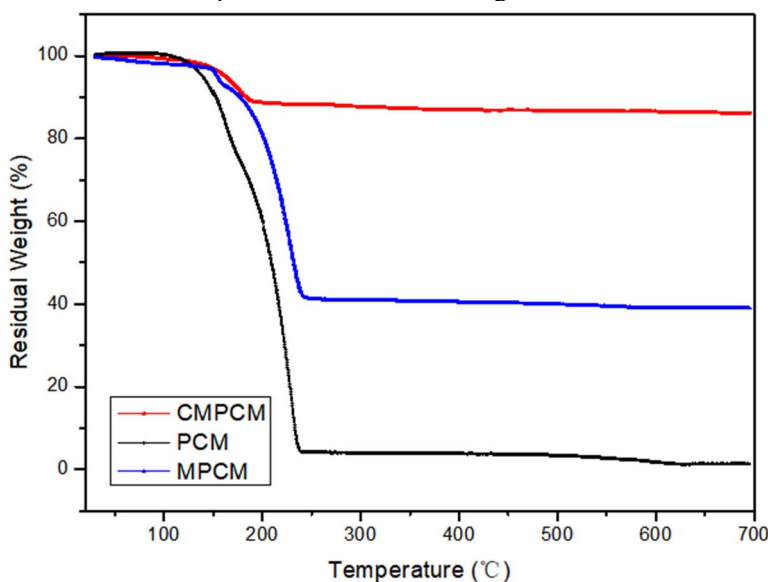

Fig. 4. TGA curve of PCM, MPCM and PCHCM

Table 2. TGA data of PCM, MPCM and PCHCM.

Samples	T (℃)	Charred residue amount (%) (700℃)
PCM	130	0
MCPM	175	38
PCHCM	175	88

Figure 4 shows the TGA curves of the PCM, MPCM and PCHCM. Table 2 shows the starting temperatures of maximum mass loss and the residual weight at 700 ℃. It can be seen from Fig. 4 that the degradation progress was divided into two processes. The first degradation process of PCM occurred between 130 ℃ and 250 ℃ and the second degradation process of the silica shell occurred between 250 ℃ and 700 ℃. The MPCM and PCHCM materials have higher starting degradation temperatures than the PCM, indicating that the silica shell could protect the core material which composed of PCM and effectively improve ignition point.

2.4. Hygroscopic properties of the PCHCM and diatomite

The moisture transfer coefficient and the moisture buffer value (MBV) were measured by positive cup evaporation method and isothermal sorption method, respectively. In order to evaluate the moisture performance of the materials, the moisture transfer coefficients and the moisture buffer values of PCHCM, gypsum, wood and diatomite samples were measured experimentally.

The moisture transfer coefficient can be calculated by following Eq. (1):

$$\lambda = \frac{\partial x}{\partial RH} \cdot q_m \tag{1}$$

The MBV can be calculated by following Eq. (2):

$$MBV = \frac{G}{\Delta RH \cdot a \cdot 100} \tag{2}$$

The moisture transfer coefficients and moisture buffer values of PCHCM, gypsum, wood and diatomite are shown in Table 3. It can be seen that the PCHCM has the highest values among these materials, which is mainly due to the fact that the microcapsule structure in PCHCM increases the porosity of the composite, and the porous microstructure contributes to the transfer of water vapor inside. It means that the PCHCM can quickly responds to the indoor relative humidity fluctuations and absorb more water vapor in a unit time. Therefore, the moisture transfer coefficient and moisture buffer value of the PCHCM are increased.

Table 3. Moisture transfer coefficient and MBV of PCHCM, gypsum, wood and diatomite

Samples	PCHCM	Gypsum	Wood	Diatomite
Moisture transfer coefficient (10^{-8}kg/m·s)	5.00	1.54	0.79	2.75
MBV (g/m^2%RH)	1.57	0.26	0.40	0.33

2.5. The effect of PCHCM on building energy consumptions

The PCHCM can be used as the surface material of interior walls. The PCM in the composite can stabilize the indoor temperature fluctuations and reduce the sensible load of the air conditioning system. The hygroscopic material (diatomite) in the composite can regulate the indoor relative humidity by absorbing/releasing water vapour and reduce the latent load of the air conditioning system.

It gives the following example of practical application to show how PCHCM can be used to reduce air conditioning load. A non-ventilated and insulated room is dimensioned 5m×6m×3m=90m^3. The initial indoor temperature and relative humidity are 24°C and 55%, respectively. The room releases 150g of water per hour and the internal heat load is 900W. In order to maintain the indoor temperature and relative humidity below 27°C and 60%, respectively, how much will the air conditioning load be in 10 h?

When there is no PCHCM, the sensible heat load, latent heat load and the air conditioning load can be calculated by Eq. (3), Eq. (4) and Eq. (5), respectively:

$$E_S = 10 \cdot q - V \cdot (27 \rho_H c_H - 24 \rho_L c_L) \tag{3}$$

$$E_L = [10 \cdot q_m - V \cdot (60\% \cdot SW_H - 55\% SW_L)] \cdot h \tag{4}$$

$$E = \frac{E_S + E_L}{COP} \qquad (5)$$

The interior wall of the room is covered with the area $A = 65m^2$ of PCHCM and the thickness is $d = 0.03m$. The E_{PCM} refers to the heat absorbed by PCM contained in PCHCM, which can be calculated by Eq. (6):

$$E_{PCM} = \eta \cdot h_{CMPCM} \cdot (\rho_{CMPCM} \cdot A \cdot d) \qquad (6)$$

Due to the conservation of the moisture, the relative humidity RH in 8h can be calculated by Eq. (7):

$$10 \cdot q_m + (SW_L \cdot 55\%) \cdot V = (SW_H \cdot RH) \cdot V + MBV \cdot [(RH - 55\%) \cdot 100 \cdot A] \qquad (7)$$

It can be determined that the $E_S = 8.92$ kWh, $E_L = 0.33$ kWh, $E = 2.64$ kWh, $E_{PCM} = 1.34$kWh and the $RH = 55\%$. It can be seen that the relative humidity within 8 hours is always below 60% under the premise of applying PCHCM. So there is no latent heat load anymore and the air conditioning load can be calculated by Eq. (8):

$$E' = \frac{E_S - E_{PCM}}{COP} \qquad (8)$$

It can be determined that the $E' = 2.17$kWh and the total energy efficiency is 17.8%, this result can also be verified by related experimentation and simulation.

3. Conclusions

This paper proposes a phase change humidity control material (PCHCM) with its hygrothermal properties and analyses its application effect in buildings. The SiO_2 prepared with methyl triethoxysilane was used as the shell material, and the alkane mixture was used as core material. The test results show that the SiO_2 shell can improve the thermal stability of PCM, and the MPCM can improve the hygroscopic performance of PCHCM.

Above all, the hygrothermal performance of PCHCM is superior to the simple combination of two separate layers of PCM and hygroscopic materials. The example shows that the PCHCM plays an important role in moderating the temperature and humidity, and energy saving rate of 18% can be achieved. Of course, the 18% energy saving rate can also be verified by the related experimentation and simulation. Therefore, the PCHCM has the potential to be the energy saving material.

Acknowledgements

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