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Research Paper

Moisture buffering phenomenon and its impact on building energy consumption

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HIGHLIGHTS

- A new mathematical expression of moisture buffer value is proposed.
- The MBV can be measured by the two-bottle method.
- Moisture buffering may have a great impact on building energy consumption.
- The potential energy saving rate could be up to 30% in certain climates.
- The relationship between MBV and potential energy saving is discussed.

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ABSTRACT

Moisture buffering is the ability of surface materials in the indoor environment to moderate the indoor humidity variations through adsorption or desorption. Materials with high moisture buffering capacity could be used to passively control the indoor moisture condition and consequently improve the indoor environmental quality and reduce the latent heat load of buildings. In order to characterize the moisture buffering ability of materials, the basic concept of moisture buffer value (MBV) is adopted. The paper first proposes a new mathematical expression of basic MBV, and then introduces a theoretical correction factor that could be used together with the MBV to calculate the moisture uptake/release by hygroscopic materials exposed to different types of humidity variations. Secondly, a simplified two-bottle test method is proposed to measure the MBV in the present study. The impact of moisture buffering on building energy consumption in different climate conditions is assessed by using numerical simulations. The results show that the potential energy saving rate could be up to 25–30% when using proper hygroscopic materials in the test building in temperate climates and semi-arid climates. Finally, the relationship between MBV and potential energy saving rate is also discussed.

1. Introduction

The building sector is responsible for one third of global greenhouse gas emissions annually and consumes up to 40 percent of global energy use [1], mainly through the use of fossil fuels during their operational phase. The energy consumption of mechanical heating, ventilation and air-conditioning (HVAC) system in developed countries accounts for half of the energy use in buildings [2]. Predictions indicate that there will be a massive growth in building energy consumption in developing countries during the next 20 years [2,3]. Many studies have been carried out to investigate the use of passive approaches, systems and materials to minimize the use of HVAC system and consequently reduce the energy use in buildings [4]. One promising approach is using novel materials to control the indoor hygrothermal conditions passively [5].

Relative humidity is a key factor of indoor environment, which has a significant effect on thermal comfort, building loads, indoor air quality and occupants' working efficiency [6,7]. Indoor relative humidity is mainly influenced by the following factors: internal moisture sources or sinks, ventilation and airflow in rooms, moisture uptake or release by hygroscopic materials (for example, surfaces of envelope, furnishing etc.) and moisture transfer across building envelopes etc. In very well insulated (with both thermal insulation and vapor barrier) modern buildings, the direct moisture transfer through building walls has been greatly reduced. However, the moisture buffering through adsorption and desorp-

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tion of the hygroscopic surface materials of building envelopes and furnishing (e.g. wood furniture, curtains, carpet, textiles etc.) has an important effect on indoor hygrothermal conditions and energy performance of buildings. Hygroscopic surface materials can uptake moisture from the air when its relative humidity increases and release moisture to the air when its relative humidity falls [8]. The moisture buffering of building materials can moderate the indoor humidity fluctuations and significantly reduce the peak indoor relative humidity [8]. However, most building energy simulation tools ignore the moisture buffering of indoor surface materials, which may lead to an overestimate of energy consumption or oversize the HVAC system [9,10]. The objects of this paper are: firstly, to develop a standardized produce to characterize the moisture buffering ability of materials under different conditions; secondly to study the impact of moisture buffering on building energy consumption.

The moisture buffering phenomenon is one of the key topics in the area of heat and moisture transport in buildings. Over the past decades, numerous studies have been conducted in terms of theory, experiment and numerical simulation [11–17]. The mechanism of moisture movement in hygroscopic materials has become increasingly clear. Properties such as moisture capacity and water vapor permeability or liquid permeability were proposed to represent the mechanism of moisture retention and transport respectively. Lumped moisture terms such as moisture diffusivity and moisture effusivity were defined later to give more comprehensive descriptions of moisture transfer [18]. However, most of the parameters above are derived from the data that measured in a standardized steady state and are not sufficient to represent the buffering process in real dynamic conditions. Rather significant differences and unreasonable results were noticed when choosing a different property to represent materials' moisture buffering capability [19]. In 2005, Rode et al. [20] proposed the concept of moisture buffer value (MBV), which indicates the amount of moisture uptake/release by a material when it is exposed to diurnal relative humidity variations between two given values. According to the test protocol proposed in NORDTEST [20], the MBV is a direct measurement of the amount of water vapor absorbed or desorbed by a hygroscopic material when it is exposed to a square wave in daily cycles (for example, 8 h of high relative humidity at 75% followed by 16 h of low relative humidity at 33%). Several other terms, for example moisture buffer capacity, moisture buffer potential etc., were proposed later [21,22]; but most of them adopted the general concept of the moisture buffer value.

The definition and test method of MBV is clear and easy to understand. However, when it comes to the application in real conditions, there are some apparent limitations. The humidity cycle of square wave signals used in test method rarely show up in real climates. When using the MBV obtained from NORDTEST to calculate the moisture uptake or release of materials exposed to real climatic conditions, the results will be larger than the real value. Moreover, the NORDTEST requires high-accuracy climatic chambers, which may not be available in many laboratories.

In addition to the efforts to define indicative properties for the description of moisture buffering phenomenon, numerical models such as the coupled heat, air and moisture transfer (HAMT) model [13,16,23] and the effective moisture penetration depth (EMPD) model [24,25] were developed for dynamical calculations. As a coupled numerical model, the HAMT model was originally developed to simultaneously calculate the heat and moisture transfer in building materials based on simplified parameters including the sorption isothermal data, surface convection mass transfer coefficient, water vapor resistance coefficient, liquid transport and liquid suction transport coefficients to determine the retention and transport of moisture. The moisture exchange between the surfaces and the indoor environment can also be calculated as a part of the heat and moisture transfer in building envelopes. Compared to the EMPD model, the HAMT model has a better accuracy and been widely validated [24,25]. The HAMT model is now available in several building simulation tools (e.g. EnergyPlus, TRNSYS etc.), which could be used to assess the impact of moisture buffering on building energy consumption in different climates.

There are many researches discussing the moisture effect on building energy performance [10,23], but few of them particularly focuses on the moisture buffering effect and the operation of HVAC system to maximize the befit of moisture buffering in different climates. The energy saving of using moisture buffer materials in domestic buildings is mainly achieved by the following mode: the hygroscopic material absorbs moisture during the conditioned period (which will reduce the latent load) and release moisture during the non-conditioned period (removed by ventilation). Therefore, both the ventilation and the outdoor climate during the non-conditioned period are critical for drying the hygroscopic material and making it ready for the next cycle (e.g. next day). These processes and interactions are complex, and realistic predictions of all factors require the use of advanced simulation tools.

The aim of the present study is to firstly develop a new mathematical expression of MBV to calculate moisture uptake and release by hygroscopic materials that exposed to different humidity conditions; secondly to propose a simple test method to measure the MBV under a cyclic step-change in relative humidity between different high and low levels. Finally, the impact of moisture buffering on building energy consumption in different climates is studied by numerical simulations. The relationship between the MBV and potential energy saving rate of different hygroscopic materials is also discussed.

2. Theory deduction of moisture uptake/release

The analogy between heat and moisture transfer has been adopted [19]. The moisture flux can be given by a modified Fick's law:

$$q_m = -\delta \frac{d\varphi}{dx} \tag{1}$$

where q_m is moisture flux (kg/m^2·s), δ is vapor transfer coefficient (kg/m·s), φ is the relative humidity (% or -), x is the thickness of the material (m).

One-dimensional governing equation for moisture transfer in multilayer hygroscopic materials can be expressed as:

$$\frac{\partial \varphi}{\partial t} = \frac{\delta}{\rho \xi} \cdot \frac{\partial^2 \varphi}{\partial x^2} \tag{2}$$

where ρ is the density of dry material (kg/m^3), ξ is the moisture capacity (kg/kg).

There are three assumptions for the governing equation. (1) The material is considered homogenous; (2) The moisture properties are assumed constant; (3) the initial humidity conditions are uniform throughout the material. These assumptions are reasonable for the moisture buffering in normal domestic buildings, and have been adopted by many studies. [26,27]

2.1. Definition of basic MBV

In a time period t_p, as described in the standard NORDTEST protocol [20], the time variation of the surface conditions is that: the high humidity (H) is maintained for αt_p hours, and the low humidity (L) maintained for $(1-\alpha)t_p$ hours, which can be written as:

$$f(t) = \begin{cases} H\ when (n-1)\cdot t_p < t < (n-1+\alpha)\cdot t_p \\ L\ when (n-1+\alpha)\cdot t_p < t < n\cdot t_p \end{cases} \tag{3}$$

Fourier transform is applied to$f(t)$, and it can be got as:

$$f(t)=\frac{a_0}{2}+\sum_{n=1}^{\infty}a_n\cos\frac{n\pi t}{t_p}+b_n\sin\frac{n\pi t}{t_p} \tag{4}$$

where

$$\frac{a_0}{2}=H\alpha+L(1-\alpha)$$
$$a_n=\frac{H-L}{n\pi}[\sin\alpha n\pi-\sin(1-\alpha)n\pi]$$
$$b_n=\frac{H-L}{n\pi}[1+cosn\pi-\cos\alpha n\pi-\cos(1-\alpha)n\pi]$$

The $\frac{a_0}{2}$ is a fixed value determined by the value of high relative humidity, low relative humidity and high relative humidity time period ratio and it will not influence the moisture flux after a certain period, so that it's neglected in the following discussion.Based on the Eqs. (1)(3), the moisture flux over the surface can be expressed as:

$$q_m(t)=\sum_{n=1}^{\infty}\delta a_n\sqrt{\frac{n\pi\rho\xi}{\delta t_p}}\cos\left(\frac{n\pi t}{t_p}+\frac{\pi}{4}\right)+\delta b_n\sqrt{\frac{n\pi\rho\xi}{\delta t_p}}\times\sin\left(\frac{n\pi t}{t_p}+\frac{\pi}{4}\right) \tag{5}$$

Then accumulated moisture uptake/release G (kg/m^2) during time αt_p is found by integrating the moisture flux as in the following equation.

$$G=\int_0^{\alpha t_p}q_m(t)dt \tag{6}$$

A detailed form was got by plugging the Eqs. (4) and (5) into Eq. (6):

$$G=(H-L)\frac{\sqrt{t_p}}{\pi}\sqrt{\frac{\delta\rho\xi}{\pi}}\sum_{n=1}^{\infty}\frac{1}{n^{\frac{3}{2}}}[\sin\alpha n\pi-\sin(1-\alpha)n\pi]\sin\alpha n\pi+\frac{1}{n^{\frac{3}{2}}}[1+\cos n\pi-\cos\alpha n\pi-\cos(1-\alpha)n\pi](1-\cos\alpha n\pi) \tag{7}$$

After a simplifying process, Eq. (7) becomes:

$$G=m(H-L)\sqrt{\delta\rho\xi}[\alpha(1-\alpha)]^k\sqrt{\frac{t_p}{\pi}} \tag{8}$$

The value of m equals to 2.253 and the coefficient k can be approximately assigned as 0.535 [20], so that the moisture uptake/release can be expressed as:

$$G\approx 1.27[\alpha(1-\alpha)]^{0.535}(H-L)\sqrt{\delta\rho\xi}\sqrt{t_p} \tag{9}$$

Then the theoretical or basic Moisture Buffer Value can be defined as the value that obtained from dividing the moisture uptake/release by the relative humidity change:

$$MBV_{basic}=\frac{G}{\Delta\varphi}=1.27[\alpha(1-\alpha)]^{0.535}\sqrt{\delta\rho\xi}\sqrt{t_p} \tag{10}$$

It is necessary to note that the surface moisture resistance at the boundary layer is ignored in the above mathematical deduction. Validations for this assumption are presented in Section 4. In fact, for many materials the internal resistance to moisture transport is considerably larger than the convective surface resistance [28].

2.2. Improved MBV with harmonic function of humidity as boundary condition

Considering a real situation, the humidity variations in buildings may not appear to be a square wave function, which is maintained at a higher level of H for a period of time and mutated to lower level of L for the rest time of a day. As a consequence, using the basic moisture buffer value directly to calculate the moisture uptake/release in real climate condition isn't proper. Exploration of the difference of moisture uptake/release when the humidity cycle differs is essential.

In order to facilitate the discussion, it is supposed that the humidity variation in real climate could be considered as a quasi-harmonic function, which can be written as:

$$f(t)=\begin{cases}\phi+(H-\phi)\sin\left(\frac{\pi}{\alpha t_p}t\right)\ when\ (n-1)t_p<t<(n-1+\alpha)t_p\\ \phi+(\phi-L)\sin\left(\frac{\pi}{(1-\alpha)t_p}t\right)\ when\ (\mathrm{n}-1+\alpha)t_p<t<nt_p\end{cases} \tag{11}$$

where Φ is the equilibrium relative humidity of material (%). The high humidity range (RH > Φ) lasts for αt_p hours with the maximum RH at H, and the low humidity range (RH < Φ) lasts for $(1-\alpha)t_p$ hours with the minimum RH at L.Considering the moisture uptake process, the absorbed moisture can be expressed as:

$$G_{in}=2(H-\phi)\sqrt{\frac{\delta\rho\xi\alpha t_p}{\pi}} \tag{12}$$

And the released moisture can be expressed as:

$$G_{out}=2(\phi-L)\sqrt{\frac{\delta\rho\xi(1-\alpha)t_p}{\pi}} \tag{13}$$

In a long period, the moisture uptake G_{in} equals to the moisture release G_{out}, so that the balanced relative humidity of the material can be written as:

$$\phi=\frac{H\sqrt{\alpha}+L\sqrt{1-\alpha}}{\sqrt{\alpha}+\sqrt{1-\alpha}} \tag{14}$$

Then plug Eq. (14) into Eq. (13), the moisture uptake/release becomes:

$$G_{in}=G_{out}=2(H-L)\frac{\sqrt{\alpha(1-\alpha)}}{\sqrt{\alpha}+\sqrt{1-\alpha}}\sqrt{\frac{\delta\rho\xi t_p}{\pi}} \tag{15}$$

According to Eq. (10):

$$G_{in}=G_{out}=0.888\frac{[\alpha(1-\alpha)]^{-0.035}}{(\sqrt{\alpha}+\sqrt{1-\alpha})}MBV_{basic}(H-L) \tag{16}$$

If define a factorβ to replace the complicate term in Eq. (16):

$$\beta=0.888\frac{[\alpha(1-\alpha)]^{-0.035}}{\sqrt{\alpha}+\sqrt{1-\alpha}} \tag{17}$$

The moisture uptake/release can be rewritten as:

$$G_{in}=G_{out}=\beta MBV_{basic}(H-L) \tag{18}$$

In Eq. (18) β is a theoretical correction factor for the case of quasi-harmonic humidity variation. When $\alpha = 1/3$, which means the high humidity condition lasts for 8 h in a daily cycle, $\beta = 0.6715$.

Eq. (18) could be used to represent the moisture transfer into/out the hygroscopic material under real daily weather condition that is similar to the quasi-harmonic function in most cases. Validations of the present method are presented in Section 4.

In addition, the moisture uptake and release during a longer period of humidity cycles, such as weekly, monthly or even annually variations, could be easily calculated by using the present method.

3. Test method

The present project defines a two-bottle method to measure the moisture buffer value of hygroscopic materials. Compared with the standard method (i.e. NORDTEST climatic chamber tests), the present method only needs simple facilities to provide cyclic step-changes in relative humidity, and could provide reliable results.

3.1. Basic principles

The two-bottle method is developed according to the basic definition of MBV descried in Section 2.1. It mainly refers to two glass bottles that contain different saturated salt solutions to represent the high humidity level and the low humidity level respectively. While holding the temperature constant at 23 °C, the specimen is first hung in bottle A (high humidity level) for 8 h and then immediately moved into the bottle B (low humidity level) for the rest 16 h. A diurnal relative humidity cycle is thus realized.

A representative specimen of the product should have a thickness enough for normal construction or bigger than the effective moisture penetration depth, and have all sides sealed well except for the surface that is intended to be exposed. The moisture uptake and release is equivalent to the sample mass change (Δm) that can be measured by an analytical balance. The final results are read when Δm variation is below 5% between the last 3 days. The Moisture Buffer Value is then calculated per area m^2 and per ΔRH.

3.2. Method and facilities

Before the test, all specimens are pre-conditioned in the climate room with temperature at 23 ± 0.5 °C and relative humidity at 50 ± 3% for over a month. When the mass change of the specimen between two consecutive days is below 1% of the total mass, the specimens are considered to be in equilibrium with the environment. After the correct precondition, the samples are sealed in bottles as shown in Fig. 1. At least three samples from the same kind of material should be selected for testing to ensure reliable results. The saturated solution of NaCl is used in bottle A to maintain the high humidity level at 75.4 ± 0.1%, and the saturated solution of $MgCl_2$ is used in bottle B to maintain the low humidity level at 32.9 ± 0.2%.

The testing specimen is hung on the support frame as illustrated in Fig. 1. The weight of the specimen can be read from the analytical balances. It's recommended to measure the weight of the sample no less than 5 times during the absorption/desorption period. At the end of each stage, the sample should be immediately moved into the other bottle with different humidity condition. The mass of the sample against time need to be plotted throughout the whole process. As long as the differences of Δm in three adjacent days are below 5%, the procedure terminates. The MBV of each sample in each stable cycle can thus be obtained. The mean value of all samples in three stable cycles can be treated as the final MBV of the testing material or system.

3.3. Adapt to local climate

The NORDTEST method only defines a humidity interval between 75% and 33%, which may not be proper for all climates. For example, in hot and humid climate (e.g. Hong Kong and Singapore etc.) the average outdoor relative humidity is often higher than 75% [9]; while in hot and dry climates (e.g. Phoenix and Salt Lake City etc.), the indoor relative humidity is sometimes very low. Therefore, defining different humidity cycles with local max./min. humidity values as the environment for test process is important to get correct Moisture Buffer Values for different climates. Site measurement and a pre-simulation with the hourly weather file are two recommended ways to determine the specific humidity cycle. The proposed two-bottle method is flexible and easy to adapt to different humidity intervals.

4. Validation of MBV_{basic} and the correction factor β

Since the theoretical deduction of the basic MBV and the correction factor β are based on the assumptions of constant material properties and no surface resistance, it is necessary to validate the method before using it to calculate the moisture buffering of hygroscopic materials in real applications.

4.1. Validation of MBV_{basic}

A comparison between the MBV calculated based on Eq. (9) and obtained by the experimental measurements that consider the air

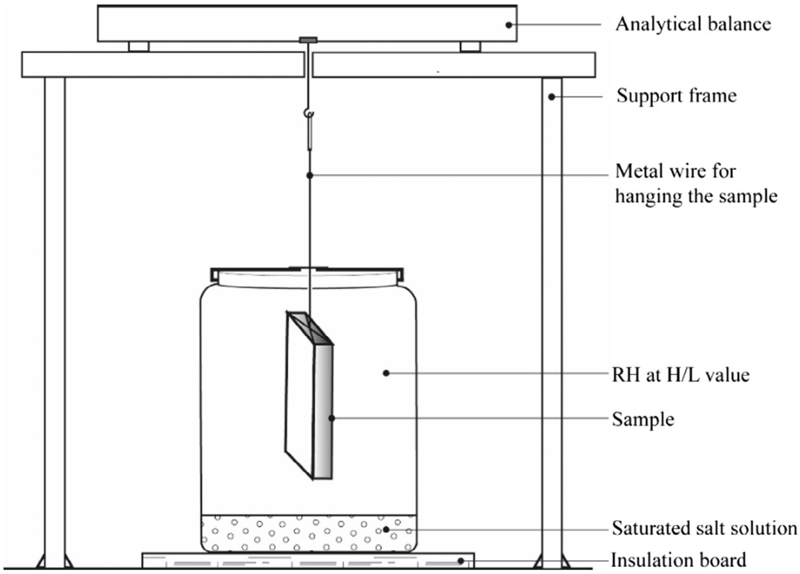


Fig. 1. Schematic of the facility.

surface resistance is presented in this section. The humidity control material – VCPCM developed in [29] was used since it has a high moisture buffer ability and all hygrothermal properties were measured in our previous studies [29].

Four types of high humidity and low humidity cycles were used in the validation, they are: 6 h (H) + 18 h (L), 8 h (H) + 16 h (L), 10 h (H) + 14 h (L), 12 h (H) + 12 h (L). The corresponding α are: 1/4, 1/3, 5/12, 1/2.The MBV of VCPCM was measured by the two-bottle method. The mass change curves for different cycles are shown in Fig. 2.

The MBVs obtained by measurements and by calculation are presented in Table 1. The results indicate that there is certain difference between the measurements and calculations. But the relative errors are all within acceptable range in engineering applications. The error decreases when increasing the α value. When $\alpha = 1/2$, namely the time for absorption equals to the time of desorption, the calculated MBV is almost the same as the measured one.

4.2. Validation of correction factor β

A comparison between the present method (calculation based on MBV&β) and advanced simulation (HAMT model) was carried out. Since the HAMT model has been widely tested and validated [13,16,23], the results from the HAMT model is considered to be correct for the comparison and analysis in this research. The air surface resistance is considered in the HAMT model. Four typical building materials are selected. They are concrete, gypsum board, aerated concrete and wood-fiber board. Their MBVs are measured by the two-bottle method and shown in Table 2.

All materials are exposed to the same environmental condition. The temperature is constant at 23 °C, the humidity varies in a harmonic function as described in Eq. (11) with $\alpha = 1/3$. The corresponding correction factor $\beta = 0.672$. The vapor transfer coefficient is set fixed as 2×10^{-8} kg/m^2 s Pa [24].

The daily moisture uptake/release can be quickly obtained by Eq. (18) and is presented in Table 2. Results from the simulation by HAMT model and the error analysis are also presented in the same table.

As seen from the table, a good agreement is found between the results from the MBV method and from the HAMT Model. Relative errors are all less than 3% in each group. More analysis and comparisons were made by using a broader range of materials in different environmental conditions. The calculation of moisture uptake/release using the MBV and the factor β is proven to be reliable.

The main advantage of the suggested MBV method in comparison with the simulation by HAMT model consists in the fact that it is faster, easier to use and gives a good result. Engineers or architects could use this method to calculate the moisture uptake/release by different materials by hand calculation at the construction field.

5. Relationship between MBV and potential energy saving

It has been recognized that moisture buffering may have great impact on the indoor relative humidity, thermal comfort and indoor air quality. The energy conservation contributed by moisture buffer effect is getting more attention recently [30–34]. In this section, the impact of moisture buffering on building energy consumption is analyzed by using numerical simulations. The relationship between MBV and potential energy saving is discussed.

5.1. Test building

The BESTEST base case building (see Fig.3) from the IEA ECBCS Annex 21 is selected as the test building [35]. For simplicity, the windows in south façade are ignored. Materials of all surfaces are set as described in the BESTEST lightweight construction. While the internal surface layers are replaced by 0.05 m aerated concrete. Since the external surfaces are set water-tight and vapor barriers are added in the structures, moisture transport through the walls is ignored.

The test building is supposed to be an office. From 09:00 to17:00, it is occupied. The internal heat gain is 15 W/m^2; and the moisture gain rate is 6 g/m^{3}h. The HVAC system is available to maintain the internal temperature between 20 °C and 26 °C and control the relative humidity under 65%. During the unoccupied period, the internal heat and moisture gains are zero and the HVAC system is off. The building has an infiltration rate of 0.5ACH throughout the day.

For the cases without moisture buffer materials, the internal surfaces are all supposed to be water-tight. While for the cases with moisture buffer materials, different hygroscopic materials with MBV ranging from 0.5 to 1.5 g/m^2 %RH are selected, and the area of the hygroscopic surfaces changes from 0 m^2, 32.4 m^2 (two internal walls), 75.6 m^2 (all internal walls), to 171.6 m^2 (all internal walls + ceiling and floor).

5.2. Site climates

The outdoor climate has a great impact on not only the indoor hygrothermal condition, but also the performance of moisture buffering. Ideally, the indoor hygroscopic materials are supposed to adsorb extra moisture to reduce the latent heat load during the occupied period; and release moisture during the unoccupied period and ready for the next cycle.

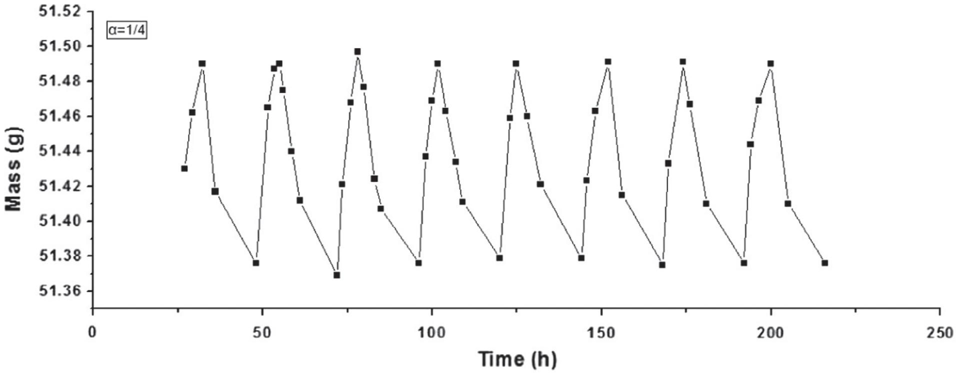
Four different cities/climates are chosen in this research. They are Shanghai (humid subtropical climate), Beijing (humid continental climate), Paris (temperate climate) and Madrid (Cold semi-arid climate).

5.3. Results and analysis

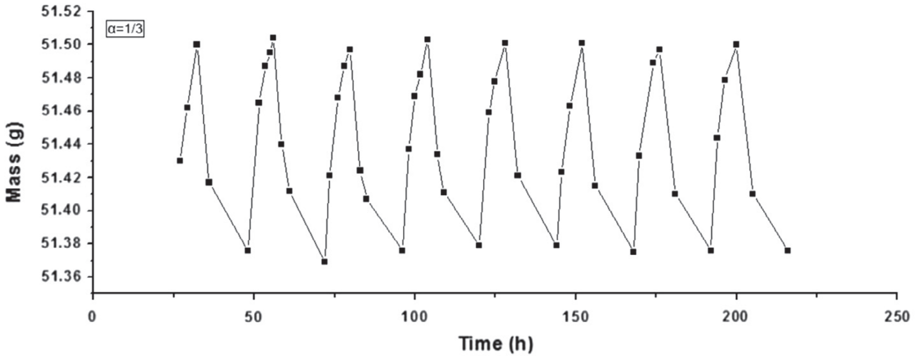
Energy consumptions (both sensible load and latent load) of different cases under four climates were simulated. It is noticed that the moisture adsorption/desorption during the buffering process may have an impact on the total sensible load. But since the impact is very small, it could be ignored in most cases [9,23]. The total energy consumptions for cases with and without moisture buffering materials were presented in Table 3. The energy savings by using moisture buffer materials with MBV = 1 g/m^2 %RH) are also presented in the same table.

It can be seen from the table that the energy saving rate increases as the surface area of moisture buffering materials increases. The tendency is more obvious in Madrid and Paris cases than that in Beijing and Shanghai cases. When all internal surfaces are covered by hygroscopic materials, the energy saving rate is over 25% in Madrid case and over 20% in Paris case. While in Shanghai and Beijing cases, the energy saving rate is relatively small. The possible reason is that both Shanghai and Beijing have a humid weather condition in summer and the humidity difference between day and night is quite small, especially in Shanghai, the humidity in night is sometimes even higher than that in the day. This kind of weather condition greatly affects the performance of moisture buffering materials.

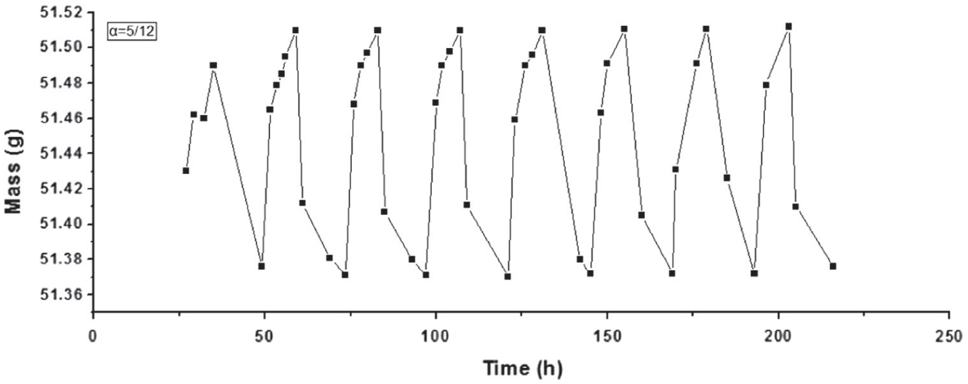
The results indicate that the moisture buffer materials perform well in the climates that have a distinct humidity difference between day and night, and the outside air during the unoccupied period is dry enough to regenerate the buffer materials. (i.e. remove the moisture absorbed during the occupied period) Temperate and semi-arid climate zones are the target areas. But



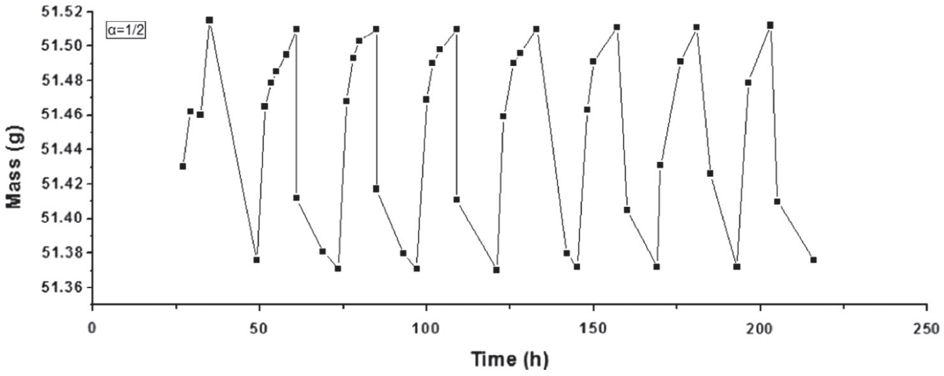
(a) α=1/4



(b) α=1/3



(c) α=5/12



(d) α=1/2

Fig. 2. Mass change curves for different cycles.

Table 1
Comparison of MBVs obtained from tests and calculations.

	α = 1/4	α = 1/3	α = 5/12	α = 1/2
MBV (g/m^2 %RH) by calculation	1.106	1.145	1.214	1.225
MBV (g/m^2 %RH) by measurement	1.045	1.125	1.202	1.220
Relative error	5.5%	1.8%	1.0%	0.4%

Table 2
Moisture uptake/release by different methods.

	Gypsum Board	Concrete	Aerated Concrete	Wood-fiber Board
MBV (g/m^2 %RH)	0.60	0.40	0.99	1.17
G-simulation (g/m^2)	17.21	11.36	27.52	32.69
G-MBV& β (g/m^2)	16.92	11.28	28.20	32.99
Absolute error (g/m^2)	−0.29	−0.08	0.68	0.31
Relative error (%)	1.70%	0.69%	−2.47%	−0.94%

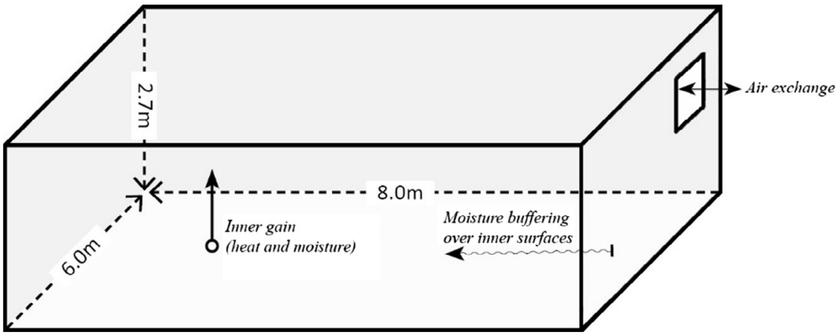


Fig. 3. IEA BESTEST base case building.

Table 3
Energy consumption results of four climates.

		Area of hygroscopic surface			
		0 m^2	32.4 m^2	75.6 m^2	171.6 m^2
Madrid	Total Energy consumption [kW h]	1542.87	1379.88	1273.05	1146.35
	Energy-saving Rate [%]	/	10.56%	17.49%	25.70%
Paris	Total Energy consumption [kW h]	1965.76	1813.08	1705.84	1547.01
	Energy-saving Rate [%]	/	7.77%	13.22%	21.30%
Beijing	Total Energy consumption [kW h]	2752.46	2648.30	2603.44	2561.13
	Energy-saving Rate [%]	/	3.78%	5.41%	6.95%
Shanghai	Total Energy consumption [kWh]	2648.73	2583.43	2542.19	2489.36
	Energy-saving Rate [%]	/	2.47%	4.02%	6.02%

of course, energy savings could be achieved in all climates with a well-designed and well-controlled ventilation system.

The relationship between MBV values (different buffer materials) and energy saving rate was also studied preliminarily. The energy performance of different hygroscopic materials in different climates were analyzed by simulation. Fig. 4 shows part of the results for concrete, gypsum board, aerated concrete and wood-fiber board as the internal surface materials in Paris case. The results show that the wood-fiber board (MBV = 1.2 g/m^2 %RH) and aerated concrete (MBV = 1 g/m^2 %RH) have higher energy saving rates than concrete (MBV = 0.4 g/m^2 %RH) and gypsum board (MBV = 0.6 g/m^2 %RH). Energy saving rate increases with increasing MBV values.

For the Paris case (shown in Fig. 4), the energy saving rate could be over 20% when using 171.6 m^2 aerated concrete or wood-fiber board on the internal surfaces. If using 171.6 m^2 concrete or gypsum board, or 75.6 m^2 aerated concrete or wood-fiber board, the energy saving rate could still be around 15%.

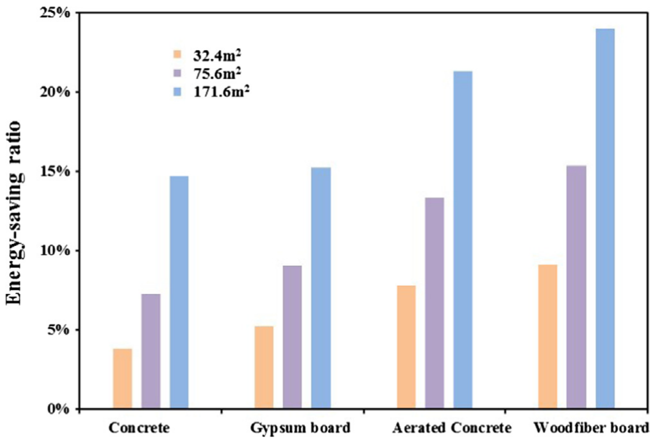


Fig. 4. Energy-saving rates in Paris case.

Table 4
Relationship between MBV values and potential energy saving rates.

		MBV (g/m^2 %RH)		
		0–0.5 (%)	0.5–1.0	1.0–1.5
Potential energy-saving rate	Madrid	0–20	20–26	26–30
	Paris	0–15	15–21	21–25
	Beijing	0–4	4–7	7–15
	Shanghai	0–3	3–6	6–12

A large amount of simulations were carried out to study the energy impact of different hygroscopic materials (different MBV values) under different climates. It was assumed that all internal surfaces of the room were covered by hygroscopic materials in the simulation. Table 4 shows the general relationship between MBV values and potential energy saving rates.

Although the MBV value is developed primarily for characterizing the moisture buffering ability of materials, the present research shows it could also be used as a good indicator for choosing materials with high energy saving potential. Architects and engineers could use MBV to choose proper internal surface materials for their green building design. Normally, the higher MBV, the higher energy saving potential.

It is important to note that the values presented in Table 4 are estimates based on numerical simulations under the conditions described in the text, and must be used with caution. Moreover, the moisture buffer effect due to furniture and fittings (curtains, carpets etc.) will also have an impact on the indoor relative humidity. More researches of MBV at product level are ongoing, and will be presented in future publications.

6. Conclusion

The paper first presents a critical review of the moisture buffering phenomenon in buildings, and then proposes a standardized produce to characterize the moisture buffering ability of materials under different conditions. A new mathematical expression of the moisture buffer value (MBV) and the correction factor β is developed to calculate moisture uptake and release by hygroscopic materials that exposed to real climate conditions. A simple two-bottle test method is proposed to measure the basic MBV under a cyclic step-change in relative humidity between different high and low levels.

The impact of moisture buffering on building energy consumption in different climates is studied by numerical simulations. The results show that the moisture buffering of indoor hygroscopic surfaces has a great impact on building energy performance in the temperate (e.g. Paris case) and semi-arid (e.g. Madrid case) climate zones. It is possible to reduce the total energy consumption by up to 25–30% when applying proper hygroscopic materials in Paris and Madrid climates. The moisture buffer materials have a high performance in the climates that have a distinct humidity difference between day and night, and the outside air during the unoccupied period is dry enough to regenerate the buffer materials. Further researches show that energy savings could be achieved in all climates by choosing proper buffer materials and using a well-designed air-conditioning and ventilation system.

The relationship between the MBV and potential energy saving rate of different hygroscopic materials in different climates is also discussed. Architects and engineers could use MBV as an indicator to choose proper internal surface materials for their energy efficient building design according to the site location (climates), function (residential or commercial etc.) and the goal for energy saving.

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