Application analysis of theoretical moisture penetration depths of conventional building material

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Abstract
Due to the significant impact of indoor humidity on indoor air quality, human comfort, and energy consumption, many researchers have investigated the use of various hygroscopic materials to moderate indoor humidity levels and save energy. The results show that the indoor relative humidity of the room with hygroscopic materials is more stable and moderate. Hygroscopic materials can be also used to reduce the energy consumption of heating, ventilation, and air-conditioning system. Although many laboratory measurements and numerical simulation studies have been done for hygroscopic materials, there is little study on moisture penetration in materials with limited thickness in practical engineering application. Moisture penetration depth has great influence on material moisture parameters and indoor humidity simulation model, such as effective moisture penetration depth model. In this article, a theoretical moisture penetration depth model is developed, and the theoretical moisture penetration depths of conventional building materials are calculated. The results show that when the wall material thickness is below the 1/e theoretical moisture penetration depth, the proportional relationship between the moisture buffer value and the square root of time is not kept. When the wall material thickness is thinner than its theoretical moisture penetration depth, ignoring the material thickness might cause significant error in indoor moisture content calculation using effective moisture penetration depth model.

Keywords
Theoretical moisture penetration depth, hygroscopic material, effective moisture penetration depth, moisture buffering value, energy conservation

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Introduction
Indoor air humidity is one of the most important factors which has a significant influence on indoor air quality (IAQ), human comfort, energy consumption of buildings, and durability of the building envelope. Excessively low or high relative humidity (RH) is easy to cause the discomfort of the skin, mold growth, and respiratory disease which are not good for living and working. Besides the influence on air quality, moisture can also impact the building energy in several situations. Due to the importance of indoor humidity, many researchers have investigated the use of various hygroscopic materials to moderate indoor humidity levels. Bailey et al. investigated the dynamic latent heat storage effects of building construction and furnishing. The simulation results indicate that moisture storage acts to increase cooling loads and cooling energy. Osanyintola and Simonson applied the

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The performance of hygroscopic materials depends on many factors including the type of the materials, the indoor and outdoor temperatures, RH, the ventilation rate, and the moisture production rate. The ability of hygroscopic materials to buffer indoor humidity changing depends on their active thickness, vapor permeability, and moisture storage capacity. Many works have been done to measure the water vapor permeability or the sorption isotherms of hygroscopic materials. The moisture capacity, $\zeta$, is a material property defined as the slope of the sorption isotherm for the chosen interval in RH. This material property for equilibrium conditions cannot represent the transient conditions of the periodic variations in the indoor environment. The moisture effusivity, $b$, is a theoretical approach proposed by NORDTEST project which may describe the ability of the material to take up and store moisture. An ideal moisture buffer value (MBV$_{ideal}$) is a theoretical definition based on the heat-moisture transfer analogy, which indicates the quantity of water absorbed or released by porous materials if a rectangular change of vapor concentration is specified. It can be calculated from the moisture effusivity and the square root of the period time, as described in equation (1)

$$\text{MBV}_{ideal} = 0.00568P_{sat}b\sqrt{\tau}$$ (1)

The MBV$_{ideal}$ is primarily a material characterization and independent of the environment condition, such as neglecting the air surface resistance, which is consider to be a reasonable approximation for the practical MBV (MBV$_{practical}$). However, Roels and Janssen found that the influence of the surface film resistance for common building materials is hard to be neglected.

The MBV$_{practical}$ indicates the amount of water that is transported in or out of a material per surface area in a certain period of time. When the hygroscopic materials expose to a periodic sinusoidal vapor concentration variation in the surrounding air, the MBV$_{practical}$ can be calculated analytically, as described in equation (2)

$$\text{MBV}_{practical} = \frac{P_{sat}}{100} \frac{1}{\sqrt{2\pi}} \times \frac{H}{\sqrt{(H + \omega')^2 + \omega'^2}} \times b\sqrt{\tau}$$ (2)

where $H = 1/R_{film}\delta_p$ and $\omega' = \sqrt{\pi\rho_{h}/\tau\delta_p P_{sat}}$.

Based on the properties and MBV of hygroscopic materials, some researchers have developed simulation models, such as effective capacitance (EC) model, effective moisture penetration depth (EMPD) model and combined heat and moisture transfer (HAMT) model for moisture transport simulation in building. Among these models, the EMPD model is widely used for its fast solution times and reasonable accuracy.

Although many laboratory measurements and numerical simulation studies have been done for hygroscopic materials, few researchers focus on the point that the thickness of some material in the building wall such as gypsum board is usually limited in practical application. The MBV and EMPD are usually measured and calculated based on the assumption that the materials are semi-infinite. If the penetration depth of the specimen for the considered time period (such as 24h) exceeds the material thickness, the performance parameters of hygroscopic material might be inaccurate, and these simulation models (such as EMPD model) may result in big deviation of the moisture evaluation. Therefore, it is necessary to evaluate whether and when the moisture will permeate through the building wall materials. In this article, a theoretical moisture penetration depth (TMPD) model is developed, and the TMPDs of conventional building wall materials are calculated. These TMPDs are used to check the accuracy and applicability of the MBV and EMPD model of the hygroscopic materials. The investigated results of the TMPD may provide some meaningful guidelines for building moisture environment simulation.

This article is organized as follows: First, a TMPD model is described and developed. At the meantime, the indoor and outdoor environment which the building wall materials usually expose to is described, and the assumptions of the TMPD model are specified. Then, the TMPDs of several conventional building wall materials are calculated based on different boundary conditions. Following, some application analysis is presented using the calculated TMPD. Finally, conclusion is given.

**TMPD model**

**Indoor and outdoor environment**

Hygroscopic materials may improve IAQ and save energy. However, it is hard to quantify due to its complicated process and multiple factors from indoor and outdoor environment. Several researchers have carried out some experiments and numerical simulation studies about the indoor humidity influenced by outdoor air. Labat et al. measured and studied six usual wooden-frame construction houses. The results show
that the influence on indoor humidity environment by wall moisture penetration from outdoor can be neglected. Steeman et al.\textsuperscript{28} developed a coupled TRNSYS-HAM model and simulated a yearly load for humidification and dehumidification. The research shows that the external surface of wall can be treated as airtight when calculating the building humidity loads.

Different from the outdoor environment, the indoor temperature and humidity is more stable and mild. Investigation\textsuperscript{29} shows that no matter the room environment is controlled by HVAC or not, the indoor RH remains almost in the range of 40\%–70\%. The indoor RH is better to be below 60\% or so for human comfortable zone. From all year around, the indoor humidity is seasonal variation. In short time, it mostly changes by diurnal period, especially for these rooms controlled by HVAC systems.

**Assumption of the moisture transportation model**

In these moisture transportation models, some researchers take moisture content as the driving force\textsuperscript{30–32} while some only consider the water vapor transport and ignore the effect of liquid water.\textsuperscript{33} When the RH does not exceed 90\%, the liquid water transport does not have a significant influence on the total moisture transfer in the material.\textsuperscript{34} Besides, when the material is within the hygroscopic range, that is, between capillary saturation and the maximum water saturation, the water vapor diffusion is predominant.\textsuperscript{35} According to the practical indoor environment and the characteristic of moisture in interior building material, some assumptions for model development is made as follows:

- The temperature fluctuation in interior surface is slight, and the process of moisture can be regarded as isothermal.
- Vapor partial pressure is the only driving force.
- The moisture diffusion coefficient, the moisture capacity, the mass transfer coefficient, and the density of the building wall material are constant.
- The ratio between the moisture penetration depth to the material surface tends to be infinity, and the moisture penetration process is considered as one-dimensional.
- The hysterisis effect in the sorption curve is neglected. The moisture capacity is within the hygroscopic range which is based on the average value of the absorption and desorption data.

**TMPD model**

Based on the above assumptions, a TMPD model is developed. The moisture diffusion within interior building wall materials is a second-order partial differential equation as described in equation (3). The moisture flux at arbitrary displacement $x$ of building wall materials and time $t$ is given by equation (4). As the water vapor partial pressure is hard to be measured, the water vapor concentration is used. Then, equations (4) and (5) can be rewritten as equations (6) and (7) with the initial governing and boundary conditions as equations (8) and (9).

$$
\rho_0 \frac{\partial}{\partial t} \left( \frac{P_v}{P_{sat}} \right) = \frac{\partial}{\partial x} \left( \delta_p \frac{\partial P_v}{\partial x} \right) \quad (3)
$$

$$
q_m = - \delta_p \frac{\partial P_v(x,t)}{\partial x} \quad (4)
$$

$$
\frac{\partial c}{\partial t} = a_m \frac{\partial^2 c}{\partial x^2} \quad (5)
$$

$$
q_m = - \delta_p R_v T \frac{\partial c(x,t)}{\partial x} \quad (6)
$$

$$
c(x,t = 0) = \tilde{c} \quad (7)
$$

$$
q_m(0,t) = - \delta_p R_v T \frac{\partial c(0,t)}{\partial x} = h_m R_v T (c_t - c(0,t)) \quad (8)
$$

$$
q_m(L,t) = - \delta_p R_v T \frac{\partial c(L,t)}{\partial x} = 0 \quad (9)
$$

where $a_m = \delta_p P_{sat} / \rho_0 \omega$, $c = P_v / R_v T$, and $h_m = 1/R_{film}$.

The material is assumed to be impermeable to vapor at $L$ which is the material thickness. In the present analysis, the material properties are considered independent of the material moisture content and temperature. Therefore, the moisture transportation in building wall materials is linear, and it can be solved analytically.

**TMPD of conventional building wall material**

**Boundary condition**

The hygroscopic materials are exposed to the indoor air. For simulating the moisture transportation in the materials, indoor humidity condition should be specified in advance. The indoor humidity fluctuations are set according to a research report\textsuperscript{28} which collected the indoor temperature and humidity over a 3.5-year period from 43 houses located mostly in the hot and humid region. It can be found from the report that in short time, such as daily and weekly period, the indoor humidity almost changes like periodic sinusoidal variation which can be described by equation (10). However, the indoor humidity may suddenly rise up or go down and then keep for a long time due to a rapidly change of the outdoor environment such as changing from a dry day to a long-term raining day. At that situation,
the indoor humidity fluctuation may be viewed as a step change, as shown in equation (11)

\[ c_i(t) = \bar{c} + c_{\text{amp}} \times \sin(\omega t) \]  (10)

\[ c_i(t) = \bar{c} + c_{\text{amp}} \]  (11)

where \( \omega = \frac{2\pi}{\tau}, \) \( \tau \) is time period.

**TMPDs of conventional building wall materials**

Based on the TMPD model and indoor boundary condition, the vapor concentration of the materials can be calculated analytically. In a sinusoidal variation condition, the materials’ vapor concentration can be calculated as equation (12)

\[ c(x, t) = \bar{c} + c_{\text{amp}} \frac{H}{\sqrt{(H + \omega')^2 + \omega'^2}} \sin(\omega' t - \Delta) \]  (12)

where \( \Delta = \text{atan}(\omega'/(\omega' + H)) \).

During time period \( \tau \), the difference between maximum and minimum of the materials’ vapor concentration decreases exponentially with the depth. Arvidsson\(^{36} \) gives a definition of the moisture penetration depth where the RH variation is equal to 1% of the variation at the surface. The TMPD is given as equation (13), and the value of the TMPD (denoted as \( d_{\text{TMPD}} \)) is evaluated as equation (14)

\[ e^{-\omega' x} = 0.01 \]  (13)

\[ d_{\text{TMPD}} \approx 4.61 \sqrt{\frac{d_{\text{mp}} \tau}{\pi}} \]  (14)

Equation (14) shows the TMPD increases along with the indoor humidity variation period. When the indoor humidity variation period is specified, the TMPD only relies on the materials vapor diffusivity.

When the period is 24 h and the indoor vapor concentration changes with \( \bar{c} = 0.00866 \text{kg/m}^3 \) and \( c_{\text{amp}} = 0.00519 \text{kg/m}^3 \), the moisture distribution of aerated concrete slab at different times (\( \tau, \tau/4, \tau/2, \) and \( 3\tau/4 \)) during the time period is shown in Figure 1. It can be seen that the vapor concentration amplitude in wall surface is smaller than that in indoor air. The moisture wave decays rapidly in materials. For daily variation, only a thin layer of the material exchanges moisture with the room.

In this study, a few kind of wall materials including the concrete, plasterboard, brick, fiberboard, wood, and polystyrene board are chosen for analysis. Table 1 presents the properties of these materials along with the TMPD in different periods. Daily, weekly, and lunar TMPDs are calculated. The TMPD is proportional to the square root of the moisture variation period, \( \sqrt{\tau} \), as equation (14). The TMPD in lunar period is about 5.5 times as long as that in daily period. For conventional building wall materials such as brick and expanded polystyrene (EPS) board, the month TMPDs have reached 0.22 and 0.27 m, respectively. When the moisture variation period is much longer such as seasonal period, the wall material will be penetrated through.

Figure 2 presents the TMPDs of several wall materials exposed to the indoor environment. The indoor temperature is kept at 20°C, and the vapor concentration changes with a 24-h sinusoidal period (\( \bar{c} = 0.00866 \text{kg/m}^3, c_{\text{amp}} = 0.00519 \text{kg/m}^3 \)). It can be seen that the TMPDs vary between each other due to the material moisture properties. Plasterboard has a large TMPD because it has large vapor permeability and small moisture capacity. In contrast, wood has a large moisture capacity and a small vapor permeability which leads to a small TMPD. Polystyrene board is usually used as an insulation material. Condensation and mildew might occur in interior because the moisture can penetrate it easily.

In a step change condition, the moisture transportation is analogous to thermal diffusivity. The analytical solution of the TMPD for hygroscopic material with a step change can be obtained as equation (15)
Olutimayin and Simonson measured the vapor boundary layer thickness of cellulose insulation. They also solved the TMPD of cellulose insulation using this formula and compared this analytical solution with the measurement. The results show very close agreement between the analytical solution and the measurement. In this article, three kinds of building wall materials, #5 gypsum plaster, #1 aerated concrete, and #7 brick, are chosen to study the TMPD's variation. Figure 3 presents the TMPD's of building wall materials which are exposed to the indoor environment. The indoor vapor concentration is 0.00866 kg/m³ initially (equivalent to RH = 50% at 20°C) and suddenly rises to 0.01209 kg/m³ (equivalent to RH = 70% at 20°C). It can be seen that the water vapor will penetrate through the materials eventually with time going by. It would only take 5 h for the moisture to penetrate through a 0.02-m gypsum plaster. This could occur when an office is in off-office hours when the air-conditioning system is off.

### Application analysis

#### Impact on MBV

In total, two test methods have been developed to characterize the moisture buffering capacities of building materials. One was proposed in NORDTEST project, and the other is presented in Japanese Industrial Standards (JIS). The specimen thickness in NORDTEST project is larger than the TMPD for daily humidity variations, while in JIS, the specimen thickness is the practical thickness of the product. Roels and Janssen compared and investigated the difference between these two methods. The results show that the specimen thickness is very important when evaluating the MBV. When the specimen (e.g. #6 gypsum board) thickness is below the 1/e TMPD, the practical moisture buffering capacity decreases rapidly, and the relationship between MBV and the square root of time (shown in equations (3) and (4)) is not kept as shown in Figure 4.

For the case of that the practical thickness of the material is 1 cm, the accumulated moisture content is proportional to the square root of time period when the time period is less than about 1 h. However, when the time period is >1 h, the accumulated moisture content in the material is almost the same because the moisture

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**Table 1. Material properties and theoretical moisture penetration depth.**

| ID | Class   | Material            | ζ₀ | ρ₀   | δρ (10⁻¹²) | aₘ (10⁻⁹) | d (mm) |
|----|---------|--------------------|----|------|------------|------------|--------|
| 1  | Concrete| Aerated concrete   | 0.066 | 650  | 30         | 1.63       | 30.9   |
| 2  | Cellular concrete | 0.013 | 510  | 1.47 | 0.51       | 17.3       | 45.7   |
| 3  | Concrete| 0.046 | 2300 | 1.09 | 0.02       | 3.7        | 9.9    |
| 4  | Plasterboard| Mineral plaster | 0.030 | 1900 | 7.87       | 0.33       | 13.8   |
| 5  | Gypsum plaster | 0.009 | 850  | 23.7 | 7.01       | 64.0       | 169.4  |
| 6  | Gypsum board | 0.052 | 850  | 32.8 | 1.75       | 32.0       | 84.7   |
| 7  | Brick   | Brick              | 0.007 | 1650 | 2.07       | 4.31       | 50.2   |
| 8  | Wood    | Lime silica brick  | 0.016 | 1900 | 7.02       | 0.53       | 17.5   |
| 9  | Wood    | Particle board     | 0.062 | 560  | 0.33       | 0.02       | 3.6    |
| 10 | Fiber board | 0.027 | 215  | 3.78 | 1.51       | 29.7       | 78.6   |
| 11 | Wood    | Wood               | 0.188 | 400  | 0.98       | 0.03       | 4.2    |
| 12 | Balsa   |                     | 0.018 | 125  | 0.49       | 0.51       | 17.3   |
| 13 | Spruce  |                     | 0.083 | 450  | 5.79       | 0.36       | 14.6   |
| 14 | Polystyrene | EPS   | 0.010 | 30   | 1.1        | 8.34       | 69.8   |
| 15 | XPS     |                     | 0.007 | 42   | 1.77       | 14.2       | 91.1   |

EPS: expanded polystyrene; XPS: extruded polystyrene.
penetrates through the material. For the case of that the practical thickness of the material is 10 cm, the accumulated moisture content is always proportional with the square root of time period even if the time period is much larger such as 1 month. This is because the moisture does not penetrate through the material, and the moisture content can be accumulated continuously.

Impact on EMPD model

In late 1980s, Cunningham and Kerestecioglu et al. proposed an EMPD model. It assumes that only a thin layer of the materials exchanges moisture with the room, while the rest of the material remains constant to the initial value as shown in Figure 5(a). The vapor balance between the wall material and the indoor air can be written as equation (16). The fictitious thickness \( d_{\text{EMPD}} \) can be calculated by equation (17). This thickness \( (d_{\text{EMPD}}) \) is about 21.7% long of the TMPD \( (d_{\text{TMPD}}) \)

\[
\frac{\rho g d_{\text{EMPD}}}{P_{\text{sat}}} \frac{dc_{\text{EMPD}}}{dt} = \frac{c_{\text{i}} - c_{\text{EMPD}}}{\frac{1}{h_{\text{m}}} + \frac{d_{\text{EMPD}}}{2p}} \tag{16}
\]

\[
d_{\text{EMPD}} = \sqrt{\frac{\delta_{\text{p}} P_{\text{sat}} \tau}{\rho g \pi}} = \sqrt{\frac{a_{\text{m}} \tau}{\pi}} \approx \frac{d_{\text{TMPD}}}{4.61} \tag{17}
\]

If the EMPD model is applied, the material thickness should be thicker than the TMPD or 4.61 times of the EMPD. For the building wall materials such as brick and concrete layer, the moisture penetration depth is in the order of several millimeters for daily variation, and the effective thickness model is suitable. However, for the building wall materials such as gypsum plaster which is usually used as interior decoration and moisture buffer, the moisture penetration depth is about 30–60 mm for daily variation. For a longer time or a thinner thickness, the material might be penetrated out as shown in Figure 5(b). For example, the gypsum plaster thickness is usually 0.01 m or so, and the daily and monthly TMPDs (#5 gypsum plaster) are 0.064 and 0.350 m, respectively. It indicates that even though the moisture variation period is short such as 24 h, the gypsum plaster is penetrated through. However, the EMPD of the gypsum plaster in daily period is about 0.014 m which exceeds the material thickness. At that situation, the conventional EMPD model is not suitable and cannot be used.

A case study is presented to evaluate the EMPD model. Aimed to better assess indoor humidity climate, energy efficiency, and durability of building, the International Energy Agency takes a research project titled "Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG)." In subtask 2 of this project, a series of experiments have been done to measure the relevant moisture properties of conventional building materials, especially for the dynamic moisture behavior of gypsum board. The material properties of gypsum board along with the area, thickness, daily EMPD, and TMPD values are shown in Table 2. It is obvious that the calculated EMPD value has exceeded the material thickness. In the experiment, the gypsum samples were exposed under isothermal conditions (25.7°C) to a harmonically changing RH which follows a sine function, varying between 40% and 85% RH. Figure 6 shows the air RH and the measured sample mass of gypsum board with time. The measured experimental values (symbols) are also curve fitted (lines) with sine function, as described by...
The air RH is conditioned as design while the weight of the sample is less symmetrical than we expected which might contribute to measurement error and nonlinear moisture transportation. The vapor flux between gypsum board and ambient air can be calculated by taking the derivative of the weight of the sample, as described in equation (20)

\[
\frac{dM}{dt} = 4.976 \times 10^{-5} \sin\left(\frac{\pi}{43,200}t - 0.2757\right) + 30.09
\]  

\[q_m = \frac{M_{\text{material}}}{A} = 1.114 \times 10^{-6} \sin\left(\frac{\pi}{43,200}t + 1.295\right)
\]  

The frequency characteristics of the vapor flux between the material and ambient air can be calculated by transfer function (TF) model (analytical model), as described in equation (21). For EMPD model (lumped model), the frequency characteristics of the vapor flux can be obtained by Laplace transformation of equation (16), as shown in equation (22)

\[
q_m,TF(s) = \frac{h_m\delta_P\sqrt{\frac{\dot{\rho}}{a_w}}}{\delta_P\sqrt{\frac{\dot{\rho}}{a_w}} + h_m \coth\left(\frac{L}{\sqrt{\frac{\dot{\rho}}{a_w}}}\right)} * P_v(s)
\]  

\[
q_m,EMPD(s) = \frac{1}{\frac{1}{h_m} + \frac{d_{\text{EMPD}}}{2\delta_P} + \frac{P_m}{a_{\text{empd}}}} * P_v(s)
\]  

Usually, amplitude and angle are used to represent the frequency characteristics. The amplitudes and angles of vapor flux calculated by experiment measurement, TF model, and EMPD model with the period of 24 h are shown in Table 3. In EMPD model, three EMPD values are applied, in which one is a conventional EMPD value \(d_{\text{con}}\) calculated by equation (17). The other two are equal to the material thickness \(d\) and half of the conventional EMPD thickness \(d_{\text{con}/2}\).

### Table 2. Material properties.

| Type          | \(\rho_0\) | \(\zeta\) | \(\delta_p\) | \(A\) | \(L\) | \(d_{\text{EMPD}}\) | \(d_{\text{TMPD}}\) |
|---------------|-------------|-----------|--------------|-------|------|---------------------|---------------------|
| Gypsum board  | 690         | 0.0101    | 2.433 \times 10^{-11} | 0.057 \times 0.057 | 0.0125 | 0.0189              | 0.0871              |

### Table 3. Amplitude and phase of vapor flux between material and ambition air.

| Vapor flux | Experiment | TF model | EMPD model |
|------------|------------|----------|------------|
|            |            |          |            |
|            |            |          | \(d_{\text{con}}\) | \(d_L\) | \(d_{\text{con}/2}\) |
| Amplitude (10^{-6} kg/m^2/s) | 1.114 | 1.103 | 1.203 | 1.060 | 0.863 |
| Phase (rad) | 1.295 | 1.222 | 0.728 | 1.095 | 1.269 |

TF: transfer function; EMPD: effective moisture penetration depth.
Figure 7 shows the relative error of the amplitudes and angles of the TF model and EMPD model compared to the experiment measurement value. It can be seen that the amplitude and angle calculated by TF model agree well with the experiment, while the EMPD model shows significant deviation. In all the EMPD models, the one whose EMPD value is calculated by conventional method is not accurate and suitable. The EMPD should be calculated again based on the material thickness. In this case, a $d_{EMPD}$ equal to the material thickness may be more reasonable and accurate.

**Conclusion**

The moisture exchange between building wall material and indoor air depends on many factors such as indoor and outdoor environment, the boundary conditions and wall material moisture property, as well as the geometrical configuration. The material moisture interaction thickness has great influence on the calculation of material moisture buffer capacity and indoor humidity environment. This article presents a TMPD model and evaluates the TMPDs of conventional building materials with different humidity variation periods. The results show that the TMPDs are various between each other due to the material moisture properties. Some building wall materials such as gypsum board and polystyrene board, will be penetrated out easily by indoor water vapor in a daily moisture variation period. When the indoor humidity increases suddenly, it would only take 5 h for the moisture to penetrate through a 0.02-m gypsum board.

The MBV is an important parameter which indicates the capacity of absorbing or releasing the water vapor. A relationship has been investigated between the moisture content change in material and the moisture variation period of the indoor air with different material thicknesses. The results show that the proportional relationship between the MBV and the square root of the time period is not kept when the material thickness is below $1/e$ TMPD.

The EMPD model is widely used due to its fast solution time and reasonable accuracy. However, it is based on an assumption that the material is thicker than the TMPD. In this article, a case is presented which compares the amplitudes and angles of vapor flux calculated by TF model and EMPD model with experiment measurement values. The results show that when the material is thinner than its TMPD, the EMPD model which ignores the material thickness might be incorrect, and the EMPD value should be reevaluated.

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**Appendix I**

**Notation**

| Symbol | Description |
|--------|-------------|
| $a_w$ | vapor diffusivity (m²/s) |
| $A$ | material exposed area (m²) |
| $b$ | moisture effusivity (kg/m²m²/s) |
| $c$ | vapor concentration (kg/m³) |
| $\bar{c}$ | mean vapor concentration (kg/m³) |
| $c_{amp}$ | vapor concentration amplitude (kg/m³) |
| $d$ | penetration depth (m) |
| $h_{int}$ | mass transfer coefficient (kg/Pa m²/s) |
| $L$ | material thickness (m) |
| $M$ | material mass (kg) |
| $P_{sat}$ | vapor pressure at saturation (Pa) |
| $P_v$ | partial vapor pressure (Pa) |
| Symbol | Description |
|--------|-------------|
| $q_m$  | vapor flux (kg/m$^2$ s) |
| $R_{film}$ | air film resistance (Pa m$^2$/s/kg) |
| $R_V$  | constant of water vapor (J/kg K) |
| $s$    | Laplace transform variable |
| $t$    | time (s) |
| $x$    | spatial coordinate (m) |
| $\delta_p$ | vapor permeability for partial vapor pressure (kg/m s Pa) |
| $\zeta$ | moisture capacity (kg/kg) |
| $\rho_0$ | density of the dry material (kg/m$^3$) |
| $\tau$ | time period (s) |

**Subscripts**
- $in$ indoor