EMPD-Based Moisture Buffering Quantification with Moisture-Dependent Properties (I): Modelling and Simulations

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Abstract. Materials with excellent moisture buffering performances have considerable application potential in the future developments of building moisture design. The appropriate application of building materials is determined via the effective assessment of their hygroscopic performance, however, currently available test methods (e.g., moisture buffer value test) can evaluate only the moisture buffering abilities of materials under limited circumstances. Advanced numerical prediction methods (e.g., heat, air and moisture transfer (HAM) models) are not practical because of unavailable hygrothermal properties and excessive computation times. Integrating the effective moisture penetration depth (EMPD) model with an inverse approach allows both identifying and predicting the effect of moisture buffering on room conditions effectively and efficiently. This paper reports that the existing EMPD models have limited application conditions, and hence proposes a modified two-layer EMPD model considering both the moisture-dependent hygric properties of materials and reasonable moisture transfer resistance distributions. A novel dynamic moisture test is presented in terms of typical moisture fluctuations in office buildings. Compared to standard hygric property tests, the combination of the inverse approach and the dynamic moisture test can extract key parameters of EMPD models efficiently and effectively. Thus, the actual performance of materials can be accurately predicted for wider spectrum of conditions. The precision of the modified EMPD model and proposed approach is validated by comparing the numerical predictions with both the measured results and HAM results. This method, with the advantages of a simple test procedure, low experimental cost, high test efficiency, and wide applicable range, is advisable for practical applications.

Keywords: EMPD model; Moisture buffering; Numerical simulation; Inverse solution; Building materials

1 Introduction

1.1 General Background

An excess or lack of moisture in a built environment can adversely affect the health and comfort of building occupants [1, 2] and the durability and sustainability of the built structures [3, 4]. To avoid such humidity-related problems in buildings, it is essential to assess and predict the interior relative humidity (RH) fluctuations efficiently and reliably in the design stage and implement correct prevention measures when constructing new buildings or renovating old buildings. Thus, the quantitative and/or qualitative assessment of the moisture buffering performance for interior finishing materials is considered significant in this process.

Currently, several common indices exist for qualitatively evaluating the moisture buffering performance of finishing materials, among which the moisture buffer value (MBV) [5] is the most popular. Complementarily, there

are three common models for the quantitative simulation of moisture buffering performance: the effective capacitance (EC) [6], the effective moisture penetration depth (EMPD) [7], and the heat, air, and moisture transfer (HAM) models [8].

1.2 State-of-the-art

1.2.1 MBV

Kreiger and Srubar presented the historical evolution of MBV, and discussed experimental methods for measuring MBV [9]. The MBV protocol was finally standardized with ISO 24353 [10], which imposed a square-wave RH change. Therefore, MBV is not an inherent property of the material because it strongly depends on the test conditions and protocols. Roels and Janssen [11] assessed the sensitivity of MBV to these protocols and conditions via parametric analysis. Using numerical simulations on four materials, they found a significant effect on the specimen thickness, time scheme, and surface resistance on the obtained MBV. McGregor et al. [12] confirmed these findings via an experimental study of unfired clay bricks; similar research was reported by Ge et al. [13]. Further, a cycle-adaptive MBV* was proposed by Janssen and Roels [14] to respond flexibly to different time schemes. The effect of moisture buffering on building energy consumption can be predicted by the MBV, according to [15]. Furthermore, Cascione et al. [16] reviewed theoretical models, laboratory-scale tests, and full-scale measurements related to the MBV.

1.2.2 EC model

As a lumped-parameter model, the EC model assumes that the moisture ad-/desorption capacity of the finishing materials and interior objects can be superimposed on the moisture capacity of the zone air; therefore, it can be solved by a simple calculation [6]. However, it is not straightforward to determine the optimal multiplier for the zone air capacity. Although Janssen and Roels [14] solved this shortcoming by defining a room hygric inertia based on the MBV, the EC model is still not commonly used in building simulations because its premise of instantaneous hygric equilibrium between the zone air and finishing materials/ interior objects leads to inaccurate results.

1.2.3 EMPD model

Relative to the EC and HAM models, the EMPD model achieves a better trade-off between prediction precision and computational speed. Therefore, it is appropriate for engineering applications. Cunningham [7] was the first to propose a one-layer EMPD model for a single-term RH fluctuation. This model assumes that moisture from the zone air is adsorbed and desorbed by a fictitious buffer layer. The thickness of this layer is determined by the penetration depth of the harmonic RH variation. Woods and Winkler [17-19] proposed a two-layer EMPD model by assuming a surface and a deep buffer layer to deal with both short- and long-term RH variations. The hygric properties (vapor capacity and permeability) of such buffer layers are always presumed to be constant in the existing EMPD models, whereas these hygric properties may vary greatly with humidity. The appropriate selection of these hygric property values remains an important question.

There remains an obstacle to achieving reliable hygrothermal properties of actual materials efficiently and feasibly. Several comprehensive and systematic tests have been performed in Western countries [20, 21]. However, the types and composition processes of materials involved in these databases are unlike those used in real buildings, hence, the direct quote is not reliable. An inverse approach has been proposed to solve this problem; this approach derives input parameters by achieving a numerical agreement between the test results of some specific operating conditions and the EMPD model prediction. Abadie and Mendonca [22] obtained the lumped EMPD parameters of

the three materials from the measured MBV. In the study by Woods and Winkler [18, 19], parts of the empirical values were assumed for the two material properties in advance, and then, the remaining intuitive parameters were extracted from two actual house tests. However, the validity of such an approach was not confirmed for any other conditions besides the test conditions. An alternative method, proposed by Janssen and Roels [14] and Vereecken et al. [23], is to inversely obtain the moisture effusivity b_m and thickness adjustment a -value instead of the hygric properties of the material in a rewritten EMPD model. These two comprehensive characterization parameters— a -value and b_m —represent the relationship between the moisture scheme and material thickness and the moisture buffering ability of the materials, respectively. This can avoid introducing assumptions between moisture transfer and moisture capacity or between moisture ability and moisture scheme; thus, it can be applied in various scenarios.

1.2.4 HAM model

The HAM model [8] is a well-known technique for solving the problems of coupled heat, air and moisture transfers using a detailed numerical approach. Contrary to the EC model, it has superior precision and acts as a criterion for testing others. The Fraunhofer Institute of Building Physics in Germany developed the WUFI software [24] based on the 1D HAM model, and it is often used to predict room performances in the researches on heat and moisture transfer.

At the design stage, multiple schemes need to be thoroughly evaluated to optimize and seek out the best solution for the target environment. Nevertheless, the HAM model has numerous complicated inputs, meanwhile, its computational time [25] is considerably longer than that of the previously mentioned models. What's more, when calculating and predicting the moisture environment of an existing room, it is necessary to consider all materials and items with the potential moisture buffering ability in the room. However, too many parameters are unknown and unavailable, rendering it difficult to apply in engineering practice that requires efficiency and conciseness. Therefore, it is necessary to propose simplified calculation methods and test schemes.

1.3 Problem Statement

Based on the state-of-the-art of hygric buffering models, we found that the EMPD model has tremendous potential to be widely applied in engineering practice, particularly at the design stage. However, the current state-of-the-art EMPD models still exhibits some limitations and deficiencies, and several key aspects need to be improved and clarified, such as (1) the current EMPD models with constant properties have many limitations; (2) there is no standardized test method consistent with the actual daily humidity scheme for identifying the moisture performance of the materials; (3) the effectiveness and advantages of the inverse approach of the EMPD models have not been confirmed; (4) research on the effect of uncertain factors on the calculation accuracy of moisture buffering is still insufficient.

To verify the accuracy of the existing EMPD models more intuitively, we simulated the indoor RH and the cumulative moisture buffering (MG_{buf}) of a one-day simulated room case with constant hygric properties of materials via the existing one-layer EMPD model and two-layer EMPD model, and the HAM model as a basic standard. And we compared the results of EC model where certain properties were obtained from an MBV measurement (Fig. 1) [14]. The values of hygric properties in the EMPD calculations were chosen at 60% RH here. The detailed simulation information of this one-day simulated room case is provided in subsubsection 2.2.3.

Fig. 1. Prediction of RH and MG_{buf} of the one-day simulated room case via the forward method of the existing models

In this one-day simulated room case, the computational time of the EMPD and EC models is less than 10 s, whereas it is approximately 5 min for the HAM model, thus, the HAM model is time-consuming. According to Fig. 1, there is a weak agreement for indoor RH between the EC and HAM models. Both EMPD models capture the trend of the indoor RH well; however, the two-layer model performs much better at the decay stage. In addition, MG_{buf} fluctuates upward before 630 min, and then changes to a downward trend. This indicates that the material first absorbs and then desorbs moisture. The MG_{buf} of the EC model increases and declines faster relative to the HAM model, which arises from the inherent defect of the EC model as mentioned in subsubsection 1.2.2. Compared to the other two models, the MG_{buf} of the two-layer EMPD model is considerably closer to that of the HAM model, however, the deviation increases with increasing humidity. Moisture buffering cannot be accurately calculated by either of the EC or EMPD models. Most importantly, because of constant input properties in the EMPD models, the deviation is enlarged to varying degrees when properties without matching prediction circumstances are applied. Acceptable first estimates are always found with values of properties at the mean RH of the variation range. Fig. 1 represents the first-rate result, where the values of properties at the mean RH of the variation range are inputs for this calculation. However, it is not generally clear at which RH the properties are to be calculated. The calculation residuals of the EMPD models have also been reported in other studies [17, 26]. This calculation further intuitively illustrates the aforementioned flaws and drawbacks in the EC and EMPD models.

1.4 Objectives

This paper proposes an integrated and feasible approach to identify and predict the moisture buffering performance of building materials based on the EMPD model. There are six parts, as follows:

- 1) **Model improvement:** Based on the limitations of the existing EMPD models, a modified two-layer EMPD model is proposed. This proposed EMPD model considers the moisture-dependent hygric properties of the materials and more reasonable material resistances.
- 2) **Proposal of test method:** A novel dynamic moisture test is presented to identify the moisture buffering ability of the materials. Experimental measurements and numerical simulations of two typical building materials were conducted under standard and variable conditions.
- 3) **Inverse solution:** The key parameters of the four types of EMPD models are extracted based on the standard box test.
- 4) **Experimental validation:** The reliability of the proposed model for actual measurements is evaluated by comparison with measured data.
- 5) **Sensitivity analysis:** The precision of the EMPD models is compared by assessing the predicted effectiveness for various variable boundary conditions.
- 6) **Verification:** The entire set of the proposed approach is verified by analyzing the prediction effects of short- and long-term room conditions.

This work potentially contributes to moisture design, HVAC control, and the build-environment improvement.

2 Materials and Methods

In this section, a modified two-layer EMPD model is proposed. Then, the fitting strategy and data analysis are presented, and a novel dynamic moisture test is proposed to identify the moisture performance of the materials. Finally, material information is introduced.

2.1 EMPD Model

The moisture balance for the room air can be written as

$$\frac{V}{R_v T_i} \cdot \frac{dp_{vi}}{dt} = (p_{ve} - p_{vi}) \frac{NV}{3600 R_v T_i} + G_{vp} - \sum_{m=1}^n G_{buf,m} \quad (1)$$

where $V/(R_v \cdot T_i)$ (kg/Pa) is the moisture capacity of the zone air, p_{vi}/p_{ve} (Pa) is the partial vapor pressure of interior/exterior air, N (1/h) is the air change rate per hour, V (m³) is the volume of the zone, R_v (462 J/kg/K) is the gas constant of water vapor, T_i (K) is the indoor air temperature, G_{vp} (kg/s) is the interior vapor production, $G_{buf,m}$ (kg/s) is the moisture exchange between indoor air and the m -th material, and $m=1,2,\dots$ is the number of the material.

The EMPD models consider both the moisture transfer resistance of the material and the surface air layer, wherein the material resistance is dependent on moisture penetration thickness (d_{EMPD}). The existing two-layer EMPD model divides the material resistance into two layers, and determines the surface and deeper effective penetration thickness ($d_{EMPD-surf}$ and $d_{EMPD-deep}$) based on the short- (usually 24 h for daily humidity variation) and long-term (usually 3 weeks for seasonal humidity variation) humidity periods, respectively [17-19]. It was proposed based on two conventional sine-wave moisture fluctuations, which implies that the material thickness is thicker than $d_{EMPD-deep}$. However, there are no ideal circumstances in the real environment, and it is very difficult to obtain the actual cycling time because of the irregular and complicated humidity variation, which may lead to a misjudgment of d_{EMPD} . In addition, the thickness of the practical materials varies.

Hence, to address these drawbacks, we propose a modified two-layer EMPD model with moisture-dependent properties and reasonable moisture transfer resistance distributions via an inverse solution. The modified model divides the materials participating in moisture transfer into two layers to consider the moisture transfer of both the

surface and deeper layers, as shown in Fig. 2.

Fig. 2. Schematic of the modified two-layer EMPD model

The surface penetration layer is defined as the active area of the moisture exchange with the zone air, and the deeper layer is expressed as the deeper area of the material involved in the moisture transfer exchanging moisture with the surface layer. A similar correction method [14] can determine the material resistance based on the relationship between d_{EMPD} and the actual thickness of the material. The two-control-volume equations can be written as

$$A \cdot \frac{p_{vi} - p_{vb,1}}{\frac{1}{\beta_i} + \frac{d_{b,1}}{2\delta_p}} + A \cdot \frac{p_{vb,2} - p_{vb,1}}{\frac{d_{b,1}}{2\delta_p} + \frac{d_{b,2}}{2\delta_p}} = A \cdot \xi \cdot d_{b,1} \cdot \frac{\partial}{\partial t} \left(\frac{p_{vb,1}}{p_{sat}(T_b)} \right) \quad (2)$$

$$A \cdot \frac{p_{vb,1} - p_{vb,2}}{\frac{d_{b,1}}{2\delta_p} + \frac{d_{b,2}}{2\delta_p}} = A \cdot \xi \cdot d_{b,2} \cdot \frac{\partial}{\partial t} \left(\frac{p_{vb,2}}{p_{sat}(T_b)} \right) \quad (3)$$

where $p_{vb,1}$ and $p_{vb,2}$ (Pa) are the vapor pressure on behalf of average value in the center of the first layer with thickness $d_{b,1}$ (m) and of the second layer with thickness $d_{b,2}$ (m), T_b (K) is the average temperature of the materials, δ_p (s) is the vapor permeability, ξ (kg/m³) the vapor capacity, p_{sat} (Pa) is the saturated vapor pressure, β_i (s/m) is the convective surface film coefficient for vapor transfer.

In combination with

$$d_{b,i} = a \cdot d_{EMPD,i} = a \cdot \sqrt{\frac{\delta_p \cdot \xi \cdot p_{sat}(T_b)}{\xi \cdot \pi}} \quad (4)$$

$$b_m = \sqrt{\frac{\delta_p \cdot \xi}{p_{sat}(T_b)}} \quad (5)$$

The Eqs. (2-3) can be reformulated as

$$\frac{\partial p_{vb,1}}{\partial t} = \frac{p_{vi} - p_{vb,1}}{\frac{a b_{m,1}}{\beta_i} + \frac{a^2 t_{p,1}}{2\pi}} + \frac{p_{vb,2} - p_{vb,1}}{\frac{a^2 t_{p,1}}{2\pi} + \frac{a^2 t_{p,2}}{2\pi} + \frac{a^2 t_{p,1} t_{p,2}}{\pi} \times \frac{b_{m,1}}{b_{m,2}}} \quad (6)$$

$$\frac{\partial p_{vb,2}}{\partial t} = \frac{p_{vb,1} - p_{vb,2}}{\frac{a^2 t_{p,2}}{2\pi} + \frac{a^2 t_{p,1}}{2\pi} + \frac{a^2 t_{p,1} t_{p,2}}{\pi} \times \frac{b_{m,2}}{b_{m,1}}} \quad (7)$$

where $i=1,2$ is the number of the material layer, $d_{EMPD,i}$ (m) is the effective moisture penetration thickness related to the cycling time of moisture fluctuations $t_{p,i}$ (s), a (-) is a comprehensive coefficient to express the proportion between $d_{b,i}$ of the i -th layer and its corresponding $d_{EMPD,i}$, b_m (kg/(m²·Pa·s^{0.5})) is moisture effusivity of the material. Then, $G_{buf,m}$ can be obtained as

$$G_{buf,m} = A \cdot \frac{p_{vi} - p_{vb,1}}{\frac{1}{\beta_i} + \frac{d_{b,1}}{2\delta_p}} \quad (8)$$

The accumulative moisture ab-/desorption quantity of all materials is normally weighted by the scale in some laboratory tests. This can be written as

$$MG_{buf} = \sum_{m=1}^n G_{buf,m} \times h \quad (9)$$

where h (s) is the time step, MG_{buf} (kg) is the accumulative moisture ab-/desorption amount of all materials.

As mentioned in the Introduction, the uncertainty of the material properties and boundary conditions are critical factors that cause deviations in the results. Thus, instead of obtaining hygric properties from two classic tests—cup

tests and static gravimetric tests—we identify some unknown parameters of the modified two-layer EMPD model from an inverse approach.

In the existing EMPD model, the hygric properties (ξ and δ_p) of the material are treated as constants. However, research indicates that, for most materials, these two crucial hygric properties are strongly related to the humidity in the pores of the materials [20, 21, 27], hence, they are processed as functions related to humidity in the modified model. In the modified two-layer model, the humidity distribution can be solved more reasonably by assigning dynamic material properties layer by layer.

In the above improved formulas, ξ and δ_p are transformed as a and b_m values, respectively. The modified two-layer model still describes dynamic hygric properties based on the moisture-dependent a and b_m values. The relevant formulas are presented in Eqs. (10–14).

The RH in any layer is calculated as

$$RH_{p_{vb,i}} = \frac{p_{vb,i}}{p_{sat,i}(T_b)} \quad (10)$$

An empirical formula proposed to account for the moisture-dependent b_m of every layer is given as

$$b_{m,i} = \left\{ \ln \left[(100RH_{p_{vb,i}} + 1)^{k_1} / (1 - RH_{p_{vb,i}})^{k_2} \right] + k_3 \times 10^{-42} \times e^{100RH_{p_{vb,i}}} \right\} \times 10^{-7} \quad (11)$$

According to Eqs. (2), (4) and (5), the material resistance of every layer is obtained as

$$R_i = a \cdot \sqrt{\frac{t_{p,i}}{\pi}} \cdot \frac{1}{b_{m,i}} \quad (12)$$

The average RH in the entire moisture buffering layer of the material can be written as

$$RH_{\overline{p_{vb}}} = \frac{RH_{p_{vb,1}} \times R_1 + RH_{p_{vb,2}} \times R_2}{R_1 + R_2} \quad (13)$$

Then, another empirical formula proposed to account for the moisture-dependent a of the entire moisture buffering layer is given as

$$a = s_1 + s_2 \times RH_{\overline{p_{vb}}}^{s_3} \quad (14)$$

where $RH_{p_{vb,i}}$ (-) is the RH in the i -th moisture buffering layer, $RH_{\overline{p_{vb}}}$ is the average RH in the whole material, R_i ((Pa·m²·s)/kg) is the moisture transfer resistance of the i -th moisture buffering layer, $k_1/k_2/k_3$ and $s_1/s_2/s_3$ are the coefficients related to the a and b_m empirical formulas. These coefficients are extracted from tests via the inverse solution, see subsection 2.4.

Eqs. (11) and (14) are the two empirical formulas used to describe the relationship between a/b_m and humidity, respectively. They are inspired by the Feng equation (a fitting equation for the sorption isotherm) [28] and the WVPC equation (a fitting equation for the water vapor permeability) [29]. Many pre-trial calculations revealed a good fit between these two empirical formulas for different materials with diverse hygric properties. The humidity in any layer and in the whole layer of the material is expressed by Eqs. (10), (12) and (13).

The existing one-layer model is a simplified form of the two-layer model, and assumes that only a surface layer of the material contributes to the moisture buffering procedure. This is different from that shown in Fig. 2 and Eq. (2) since no moisture transfer to and from $p_{vb,2}$ exist.

Four types of EMPD models were used for the moisture buffering calculation in this study to observe the contributions of the two layers and variable properties: 1) a one-layer model with constant properties, 2) a one-layer model with variable properties, 3) a two-layer model with constant properties, 4) a two-layer model with variable properties.

2.2 Test Method

A novel test based on realistic moisture scenarios in buildings is proposed; it is defined as the dynamic moisture test in this study. This test method aims to identify the moisture performance of one material or the moisture buffering performance of one whole room, as tested in a sealed box or the target room. Two simplified steps in one humidity period are involved in test conditions, and they include a constant-rate moisture production step with limited ventilation and a constant-rate ventilation step with limited moisture production. In this study, both experimental measurements and numerical simulations are performed on the tests of two typical building materials. The measurements are designed to validate the reliability of the modified EMPD model under some given conditions. The simulations performed in WUFI-Plus—a well-known HAM model-based tool—are used for the sensitivity analysis and room performance tests under diverse real conditions. The time step is 1 min, and the simulations are one-dimensional. This combination is believed to be beneficial for verifying the proposed EMPD models.

2.2.1 Overview of Standard Test

The test condition of the dynamic moisture test is different from that of the MBV test standardized by ISO 24353 [10]. The humidity scheme is designed based on typical RH variations in office buildings, which include the humidification process mainly by moisture source first and then the decay process mainly by ventilation. For flexible and intuitive operation, the standard condition of the box test simplifies to no ventilation in the first stage and no moisture production in the second stage (Fig. 3). Although no simplification occurs in the real environment, it makes sense because the effect of ventilation (the first term on the right side) and moisture production (the second term on the right side) on the zone humidity change (the term on the left side) are equivalent, as indicated in Eq. (1).

Fig. 3. RH scheme of the standard test in one period

For box tests, the T and RH of the preconditioning environment of the materials, the initial zone, and the ventilation rate are identically selected based on the target environment (e.g., 18 °C and 55% RH, 27 °C and 30% RH). For the room tests, tests should be conducted under normal weather conditions.

In the moisture production stage, the amount of moisture production should be determined based on the net indoor moisture increase gain (the moisture dissipation rate from the source minus the moisture exchange caused by ventilation) of the target application environment and the moisture performance of the test material. Excessive moisture dissipation will lead to internal condensation because of the poor moisture performance of the material; hence, the test should be adjusted to a smaller moisture dissipation rate. Based on numerous calculations, an approximate average 20% increase in indoor RH can be obtained for materials with poor to superior moisture performance when 2–12 g/(h·m³) of the moisture rate is produced in a standard box case with 1.1 m²/m³ surface to volume ratio.

The air change rate should be within a reasonable range during the ventilation stage. When the rate is too high, the indoor RH rapidly drops at the beginning of the ventilation step. In this case, it is very difficult to identify the effect of the moisture performance of the material on the indoor RH. When the rate is too small, there is no sufficient monitoring of the desorption process of the material. According to several trial calculations, the recommended value for the air change rate is 0.1-1.

The test cycles (usually 1-4 times) can be selected based on the test indoor RH range which need to be larger than the acceptable RH range of the target environment (Fig. 4).

Fig. 4. Relationship between the number of test cycles and indoor RH

2.2.2 Box Tests

A special developed box was established in a well-controlled climate chamber to perform box measurements (Fig. 5). This box is made of stainless steel, being non-hygroscopic and highly conductive, and it measures 1.5 m long by 0.81 m wide by 0.926 m high, with a net volume of 1.1 m³ and a maximum sample test area of 1.215 m².

Fig. 5. Box

All samples were processed to a rectangular shape with a thickness similar to the intended practical application. They were then sealed on all surfaces except for the top side with metal tape. Before testing, all samples were preconditioned to be in equilibrium with the set T_i & RH. They were then placed on sample holders at the bottom of the box. In this study, gypsum board and cement mortar were selected for testing.

During the test, the air temperature of the box was maintained by the chamber air through ventilation and heat conduction. In the moisture production stage, water vapor is produced by energizing the electric heating wire imbedding in a water tank in the box, and the amount of moisture production is achieved by controlling the degree of coincidence between the actual water weight measured by the electronic scale and its set value. In the ventilation stage, the ventilation is realized by the cooperation of the gas flow meter, pump, and surge tank, and the air change rate is achieved by controlling the degree of coincidence between the actual ventilation volume

measured by the air flow meter and its set value.

The amount of moisture production, the T_i & RH of the zone, the T & RH of the ventilation, the ventilation volume and the airflow velocity through the material surface are continuously recorded by using the calibrated instruments summarized in Table 1 during the tests. The airflow sensors are placed at a distance of approximately 2.5 cm to the sample surface. According to the airflow velocity and Lewis formula, β_i can be obtained as

$$\beta_i = \frac{6+4 \times u}{\rho \cdot c_p \cdot R_v \cdot T_i} \quad (15)$$

where c_p (J/(kg·K)) is the heat capacity of air at constant pressure, ρ (kg/m³) is the air density, u (m/s) is the airflow velocity above the sample.

Table 1. List of instruments for the box tests

Equipment	Measurement	Measuring range	Test accuracy	Manufacture
Electronic scale	Moisture production	0–6200 g	0.01 g	Japanese UW6200H
T & RH sensor	T & RH	T: -20–80 °C	T: ±0.2 °C	Finnish VASALA
		RH: 0–100%	RH: ±1.8%	
Airflow meter	Ventilation volume	0–30 SLPM	±(1.5+0.2FS)%	Chinese MEMS-MF4008-30
Airflow velocity sensor	Airflow velocity	0–10 m/s	3%	Austrian E+E Elektronik EE605

Box tests were conducted via measurements and simulations. First, the standard box cases were performed on gypsum board and cement mortar respectively to extract the input parameters of the EMPD model. Then, some prediction cases under diverse conditions were designed for the model validation and sensitivity analysis. All the tests were conducted at a constant temperature of 27 °C.

In the experimental measurements, the information of the standard box cases and prediction cases a–c are as follows:

- Standard box cases: Preconditioning condition = 27 °C and 55% RH; moisture production rate = 5 g/h; ventilation rate = 1 ACH; surface to volume ratio = 1.1 m²/m³; 1 time humidity scheme cycle.
- Case a: For only the gypsum board, surface to volume ratio = 0.7 m²/m³; moisture production rate = 3.5 g/h; other conditions are the same as the standard box case.
- Case b: For only the cement mortar, moisture production rate = 3.5 g/h; ventilation rate = 0.85 ACH; other conditions are the same as the standard box case.
- Case c: Gypsum board and cement mortar together, ventilation rate = 0.8 ACH; other conditions are the same as the standard box case.

In the numerical simulations, the model was built according to the aforementioned box and samples. Standard box tests were performed using two methods to focus on the effect of the test method. Round robin prediction cases 1–11 were classified into five categories to analyze the potential uncertain factors including initial RH (Cases 1, 4, and 5), surface to volume ratio (Cases 2, 3, and 6), the amount of moisture production (Cases 1, 6, and 7), quantity of ventilation (Cases 6, 8, and 9), and the moisture schedule (Cases 6, 10, and 11). Only one influence factor was modified in every category to diverse values in different cases; the other parameters of the boundary conditions were kept the same. The information of the standard box cases and prediction cases 1–11 is provided below.

- Standard box cases
 - 1) Test method 1: Preconditioning condition = 27 °C and 30% RH; moisture production rate = 12 g/h; ventilation rate = 0.5 ACH; 1 time humidity scheme cycle.
 - 2) Test method 2: Preconditioning conditions = 27 °C and 30% RH; moisture production rate = 5 g/h; ventilation rate = 0.1 ACH; 4 times humidity scheme cycles.

- Cases 1–11: For gypsum board and cement mortar, respectively; other conditions are listed in Table 2.

Table 2. Simulation conditions of cases 1–11

Simulation cases	Surface to volume ratio (m ² /m ³)	Initial RH (%RH)	Moisture production (g/h)	Ventilation (1/h)	Humidity period (h) / Decay period (h) / Cycling time (h)
Case 1	1.159	30	5	0.1	8/16/24
Case 2	2.209	30	8	0.1	8/16/24
Case 3	3.889	30	8	0.1	8/16/24
Case 4	1.159	45	5	0.1	8/16/24
Case 5	1.159	60	5	0.1	8/16/24
Case 6	1.159	30	8	0.1	8/16/24
Case 7	1.159	30	10	0.1	8/16/24
Case 8	1.159	30	8	1	8/16/24
Case 9	1.159	30	8	2	8/16/24
Case 10	1.159	30	8	0.1	2/4/6 (4 times)
Case 11	1.159	30	8	0.1	6/6/12 (2 times)

Note: The color background highlights the changed parameters, and the three cases with the same color background can be compared in terms of the effect of a single factor.

2.2.3 Room Tests

Simulations were performed for the room tests which are used to evaluate the moisture buffering of the entire room in an actual environment. The room model was built following a typical office, which was a small cube space, with a net volume of 27 m³ and a height of 3 m. The walls (3×3×4 m²) were all finished with mortar cement, and the ceiling (3×3 m²) was covered by gypsum board. The room contained one exterior wall facing south and other interior walls adjacent to rooms and corridors. There was a vapor barrier between the hygroscopic materials and the main structures of the room. Owing to the controlled indoor temperature, the hygroscopic materials are assumed to be adiabatic. In this situation, the concrete form of the main structures is not relevant for the outcomes. First, a one-day simulated room case was conducted. The initial indoor condition of the room and the materials were preconditioned at 27 °C and 55% RH, and T_i was maintained at 27 °C during the test. Other boundary conditions from a reasonable assumption based on the typical environment are shown in Fig. 6, which include the T and RH of outdoor air, moisture production, and air change rate.

Fig. 6. Some boundary conditions of the room test

A 60-day simulated room case was conducted to further observe the accuracy of the models for long-term tests. The test period was from January 1st to March 1st. The meteorological data of Guangzhou in China was selected instead of the T and RH of outdoor air, as indicated in Fig. 6. The other parameters of the boundary and initial conditions are the same as above.

2.3 Materials

Two typical building materials—gypsum board and cement mortar—with diverse hygric properties were studied. The materials for measurements were purchased from the Chinese local market, and those for the simulations were selected from the WUFI-plus database. Fig. 7 and Table 3 present the physical properties of the materials. Both δ_p and w vary with RH. The sorption isotherms are the average of the adsorption and desorption curves, excluding capillary hysteresis. The samples have a thickness lower than d_{EMPD} during some test conditions (55%–100% RH) for the gypsum board and it is wider for the cement mortar.

Fig. 7. Some hygric properties of gypsum board and cement mortar

Table 3. Physical properties of gypsum board and cement mortar

Material	Density	Porosity	Specific heat capacity	Thermal conductivity	Thickness	MBV [75%–33%]
	kg/m^3	-	$\text{J}/(\text{kg} \cdot \text{K})$	$\text{W}/(\text{m} \cdot \text{K})$	cm	$\text{g}/(\text{m}^2 \cdot \%RH)$
Gypsum board (For measurements)	583	-	-	-	1.22	-
Gypsum board (For simulations)	732	0.72	1384	0.1925	1.23	1.248
Cement mortar (For measurements)	1913	-	-	-	2.22	-
Cement mortar (For simulations)	1910	0.25	850	0.8	2.22	1.343

2.4 Fitting Strategy and Data Analysis

As a traditional method, the forward solution is extensively applied in numerical calculation via an onward flow from input to output. However, considering the indetermination of the distribution depth of the two layers and the uncertainty of the material properties, the inverse solution is strongly recommended for solving the questions with some unknown and indefinite parameters via a reversed flow from output to input. Subsequently, inverse parameters are extracted using the inverse solution to be further input for other predictions.

In the inverse solution, the measured physical parameter Π_i was selected as the criterion. The least square method—as an optimization algorithm—was adopted to fit the EMPD model predictions with the measured results.

$$f = \sum_{i=1}^n [\Pi_i^{EMPD} - \Pi_i^{measured}]^2 \quad (16)$$

The fitting is done by taking the inverse parameters combination. The optimal inverse parameters combination cannot be extracted until f reaches its minimum value, and they include a (or via $s_1/s_2/s_3$) and b_m (or via $k_1/k_2/k_3$) in all EMPD models and the extra $t_{p,2}$ in the two-layer EMPD models. Several types of measured physical parameters

Π_t including p_{vi} , RH, G_{buf} and MG_{buf} can be selected as the target fitting parameters for the inverse solution. MG_{buf} is the accumulative quantity of G_{buf} , and p_{vi} is linearly related to RH in the constant-temperature state. Therefore, G_{buf} and MG_{buf} are essentially the same, and p_{vi} and RH are essentially the same. However, continuous testing of MG_{buf} is difficult to measure accurately and requires a high-precision electronic scale, especially when the moisture absorption is small and the test sample is heavier. Furthermore, the MG_{buf} in the room tests is unknown. Thus, p_{vi} or RH is still recommended as a target-fitting parameter in terms of availability and accuracy. In this study, p_{vi} was selected as the fitting parameter, and it is also the most important parameter for determining the interior conditions.

The goodness of fit between the two sets of data was evaluated using the following two indices:

$$NRMSE = 1 - \frac{\|\Pi_t^{EMPD} - \Pi_t^{measured}\|}{\left\|\frac{\Pi_t^{EMPD} - \Pi_t^{measured}}{n}\right\|}, \quad (17)$$

$$NMSE = 1 - \frac{\|\Pi_t^{EMPD} - \Pi_t^{measured}\|^2}{\left\|\frac{\Pi_t^{EMPD} - \Pi_t^{measured}}{n}\right\|^2}. \quad (18)$$

Both NRMSE and NMSE costs vary between -Inf (bad fit) and 1 (perfect fit).

The prediction performances of the EMPD models based on the key derived parameters were evaluated using the following four indices:

$$e_i = \Pi_t^{EMPD} - \Pi_t^{measured} \quad (19)$$

where e_i expresses the absolute deviation between every predicted value and its corresponding actual value.

$$\gamma = \frac{\sum_{i=1}^n |\Pi_t^{EMPD} - \Pi_t^{measured}|}{n} \quad (20)$$

where γ expresses the average relative deviation between the set of predicted values and the corresponding set of actual values.

$$\chi = \frac{\gamma}{\max(\Pi_1^{measured}, \Pi_2^{measured}, \dots, \Pi_n^{measured}) - \min(\Pi_1^{measured}, \Pi_2^{measured}, \dots, \Pi_n^{measured})} \times 100\% \quad (21)$$

where χ expresses the percentage of γ in the fluctuation range of the actual values.

$$R^2 = 1 - \frac{\sum_{i=1}^n (\Pi_t^{EMPD} - \Pi_t^{measured})^2}{\sum_{i=1}^n (\Pi_t^{measured} - \Pi_t^{measured})^2} \quad (22)$$

R^2 is an overall index for the precision evaluation level, and it varies between 0 (bad accuracy) and 1 (good accuracy).

3 Results and Discussion

This section aims to analyze and discuss five questions. The first deals with the advantages of the modified two-layer EMPD model over the existing EMPD models. The second is whether the two test methods of the standard box tests affect the extracted inverse parameters. The third is to explore the reliability of the EMPD models at the level of experimental measurements. The fourth focuses on the effectiveness and feasibility of inverse solution to obtain a more accurate prediction compared to the traditional forward calculation. The fifth is whether the inversed EMPD model parameters of the test material obtained by the standard box test can precisely predict the environment under different boundary conditions. To solve these questions, a series of experimental measurements and numerical simulations were conducted on gypsum board and cement mortar, respectively. Then, the inverse calculations of the two types of standard box tests were performed using four types of EMPD models. The fitting accuracies were compared and discussed. Subsequently, agreements between the prediction of the EMPD models and measured data were analyzed. After that, round-robin cases under various variable boundary conditions were

predicted for the sensitivity analysis of different models based on the derived parameters from the standard box test. Ultimately, the entire inverse approach of the EMPD models was verified by short- and long-term room tests, and its improvement effect was revealed by comparing the results with those of the traditional forward method in the problem statement. In the numerical simulations, the results of the HAM model were used as a reference benchmark instead of the measured results.

3.1 Inverse Solution of the EMPD Models

3.1.1 Fitting Calculation

$t_{p,1}$ can be assigned a rough value in advance, as the surface moisture resistance is related to the combination of $t_{p,1}$ and a -value. Therefore, $t_{p,1}$ was set to 86400 s (24 h). β_1 was set to 2.56×10^{-8} kg/(Pa·m²·s) in the simulation cases, and was set based on the actual airflow velocity in the measurement cases. Then, we performed fitting of the two sets of p_{vi} between the EMPD models results and the measured results/HAM model results using the least square method based on standard box tests for the two test methods. After the fitting process, the comparisons of RH are presented in Fig. 8.

(3) Gypsum board—Test method 1 (For simulations)

(4) Gypsum board—Test method 2 (For simulations)

(5) Cement mortar—Test method 1 (For simulations)

(6) Cement mortar—Test method 2 (For simulations)

Fig. 8. RH fitting results compared to the measured data/HAM model results

As shown in Fig. 8(1–2), the RH curves show a fluctuating upward trend at the moisture production stage for the experimental measurements, and this trend originates from the temperature fluctuation caused by the discontinuous heat production from the humidifier. For both the gypsum board and cement mortar cases, the results of the two-layer variable properties EMPD model indicate better goodness of fit with the measured data, compared with those of the other EMPD models.

The fitting results of the numerical simulations with a wide range of RH variations are shown in Figs. 8(3–6). For the gypsum board cases, the variable properties EMPD models show better performances than those of the constant properties EMPD models. Fig. 8(4) indicates that the increasing range of indoor RH calculated by the HAM model on a later day is gradually reduced compared to the previous day. The reason for the smaller indoor RH increase during high humidity is attributed to the moisture adsorption performance of the materials that becomes stronger with increasing humidity. However, it cannot be expressed in models that treat properties as constant values. For the cement mortar cases, the different scenario occurs wherein the two-layer EMPD models show better performance than the one-layer models. In comparison to the curves of the HAM model, at the start of two steps, those of the one-layer models increase and decline more rapidly, respectively, and then continue smoothly. This confirms that the one-layer EMPD models are limited in some scenarios. That is, it may be acceptable to samples with thickness less than their d_{EMPD} , but not for others. For the daily moisture fluctuation, the deep layer may absorb the moisture from the surface layer at all time.

In summary, whether via experimental measurements or numerical simulations, the curves of the modified two-layer EMPD model (two-layer variable properties EMPD model) are highly identical with those of the measured data/HAM model in all cases, however, this is not the case for the curves of other EMPD models.

Fig. 9 shows the NRMSE of the inverse calculations for the numerical simulations. The NMSE aligns with the NRMSE.

Fig. 9. RH fitting precision of four types of EMPD models (For simulations)

Fig. 9 indicates that the two-layer variable properties model always has the highest precision in every case. Figs. 8 and 9 are very good illustrations of what is gained by the different improvements for the numerical simulations. For the gypsum board cases, the variable properties have the largest impact, and the impact of more layers is smaller. For the cement mortar cases, the two layers have the most effect, and the effect of the variable properties is smaller. Moreover, it can be found that the test methods have no major impact on the fitting precision for the two-layer variable EMPD model.

3.1.2 Inverse Parameters

The inverse parameters were extracted according to these fitting calculations. As mentioned in Eqs. (11) and (14), the a and b_m curves of the variable properties EMPD models for the simulated standard box cases are shown in Fig. 10, and the b_m curves resulting from the constant properties are compared.

Fig. 10. Dynamic hygric properties of the materials for simulations with humidity variation

According to Fig. 10, in the numerical simulations, the a and b_m curves of the two-layer variable properties model obtained by the two test methods for both materials cases are very close in whole, but not for those of the one-layer variable properties model. In the gypsum board cases, there is a relatively small deviation for the a and b_m curves of the one-layer variable properties model when using the two test methods. Moreover, the tendency of the b_m curves from the one-layer variable properties model and the two-layer variable properties model is similar. It is confirmed that in the gypsum board cases, the one-layer variable properties model is available for rough results. Nevertheless, the a and b_m curves of the one-layer variable properties model via the two test methods are not consistent in the cement mortar cases. The inverse parameters are distorted because of overfitting, and they possibly result in the prediction results being unreliable. Thus, there is a certain deviation in b_m curves obtained by any EMPD model and by the original hygric properties, particularly in the cement mortar cases. Hence, it is essential to perform the prediction cases to verify the effectiveness of this approach.

3.2 Prediction and Verification

3.2.1 Experimental Validation

The inverse parameters extracted from the measured standard box tests were used to predict the indoor RH in cases a–c with the four types of EMPD models, as shown in Fig. 11. The measured data was used as the reference benchmark.

Fig. 11. Precision of prediction for four types of EMPD models in experimental measurements

According to Fig. 11, the average γ and average χ of the two-layer variable EMPD model are approximately 0.5% and 1.5%, respectively, and R^2 approaches 1. In contrast, the prediction accuracy of the other EMPD models is weaker by varying degrees. The proposed EMPD model and the related inverse approach with the standard box test are verified through measurements of the test cases.

3.2.2 Sensitivity analysis

The presented modified two-layer EMPD model agreed with the results of the HAM model for two materials in the fitting calculations of the numerical simulations, as indicated in subsection 3.1. However, the standard condition is only one type of simplified typical boundary condition. In an actual environment, various factors change intricately. Thus, it is essential to know whether the inverse parameters obtained based on standard conditions can be effectively and critically utilized in predicting other boundary conditions.

We used the inverse parameters extracted by the simulated standard box tests of the first test method to predict the moisture buffering of cases 1–11 with various boundary conditions, and observed the sensitivity of the modified EMPD model. The four types of EMPD models were compared, and the HAM model served as the reference benchmark. Fig. 12 shows a comparison of the prediction accuracy of indoor RH based on different EMPD models.

Fig. 12. Precision of prediction for four types of EMPD models in the sensitivity analysis

According to Fig. 12, in the gypsum board cases, the one-layer variable properties EMPD model and the two-layer variable properties EMPD model have higher R^2 and lower γ and χ . In the cement mortar cases, the two-layer variable properties EMPD model and the two-layer constant properties EMPD model have higher R^2 , however, the γ and χ of the two-layer constant properties EMPD model are high. Thus, only the two-layer variable properties EMPD model can accurately predict all cases for both materials. The R^2 of RH predicted by the two-layer variable properties EMPD model exceeds 0.98, and the average γ and average χ are only 0.6% and 1.8%, respectively. However, the precision of other EMPD models is far less than that of the two-layer variable properties EMPD models. Meanwhile, it is concluded that the prediction precision will be higher when the boundary conditions of the prediction conditions correspond to those of the standard condition. In summary, the modified EMPD model compensates for the defects and weaknesses of the existing models, moreover and can be applied to predict various variable environments.

3.2.3 Predicting room cases

The advantages of the modified EMPD model and its integrated inverse approach are further proved by predicting the indoor RH and MG_{buf} of the room cases using the inverse parameters extracted by the simulated standard box tests of the first test method. The prediction results of the four types of EMPD models were compared, and the simulation results of the HAM model served as the reference benchmark.

First, we refer to the problem statement in the Introduction. Compared with the results obtained by the existing traditional calculation, the improvement effect of the proposed approach can be proved. Fig. 13 shows the comparison curves between the predicted results of the four types of EMPD models and the simulation results of the HAM model for the one-day room simulated case.

Fig. 13. Prediction of RH and MG_{buf} of the one-day simulated room case based on the inverse parameters. According to Fig. 13, the two RH curves between the HAM model and the modified two-layer EMPD model are similar. However, the RH curves of other types of EMPD models deviate to various degrees. The same conclusion can be drawn as in the previous section: Models with one-layer or constant properties cannot predict the exact course of the RH. It appears that the estimation of the modified two-layer EMPD model is reliable. Compared to Fig. 1, an obvious improvement is observed in the proposed calculation. This reveals the important roles of treating the hygric properties of materials as dynamic values and obtaining reasonable moisture transfer resistance distributions via the inverse solution.

Fig 14 shows comparison curves between the predicted results of the four types of EMPD models and the simulation results of the HAM model for the long-term simulated room case.

Fig. 14. Prediction of RH and MG_{buf} of the long-term simulated room case based on inverse parameters
The precision of the two-layer variable properties EMPD model is considerably better than that of the other EMPD models. Hence, the reliability of the two-layer variable properties EMPD model for long-term prediction is further verified.

4 Conclusion

It is a feasible and profitable approach to solve humidity-related problems in buildings utilizing the moisture buffering of materials. Moreover, the reliable evaluation of the moisture performance of the materials is crucial for the correct moisture design of new buildings or the remediation of existing defective buildings. Nevertheless, there is a wide gap in engineering practice because of the limitations of the current evaluation methods. Therefore, this paper presented an integrated set of a fast and simple approach to identify and predict the moisture performance of building materials to address this issue. The main contributions and conclusions of this study are listed below.

- (1) The prediction for the moisture buffering of materials under real moisture fluctuations in civil buildings may be inaccurate when using the forward solution of the existing EMPD models.
- (2) A modified two-layer EMPD model is proposed to consider both dynamic material hygric properties and reasonable moisture transfer resistance distributions because the existing EMPD models have limitations on specific occasions.
- (3) A dynamic moisture test is proposed to identify the moisture performance of one material or the moisture buffering performance of a whole room based on realistic moisture scenarios in buildings.
- (4) The inverse solution has obvious advantages over the traditional forward solution in terms of solving these questions with some unknown and indefinite parameters.
- (5) The two methods of the standard box test are valid for obtaining and capturing the extracted parameters via the

inverse solution.

(6) Both moisture-dependent hygric properties of the materials and deep-layer moisture transfer resistance play significant roles in the EMPD models.

(7) The modified two-layer EMPD model yields reliable RH prediction results for various broader conditions by utilizing the inverse parameters obtained from the standard box test.

(8) For the considered cases, the modified two-layer EMPD model performed better than the existing EMPD models. So it is recommended to implement it as such in the currently available simulation softwares (Energyplus, WUFI, Delphin, ...).

These conclusions lead to the following suggestions for further research:

(1) As isothermal models, the current EMPD models have some limitations. This is acceptable in some circumstances with small fluctuations in indoor temperature. However, developing a non-isothermal EMPD model is valuable for various conditions.

(2) The prediction accuracy is slightly weaker when there is an obvious difference between the standard condition and prediction conditions. Thus, an effective conversion method for inverse parameters will be helpful to obtain more reliable prediction results.

(3) In some cases, hygroscopic materials may have surface coatings or they may consist of different material layers in practical applications. Therefore, it is necessary to propose an efficient test and prediction method for more complex cases.

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Declaration of Competing Interest

The authors declare no conflicts of interest.

CRediT authorship contribution statement

Yumeng Cui: Conceptualization, methodology, software, formal analysis, data curation, validation, and writing of the original draft. **Yufeng Zhang:** Conceptualization, supervision, project administration, funding acquisition.

Hans Janssen: Writing (Review & Editing), Supervision

Nomenclature

Symbol	Unit	Meaning
p_{vi}	Pa	Partial vapor pressure of indoor air
p_{ve}	Pa	Partial vapor pressure of outdoor air
$p_{vb,i}$	Pa	Average vapor pressure in the center of the i-th moisture buffering layer
N	1/h	Air change rate per hour
V	m^3	Zone volume

A	m ²	Material area
R _v	J/(kg·K)	(= 462) Gas constant of water vapor
c _p	J/(kg·K)	Heat capacity of air at constant pressure
ρ	kg/m ³	Air density
u	m/s	Airflow velocity above sample
T _i	K	Indoor air temperature
T	K	Temperature
p _{sat}	Pa	Saturated vapor pressure
T _b	K	Average temperature of the materials
β _i	s/m=kg/(Pa·m ² ·s)	Convective surface film coefficient for vapor transfer
G _{vp}	kg/s	Indoor moisture production
G _{buf,m}	kg/s	Moisture exchange between indoor air and m-th material
MG _{buf}	kg	Accumulative moisture ab-/desorption amount of materials
h	s	Time step
d _{b,i}	m	Thickness of i-th moisture buffering layer
d _{EMPD,i}	m	Effective moisture penetration thickness associated with the cycling time of moisture fluctuations
t	min	Time
a	-	Comprehensive coefficient to express the proportion between d _{b,i} of the i-th layer and its corresponding d _{EMPD}
s ₁ ,s ₂ ,s ₃	-	Coefficients associated with the a empirical formula
b _m	kg/(m ² ·Pa·s ^{0.5})	Moisture effusivity
k ₁ ,k ₂ ,k ₃	-	Coefficients associated with the b _m empirical formula
t _{p,i}	s	Coefficient associated with the cycling time in the i-th layer
RH _{pvb,i}	%RH	Relative humidity of air in the pore of the i-th moisture buffering layer
RH _{$\overline{pvb}$}	%RH	Average relative humidity of air in the pore of the whole material
R _i	(Pa·m ² ·s) / kg	Moisture transfer resistance of the i-th moisture buffering layer
w	kg/m ³	Moisture content
δ _p	kg/(m·s·Pa)	Vapor permeability
ζ	kg/m ³	Vapor capacity
RH	%RH	Relative humidity
NMSE		Normalized mean squared error
NRMSE		Normalized root mean squared error
EC		Effective capacitance model
EMPD		Effective penetration depth model

HAM		Heat, air and moisture transfer model
e_i		Absolute deviation between every predicted value and its corresponding actual value
γ		Average relative deviation between the set of predicted values and their corresponding set of actual values.
χ		Percentage of γ in the fluctuation range of actual values
R^2	-	Coefficient of determination
Π_i^{measured}		A physical parameter calculated by HAM model or measured from test for fitting
Π_i^{EMPD}		A physical parameter calculated by the EMPD model for fitting

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