QUALITATIVE AND QUANTITATIVE ASSESSMENT OF INTERIOR MOISTURE BUFFERING

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ABSTRACT

The significance of interior humidity in attaining sustainable, durable, healthy and comfortable buildings is increasingly recognised. Any interior humidity evaluation requires a qualitative and/or quantitative assessment of interior moisture buffering. This paper introduces the production-adaptive characterisation of the moisture buffer potential of single elements and corroborates their superposition toward a room-enclosure moisture buffer potential. It is verified that this allows qualitative comparison of enclosures in relation to interior moisture buffering. It is moreover demonstrated that it forms an alternative basis for quantitative evaluation of interior moisture buffering by the effective moisture penetration depth and effective capacitance models. The presented methodology uses simple and fast measurements only, and can also be applied to multimaterial and/or multidimensional interior elements. The in-situ determination of this buffer potential is presented in a complementary paper.

INTRODUCTION

The influences of interior humidity on the performance of building zones, building parts and building occupants are strongly multifaceted and highly interrelated. Interior humidity significantly affects the energy performance of building zones, via latent cooling loads and ventilation heating loads. Interior humidity furthermore considerably affects the appearance and stability of building parts, via biological activities of fungi and moulds. Finally, interior humidity substantially affects the health and comfort of building occupants. Development of sustainable, durable, healthy and comfortable buildings hence requires the assessment of interior humidities.

Interior humidities are governed by interior moisture sources, moisture transfer by ventilation and moisture exchange with the room enclosure. The latter occurs in all enclosure elements, both in interior finishes and interior objects (furniture, carpets, drapes, books, …). Several authors stress the importance of such interior moisture buffering in the interior humidity evolution, supported by measurements and simulations (e.g. Simonson et al., 2004a, 2004b). Design and development of sustainable, durable, healthy and comfortable buildings thus necessitate quantitative and/or qualitative assessment of interior moisture buffering.

Qualitative assessment of interior moisture buffering requires a dependable, single-valued characterisation of the moisture buffer potential (MBP) of a room enclosure, allowing comparison of different enclosures. Recently, different protocols to characterise the MBP of single elements have been proposed (JIS A1470-1, 2002; ISO/DIS 24353, 2006; Delgado et al., 2006; Rode et al., 2007). Their superposition to the enclosure level has been suggested too (Ramos and de Freitas., 2006). At present though, these suggested single-element MBP characterisations are not dependable for the wide variety of moisture production schemes in practice. Moreover, their superposition to a room-enclosure MBP remains uncorroborated. Enhancement to the production-adaptive single-element MBP, and corroboration of the superposition to room-enclosure MBP form the first aims of the article.

Quantitative assessment of interior moisture buffering requires simulations of the interior humidity, including the moisture exchange with interior elements. Such simulations are very complicated though: while currently being applied for single rooms with simple finishes, full simulations of the moisture storage and transport in interior elements remain unrealistic. This would require a detailed knowledge of the geometry and material properties of all interior elements – info that is generally unavailable –, and it would result in unacceptable calculation times. Simplified methods are thus usually preferred with the ‘effective moisture penetration depth’ and ‘effective capacitance’ models as common approaches. This article indicates though that their reliance on the moisture penetration depth concept implies the time-consuming determination of moisture capacities and permeabilities of the materials involved and hampers its application to multimaterial and/or multidimensional elements. Establishing that the presented production-adaptive room-enclosure MBP – which is simple and fast to measure, and applicable to both finishes and objects – can be used to quantify interior moisture buffering forms the second goal of this paper.

Initially, the effective moisture penetration depth and effective capacitance models are reiterated, with emphasis on their key flaws. The second and third sections introduce the qualitative and quantitative assessment of moisture buffering: the single-element and room-enclosure MBP characterisation and its use for quantification purposes.

SIMPLIFIED MODELS FOR INTERIOR MOISTURE BUFFERING

To predict the interior humidity evolution, the moisture balance equation for the room air is to be solved. Most building energy and hygrothermal models assume the room air well mixed, such that temperature, humidity and pressure are equal over the entire building zone. Assuming such ideal convective mixing and no surface condensation, supposing air exchange with the exterior environment only and neglecting the temperature dependency of the air density, the moisture balance for the room air can be written as:

$$\frac{V}{R_v T_i}\cdot\frac{\partial p_{vi}}{\partial t} = (p_{ve} - p_{vi})\frac{nV}{3600 R_v T_i} + G_{vp} - G_{buf} \qquad (1)$$

with $V/(R_vT_i)$ (m^3.kg/J) the moisture capacity of the room air, $p_{vi/e}$ (Pa) the partial vapour pressure of interior/exterior air, n (1/h) the air change rate per hour, V the volume of the zone (m^3), R_v (J/kg/K) the gas constant of water vapour, T_i (K) the interior air temperature, G_{vp} (kg/s) the interior vapour production, and G_{buf} (kg/s) the moisture exchange between room air and room enclosure. The latter is governed by the vapour transfer and storage in the various elements of the enclosure. While full numerical simulation of the moisture transport and storage in room air and enclosure can be achieved for simple cases, general application remains difficult, since the complexity of multiple, multimaterial and/or multidimensional interior elements results in a far too large computational load. Furthermore, the material properties needed similarly yield a too high experimental load. Moisture exchange between room air and room enclosure is thus commonly simplified, for which two models prevail.

The first model is best known as the 'effective moisture penetration depth' (EMPD) model (Kerestecioglu, 1999; Cunningham, 2003). Its key assumption is that only a thin surface layer of the interior element's material contributes to the moisture buffering. Moisture transport and storage in this buffer layer is modelled with a single control-volume equation. For a single buffer layer with exposed surface A (m^2):

$$G_{buf} = A\cdot\frac{p_{vi} - p_{vb}}{\frac{1}{\beta} + \frac{d_b}{2.\delta_p}} = A\cdot\xi\cdot d_b\,\frac{\partial}{\partial t}\left(\frac{p_{vb}}{p_{v,sat}(\theta_b)}\right) \qquad (2)$$

with p_{vb} (Pa) and θ_b (°C) the single vapour pressure and temperature in the buffer layer with thickness d_b (m) and δ_p (s) and ξ (kg/m^3) vapour permeability and moisture capacity of the buffering layer. The thickness d_b of the buffering layer is related to the moisture penetration depth d_p (m), which in turn depends on the period of the humidity variations in the room:

$$d_b = a\cdot d_p = a\cdot\sqrt{\frac{t_p\cdot\delta\cdot p_{v,sat}(\theta_b)}{\pi\cdot\xi}} \quad a=\min(d/d_p,1) \qquad (3)$$

with t_p (s) the period and a (-) a thickness adjustment, as the actual material thickness d (m) may be smaller than the moisture penetration depth d_p.

The main disadvantage of the EMPD model is its reliance on the moisture penetration depth of the material. Until now this property can only be derived from the moisture capacity and vapour permeability, measurements which are time and labour intensive. Furthermore, the moisture penetration depth is not well-defined for interior finishes with multiple material layers. The most important limitation however is that it is primarily developed for interior finishes (one-dimensional building walls), while only with great difficulty applicable to interior objects (carpets, drapes, furnishing or other multidimensional objects), which most often form the main buffer capacity of the room enclosure. The EMPD method moreover necessitates a solution of Eq. (2) for each interior element, rapidly increasing the computational load when realistic enclosures are to be considered. Finally the EMPD model does not support any qualitative assessment of the room-enclosure MBP. The buffer thicknesses, surface areas, vapour permeabilities and moisture capacities of the different elements in the enclosure can not be easily superposed to one simple enclosure MBP.

In the second method, often named 'effective capacitance' model (EC model), it is assumed that the humidity in the buffer is always in equilibrium with the room air (Stehno, 1982). In that case:

$$G_{buf} = \frac{\partial M_{buf}}{\partial t} = N\frac{\partial p_{vi}}{\partial t} \qquad (4)$$

with M_{buf} (kg) the moisture stored in the buffer layer and N (kg/Pa) the moisture capacity of the enclosure. N can then simply be added to the room air:

$$\left(V/(R_vT) + N\right)\cdot\frac{\partial p_{vi}}{\partial t} = M\cdot V/(R_vT)\cdot\frac{\partial p_{vi}}{\partial t} \qquad (5)$$

with M (-) a multiplication factor. Such renders the effective capacitance model a very easy method as no extra equations are to be solved. M could furthermore also qualitatively assess the room-enclosure MBP: a larger M implies more moisture buffering.

The correction factor M however remains very vaguely defined. Often only rough minimum and maximum values are given (e.g. Stehno, 1982, TRNSYS, 2006). Alternatively, N can be derived from the surface area's, moisture capacities and moisture penetration depths of the interior elements:

$$N = \sum_k A_k\cdot\xi_k\cdot d_{b,k} \qquad (6)$$

In that case though, some of the drawbacks mentioned for the EMPD model also enter here. Additionally, such definition of N can not be considered a reliable characterisation of the room-enclosure MBP: its value focuses mainly on the moisture capacities, while only indirectly accounting for the moisture permeabilities involved.

The current EMPD and EC model formulations hence do not allow easy qualitative and quantitative assessment of interior moisture buffering. Determination of the required input parameters from single-element or room-enclosure MBP values will correct those flaws.

QUALITATIVE ASSESSMENT

Single-element MBP characterisation

The hygric interactions between room air and enclosure are determined by the contributions of the different elements comprised in the enclosure: the interior finishes and interior objects – furniture, carpets, drapes, books, …. A characterisation of the MBP of single elements is thus needed first. Janssen and Roels (2009) verify that an MBP characterisation from cyclic step-change (de)sorption experiments (JIS A1470 -1, 2002; ISO/DIS 24353, 2006; Rode et al., 2007) best serves this aim. In such an experiment, a sample of the element is conditioned to a specific relative humidity, and sealed at all but its normally exposed sides. It is then alternatingly exposed to high and low ambient humidity for predefined time intervals. The sample's moisture mass evolution is recorded and the moisture buffer value (MBV) is obtained from the normalised amplitude:

for interior finishes: (7)

$$MBV_{8h} = \frac{m_{max} - m_{min}}{A \cdot (\varphi_{high} - \varphi_{low})} \quad (kg/(m^2 \cdot \%RH))$$

for interior elements:

$$MBV_{8h}' = \frac{m_{max} - m_{min}}{\varphi_{high} - \varphi_{low}} \quad (kg/\%RH)$$

with $m_{max}/_{min}$ (kg/m²) the maximum/minimum moisture mass of the finish sample, A (m²) the surface of the sample, and $\varphi_{high/low}$ (-) the high/low humidity levels applied in the measurement. Janssen and Roels (2009) elect the Nordtest protocol (Rode et al., 2007): high and low humidities are 75 %RH and 33 %RH, maintained over 8 and 16 hours respectively. A sensitivity analysis by Roels and Janssen (2006) however allows to state that measurements should be made:

- on a sample with a build-up and dimensions similar to practice,
- with a surface vapour transfer coefficient as anticipated in practice,
- with humidity levels in accordance with the expected ambient humidity,
- with time intervals in agreement with the likely moisture production.

to attain a dependable single-element MBP characterisation. Given the diversity of practical moisture production schemes, particularly the last statement may present a problem.

Production-adaptive MBP characterisation

While the first three conditions mentioned above can most probably be met within reasonable limits, the diversity of practical moisture production schemes may present a problem. Janssen and Roels (2009) refer to measurements of the temperature and relative humidity in 39 Belgian dwellings in the period 2002-2003 (BBRI, 2004), which yield insight on the humidity variations that can typically be encountered in different rooms of dwellings. The measurements show that a bedroom agrees well with the Nordtest 8/16 h loading/unloading protocol. The bathroom, on the other hand, yields typical short-term moisture peaks while the kitchen and living room experience moisture production intervals with lengths varying from one to five hours. Such variable schemes will also be observed in non-residential buildings. By analysis of moisture buffering simulations – quantifying the humidity variation in a room finished with a hygroscopic finish – Roels and Janssen (2006) demonstrated that the current Nordtest protocol is only reliable for an 8-hour moisture production scheme, in agreement with the 8-hour "high RH" interval imposed in the MBV measurement. It was shown that there is an appreciable unique relationship between the MBV of the hygroscopic finish and the dampening of the RH amplitude in the analysed room. For shorter moisture productions however, such unique relations were not obtained. To correct that flaw, a weighted-average MBP characterisation is proposed here:

$$MBV^* = \alpha \cdot MBV_{8h} + (1-\alpha) \cdot MBV_{1h} \quad (8)$$

with MBV* the production-adaptive MBV, $MBV_{8h/1h}$ measured MBV values and α (-) the weighting factor. The MBV* is introduced here from the Nordtest protocol, but the methodology is similarly applicable to the other step-change (de)sorption protocols.

The newly introduced MBV_{1h} does not require extra measurement effort, as it additionally results from the normal MBV_{8h} measurement. Just like MBV_{8h} is derived from the accumulated moisture after eight hour at high RH, MBV_{1h} is derived from the accumulated moisture after just one hour at high RH, hence within the usual 8/16 h measurement. The following values are proposed for the weighting factor α:

- 0 hour < production ≤ 2 hour: α = 0.0;
- 2 hour < production ≤ 6 hour: α = 0.5;
- 6 hour < production ≤ 10 hours: α = 1.0;

When accurate information on the production regime is available, more detailed values for α may be used. Verification of Eq. (8) follows below.

Room-enclosure MBP characterisation

Real rooms are usually cladded with different finishes and may moreover comprise interior objects: furniture, decoration, carpets, drapes, books, etc. Recently, Ramos and de Freitas (2006) proposed to characterise the hygric inertia of a room by superposition of the MBP of the interior elements in the room. Adapted to the definition of MBV* in Eq. (8), this becomes:

$$HIR^* = \left(\sum A_k \cdot MBV_k^* + \sum MBV_l'^*\right) / V \quad (9)$$

with HIR* (kg/m³/%RH) the hygric inertia per cubic meter of room, MBV^*_k (kg/m²/%RH) and A_k (m²) the moisture buffer potential and area of finish k, MBV'^*_l (kg/%RH) the equivalent moisture buffer potential of object l and V (m³) the room volume. While its thermal analogue is generally accepted and widely used, the validity of Eq. (9) still requires verification.

Verification of the methodology

To verify the proposed methodology, the MBV of 15 different finishes and the resulting humidity variation in a room cladded with those are determined numerically. For MBV* to be a dependable characterisation of the single-element MBP, an appreciably unique relation between MBV* and the interior RH amplitudes should exist. Notwithstanding the recent introduction of multiple MBP protocols, this dependability has never been studied. The interior elements have been limited to single-layer homogeneous finishes only, applying 7 different building materials at thicknesses of 1 cm and 10 cm (for more details, see (Janssen and Roels, 2009)). It is reasoned that the resulting range of interior finishes can be considered representative for the moisture buffering by a wide diversity of real interior finishes and objects.

All simulations are performed with a numerical model for moisture transport in building parts (Janssen et al., 2007). All simulations are entirely isothermal, with temperatures constant at 20 °C. While such isothermality may be considered a limitation, it is in line with the practice of isothermal measurement of moisture capacities, vapour permeabilities – for use in the EMPD and EC models – and moisture buffer values. Any deficiency of the EMPD and EC model for non-isothermal conditions will hence not be solved by the current approach: this is however not the aim of this paper. For the single-element MBV the surface mass transfer coefficient governed response of the material to a rectangular wave in ambient relative humidity is calculated. The Nordtest's 33-75 % RH levels and 8-16 h time intervals are used, in combination with the JIS' real thickness and $2\ 10^{-8}$ s/m surface mass transfer coefficient. For the interior moisture buffering simulations, the humidity variations in a room with hygroscopic finish are simulated.. A room of 90 m³ is assumed finished with 60 m² of hygroscopic materials. 0.5 ACH with exterior air at 10 °C and 65 % RH and a transfer coefficient of $2.0\ 10^{-8}$ s/m are assumed, and three moisture production regimes are simulated:

- long: 0-8am: 300 g/h, other: 0 g/h.
- peak: 6-8am, 5-9pm: 325 g/h, other: 25 g/h.
- short: 0-1am, 6-7am, 12am-1pm, 6-7pm: 600 g/h, other: 0 g/h.

Both the MBV and the moisture buffering simulations are calculated for a 10-day interval: a steady-periodic cycle is readily achieved after this interval. The resulting relations between the finish's MBV and the interior RH amplitude are illustrated in Figure 1. It is obvious that the production-adaptive MBV* results in a dependable single-element MBP characterisation, for a wide diversity of moisture production schemes. To support its superposition to the room-enclosure HIR*, similar moisture buffering simulations are performed with single finishes with different surface area's, and with combinations of different finishes. The relation between HIR* and interior RH amplitude is shown in Figure 1 for the long moisture production regime.

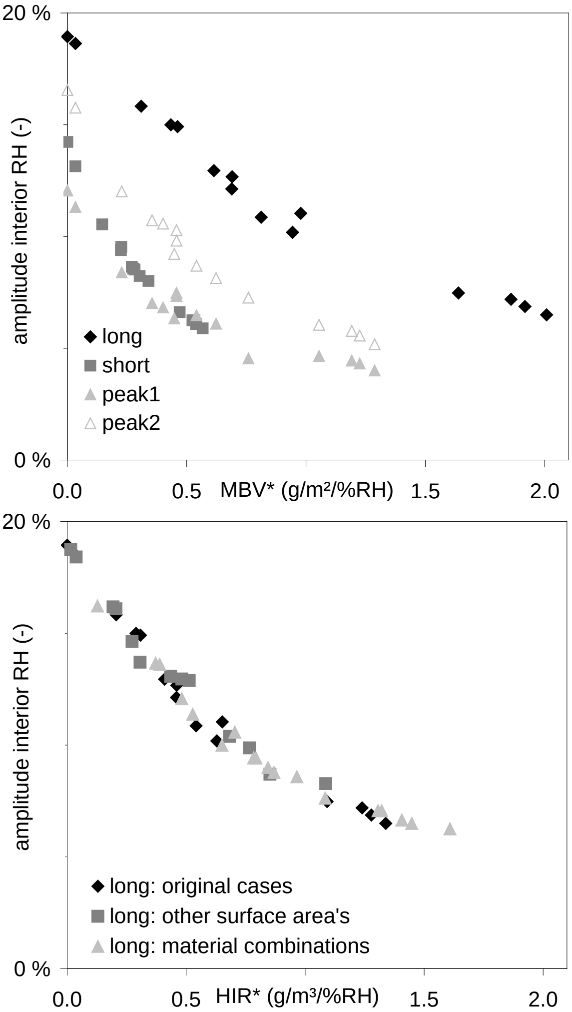

Figure 1 Relation between MBV and interior RH amplitude for the long, peak and short regimes (top) and relation between HIR* and interior RH amplitude for the long regime (bottom).*

HIR* hence characterises the moisture buffer potential of enclosures, and can be used for qualitative assessment of interior moisture buffering: larger HIR* entail stronger dampening of interior humidity variations.

QUANTITATIVE ASSESSMENT OF INTERIOR MOISTURE BUFFERING

The previous section indicated that – analogous with the thermal inertia – the hygric inertia of room enclosures can be obtained through superposition. The resulting HIR* value allows to qualitatively assess the moisture buffer potential of the enclosure, as it is related to the resultant dampening of interior humidity variations. Ultimately though one does not only want qualitative assessment, but also aims at quantitatively assessing the influence of interior moisture buffering on interior humidity variations. This section will demonstrate that the introduced HIR*-value can equally be used to arrive at parameters required in the simplified EMPD and EC models, now based however on simple and fast measurements only and applicable for interior finishes and objects alike.

Effective moisture penetration depth model

The EMPD model is originally developed for moisture storage in building walls, assuming that only a thin layer near the interior surface interacts with the interior air: the buffer storage layer. Some models solve Eq. (2) separately for all available humidity buffering finishes, however in most building-energy-simulation all interior elements need to be lumped into one equivalent buffer layer. The hygric properties of the layer need to be chosen such that they result in similar storage behaviour. This approach could also be applied to take in multidimensional interior objects (furniture, drapes, books, …). No suitable methodology for this lumping process is available however.

In this section such methodology is presented, transforming the enclosure's HIR* to an equivalent single buffer layer, to be applied in the EMPD model. For a single homogeneous material, by describing the active layer thickness d_b as fraction a of the moisture penetration depth d_p (Eq. (3)), Eq. (5) becomes:

$$A \cdot \frac{p_{vi} - p_{vb}}{1/\beta_i + a/(2 \cdot b) \cdot \sqrt{t_p/\pi}} = A \cdot a \cdot \sqrt{\frac{t_p}{\pi}} \cdot b \frac{\partial p_{vb}}{\partial t} \qquad (10)$$

with b ($s^{1.5}$/m) the material's effusivity and t_p the period of the considered interior humidity variation. Eq. (10) implies that the moisture response of an element is essentially governed by the material's effusivity b and the thickness adjustment factor a.

The analytic solution for moisture accumulation in a finite homogeneous slab due to a step-change in environment vapour pressure – used in the MBV-protocol – can also be described with b and a (Carslaw, 1990). This implies that for a single homogeneous material b and a can be determined from the measured $MBV_{8h/1h}$ and thus that $MBV_{8h/1h}$ values can be used for quantification of interior moisture buffering with Eq. (10):

$$\begin{aligned} MBV_{8h/1h} &= d \cdot \xi \cdot \Delta p_{vi} \cdot \left(1 - \sum_{i=1}^{\infty}\left(\frac{2\omega^2}{\gamma_i^2(\omega(\omega+1)+\gamma_i^2)}\exp(-\gamma_i^2\tau)\right)\right) \\ &= a \cdot b \cdot \sqrt{t_p/\pi} \cdot \Delta p_{vi} \left(1 - \sum_{i=1}^{\infty}\left(\frac{2\omega^2}{\gamma_i^2(\omega(\omega+1)+\gamma_i^2)}\exp(-\gamma_i^2\tau)\right)\right) \end{aligned} \qquad (11)$$

$$\omega = \frac{a \cdot \beta}{b}\sqrt{\frac{t_p}{\pi}}, \quad \tau = \frac{\pi \cdot t_{8h/1h}}{a^2 \cdot t_p}, \quad \gamma_i \text{ roots of } \gamma \cdot \tan(\gamma) = \omega$$

with $t_{8h/1h}$ (s) 8 and 1 hour respectively for MBV_{8h} and MBV_{1h} and t_p 24 hours. HIR-values comprising multiple multimaterial finishes and multidimensional objects can likewise be transformed to enclosure-equivalent b_{eq} and a_{eq}, by use of:

$$MBV_{eq,8h/1h} = (V \cdot HIR_{8h/1h})/A_{TOT} \qquad (12)$$

with A_{TOT} the global exchange area between room air and enclosure. From $HIR_{8h/1h}$, the effusivity b_{eq} and adjustment factor a_{eq} of the equivalent single buffer of the complete room enclosure can be obtained from Eq. (11).

Note that due to the influence of the surface transfer coefficient, a reliable fit of a_{eq} and b_{eq} can only be attained with a good assumption for the total exchange area A_{TOT}. The actual surface area's can be taken for interior finishes, for interior objects a rough estimate suffices (see below).

Effective capacitance model

The EC model assumes the moisture buffered in the hygric inertia of the room always in equilibrium with the room humidity. Hence, Eq.(6) also can be written as:

$$N = 100 \cdot HIR^* \cdot V/\rho_{v,sat}(\theta_i) \qquad (13)$$

The factor 100 appears in the equation to convert the kg/%RH/m³ unit of HIR* back to kg/m³. Eq. (13) defines the multiplication factor M as:

$$M = \left(1 + 100 \cdot HIR^*/\rho_{v,sat}(\theta_i)\right) \qquad (14)$$

with $\rho_{v,sat}$ (kg/m³) the saturated interior vapour density. Compared with the rough estimates for M suggested in some building-energy-simulation code manuals or the value determined from the EMPD model (Eq. (6)), the value proposed in Eq. (14) corresponds to a reliable moisture capacity of a whole room enclosure.

Verification of the methodology

The proposed MBP characterisation of room enclosures via MBV* and HIR* does hence allow to quantitatively assess interior moisture buffering as the EMPD and EC parameters can be calculated from them. This means that these EMPD and EC parameters can now be obtained from simple and fast measurements.

To illustrate the quantitative capacities of HIR*, interior moisture buffering simulations are performed based on the simplified EMPD and EC models. We limit the hygric inertia in the room to 60 m² of finish, so the two simplified approaches can be compared to full numerical simulations of moisture exchange with the enclosure. Two different finishes are considered: 1 cm of wood fibre board (WFB) and plywood (PW). While being academic it is assumed that they are still illustrative. Simulations are made for a room finished with WFB and PW separately, and for both materials combined. In the combined case, WFB and PW are each applied with 30 m² surface area.

To translate the HIR*-values to one equivalent buffer layer for the effective moisture penetration depth model, the period t_p is set to 24 hours. For use in the buffer flow calculation via Eq. (10), t_p is function of the moisture production regime. For the current study it is set 24, 12 and 6 hours for respectively the long (α=1.0), peak (α=0.5) and short regime (α=0.0).

Figure 2 shows the results for the 30 m² WFB & 30 m² PW combination. Similar results are obtained for other cases. Observe that, while only single finishing materials are considered here for reasons of comparison, the MBV of WFB or PW could similarly represent the MBV' of an interior object. The methodology is thus valid for both interior finishes and objects.

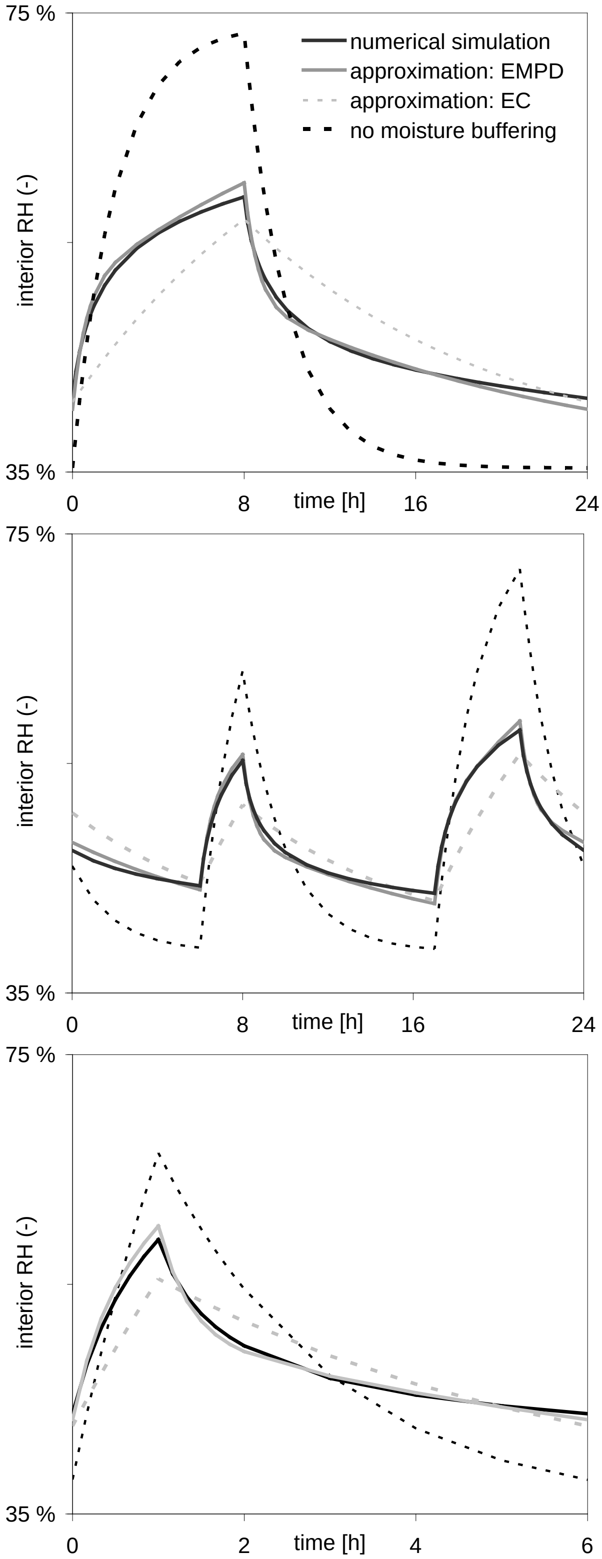

Figure 2 Comparison of interior RH variations simulated with the numerical model and with the EMPD and EC models, for the long (top), peak (middle) and short (bottom) moisture production regimes.

A close agreement is found between the full numerical and the EMPD solution. This supports the applicability of HIR* for the reliable quantification of the equivalent single buffer's capacity and permeability.

For the EC model on the other hand, fair predictions of the RH minima and maxima are found, but it is not able to predict the exact course of the indoor RH-variations. Such is no flaw of the developed HIR* methodology but a well-known defect of the EC model.

PRACTICAL EXAMPLE

To illustrate the capability of the HIR*-approach and to stress the importance of a correct characterisation of a room enclosure's hygric inertia, the present section exemplifies the developed methodology with a practical case. We consider a small library of 14 by 15 m², with a height of 4 meter. The library contains in total 24 book racks of 5 by 1.8 meter, lined up in twos back to back. One of the walls is totally glazed, the other walls are finished with 1cm gypsum plaster. A 3 cm wood fibre board acoustical ceiling is applied on the ceiling surface. The buffering elements considered and their respective $MBV_{8h/1h}$- & $HIR_{8h/1h}$-values are collected in Table 1. The MBV- & HIR-values were determined earlier in (Janssen and Roels, 2009). Table 1 clearly indicates the weight of the book racks in the total hygric inertia: its HIR-values are far higher than those for the walls and ceiling. Nevertheless, many simulation models do not (easily) allow the integration of such interior objects for interior moisture buffering assessments. The HVAC-system constantly injects preconditioned air at 20°C and 50% RH at 0.5 ACH. The surface transfer coefficient at all surfaces is set at $2.0 \cdot 10^{-8}$ s/m. The interior humidity of the library is simulated for a rainy day when visitors enter the library with wet clothes. The moisture source G_{vp} (kg/s) is related to the varying number of visitors:

$$G_{vp} = n_{visitors} \cdot (\beta \cdot A_{visitor} \cdot (p_{v,sat} - p_{vi}) + 1.67\,10^{-5}) \qquad (15)$$

Two cases are distinguished. First the response of the library is simulated with the wall and ceiling surfaces as only buffering elements. In the second case the hygric buffering by the book shelves is also considered. Weighting factor α in the production-adaptive hygric inertia HIR* is taken as 1. In both cases the humidity course inside the library is predicted with the EMPD and the EC model. In the EC model, the multiplication factor is derived from the HIR*-value of the library with Eq. (14). In the EMPD model, the global hygric inertia of the library is translated to an equivalent single buffer layer. The MBV_{eq}-values and the derived effusivity and thickness adjustment factor of the equivalent single moisture buffer layers for all cases are brought together with the HIR*-values in Table 2.

Table 1
Enclosure elements and their HIR-values

	WALL	**CEI-LING**	**BOOK RACK**
Area (m²) or length (m)	172	210	720
$MBV^{(\cdot)}_{8h}$ (kg/m$^{(2)}$/%RH)	0.43	1.85	2.45
$MBV^{(\cdot)}_{1h}$ (kg/m$^{(2)}$/%RH)	0.28	0.52	0.72
HIR_{8h} (kg/m³/%RH)	0.09	0.46	2.10
HIR_{1h} (kg/m³/%RH)	0.06	0.13	0.62

Table 2
Analysis of different buffering configurations

CASE	1	2	2A	2B
HIR_{1h} (kg/m³/%RH)	0.19	0.80	0.80	0.80
HIR_{8h} (kg/m³/%RH)	0.55	2.65	2.65	2.65
HIR^* (kg/m³/%RH)	0.55	2.65	2.65	2.65
M (-)	4.19	16.3	16.3	16.3
A_{TOT} (m²)	382	598	382	778
$MBV_{eq,1h}$ (kg/m²/%RH)	0.41	1.12	1.76	0.86
$MBV_{eq,8h}$ (kg/m²/%RH)	1.21	3.72	5.82	2.86
b_{eq} (10^{-7} $s^{1.5}$/m)	3.28	19.2	122	10.2
a_{eq} (-)	1.13	0.54	0.14	0.82

To apply the EMPD model's Eq. (11-12), the total exchange surface A_{TOT} has to be determined. For the first case that exchange surface is taken as the total surface area of ceiling and walls. In the second case, when also taking into account the hygric buffering by the book shelves, the front areas of the book racks is added to the total surface area of case 1.

Figure 3 compares the predicted RH-courses for both cases and both models. As a reference, the predicted RH-course when no moisture buffering is considered is given as well. The number of visitors over the day is plotted on the right axis of the graph. The influence of the visitors entering the library with wet clothes is clearly visible on the predicted RH-course. However, when only the walls and ceiling are taken as buffering materials, the effect is strongly overrated: the interior RH runs up from 50 to 75%, while when also incorporating the buffering by the books the increase is limited to 11%. Comparing the EMPD model with the EC model the same conclusions can be drawn as in the previous section: the EC model acceptably predicts the global amplitude, but is not able to simulate the exact course of the relative humidity.

Weakest point of the presented EMPD methodology is the fact that the total exchange surface has to be determined. For the first case this is straightforward, as the surface areas of walls and ceiling can be summed. When dealing with interior objects an exact determination of A_{TOT} is much more complicated. To investigate the sensitivity of the results to A_{TOT}, two extra simulations of the second case are performed. First the exchange surface is limited to the area of the walls and ceiling, neglecting the book fronts. Second the value is extended by adding both the back and top areas of the books. The values for the additional simulations are also given in Table 2. The influence of A_{TOT} on the predicted response is rather small, as can be seen in Figure 3, comparing the original case with the two additional simulations. It appears that an accurate exchange area is not needed: a rough estimate gives sufficiently reliable results since changes in the exchange surface also affect the fitted effusivity and adjustment factor of the equivalent single buffer layer (see Table 2). This is a crucial conclusion, because it makes the presented HIR*-approach easily applicable for more complicated enclosures.

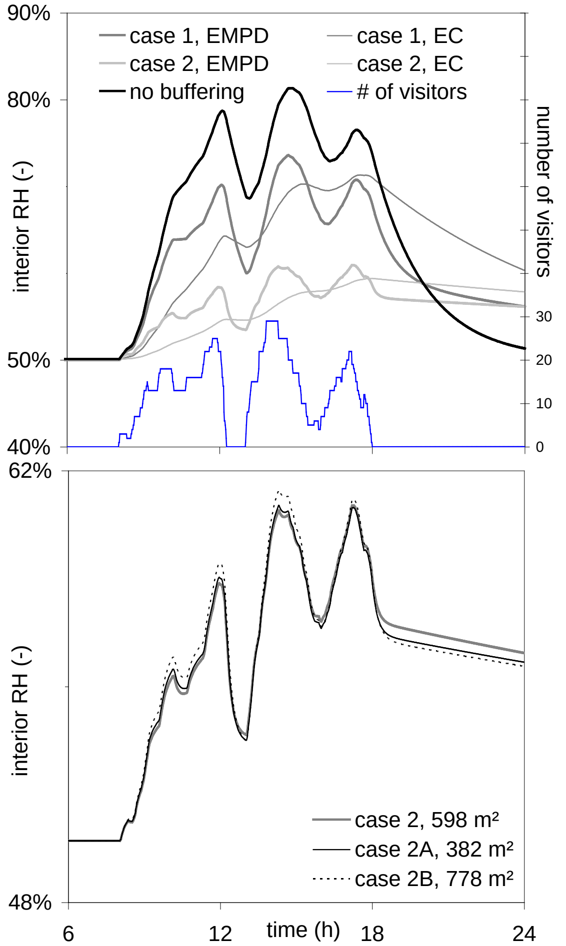

Figure 3 Simulated humidity variations in the library for the non-hygroscopic case and cases 1, 2 (top) and for cases 2, 2A, 2B (bottom).

CONCLUSIONS

The significance of interior humidity in attaining sustainable, durable, healthy and comfortable buildings is increasingly recognised. Interior humidity is highly affected by interior moisture buffering by the room enclosures: experimental and numerical studies have comprehensively shown that application of hygroscopic interior elements substantially tempers the peaks in the interior humidity variations. Ideally hence, implementation and assessment of hygric inertia should form an integrated part of building design, for which a qualitative and quantitative characterisation of interior moisture buffering is required.

Whereas the effective moisture penetration depth and effective capacitance models do allow quantification, it has been argued that their reliance on the 'moisture penetration depth' concept necessitates comprehensive material properties and hinders their application to multimaterial interior finishes and multidimensional interior objects, often the primary share of an enclosure's hygric inertia. Moreover, while enabling quantification, it has been shown that the parameters required for the EMPD and EC models do not support qualitative assessment of interior moisture buffering.

On the other hand, recently different protocols for the simple and fast characterisation of the moisture buffer potential of interior finishes have been introduced. From these, only the protocols based on cyclic (de)-sorption measurements have been retained, based on arguments set forward in (Janssen and Roels, 2009). Their superposition toward a room-enclosure moisture buffer potential had not been corroborated yet.

In response to these flaws in the current quantitative and qualitative assessment of interior moisture buffering, this paper introduced a production-adaptive characterisation of the moisture buffer potential of interior elements and corroborated their superposition to a room-enclosure moisture buffer potential. This room hygric inertia was in the end shown to support quantification via the EMPD and EC models. In short, this paper proposed a comprehensive methodology for the qualitative and quantitative assessment of interior moisture buffering by room enclosures applicable to both interior finishes and objects and based on simple and fast measurements only, which may even be performed in situ (Vereecken et al., 2009). This paper thus presented a missing link between currently available approaches for characterisation and quantification of interior moisture buffering, greatly facilitating the appraisal of interior humidity.

ACKNOWLEDGEMENTS

The results in this paper have been partially obtained within KUL OT/04/28 'Towards a reliable prediction of the moisture stress on building enclosures', funded by the K.U. Leuven. This financial support is gratefully acknowledged.

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