

Dynamic modelisation of interaction between wall and indoor air

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Abstract

The current methodology used for testing the thermohygro-metric behaviour of building structures is proposed by the standard UNI EN ISO 13788.

This Standard evaluates the risk of hygro-metric damages due to:

- 1) critical moisture conditions of the inner surfaces of the building;
- 2) interstitial condensation within the structures

The proposed procedures are valid in the case of steady state and are applied on a monthly basis. However, the steady state calculation is not completely correct mainly because the vapour production is not constant neither in time nor in space. For example, residential buildings are not occupied during most of the day. Therefore, in the case of a residential building, there is an intense generation of moisture mainly during a certain period of the day. Then, for a better control of the indoor values of relative humidity (and of partial vapour pressure) inside a given room, the indoor moisture production should be not considered constant and it may be appropriate to assess the importance of the hygroscopic properties the walls and furniture, able to act as a moisture buffer.

In this paper, using a simplified model taking into account the interactions between the vapour concentration of the indoor air and the interior walls and furniture, the role played by the hygroscopic capacity of the indoor walls and furniture for the evaluation of indoor relative humidity is analyzed.

1. Introduction

Moisture is produced inside a building by human activity (respiration, perspiration, washing clothes and cleaning, baths and showers), from

houseplants, humid basements and other sources [Tenwolde, A. et alii, 2001; Tenwolde, A., 1994]. The modern lifestyle forces people to work or go to school during the day and only during the evening and night are residential buildings fully occupied. The consequence can be a cycle of falling relative humidity RH during the day and rising RH in the evening, also related to air temperature control. The standard EN ISO 13788 aims to avoid both interstitial condensation and condensation on the internal surfaces that could promote the mould growth [Fang L. et alii, 1998; Grant C. et alii, 1989; Viitanen, H., 1996]. The basic assumption for the calculations required by this standard is that the walls and house itself do not appreciably affect the internal moisture level. This is a realistic assumption if the materials used have a poor moisture sorption capacity and furthermore if the interior surfaces are coated with paint impermeable to moisture. In this paper, it is shown how it is possible to obtain a notable effect on the dampening of the indoor relative humidity variations using moisture adsorbent materials and permeable paint in the interior surfaces of the house.

2. Theoretical model

The most popular models for the evaluation of humidity inside the indoor environment provide a simple steady state balance, between the production of moisture due to the activities of people and ventilation, neglecting the moisture buffering effects of materials in contact with indoor air.

The absorption properties of the walls can play an important role to moderate the variation of indoor relative humidity.

The model presented here is not appropriate for detailed building simulations, but it can be used as a basis to take into account the hygroscopic interaction between the indoor air and different materials of walls and furniture.

The model assumes that the moisture production has a sinusoidal variation along the day around a mean value \bar{G}_w . This is an approximation of a day night cycle of moisture production in the ambient. The hygroscopic surface is assumed to behave as a semi-infinite solid.

2.1 Heat transfer model

The heat flux in an isotropic medium is governed by Fourier's law:

$$\mathbf{q} = -\lambda \nabla T \quad (1)$$

where λ [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$] is the thermal conductivity and T [K] the temperature.

The general differential equation of heat conduction is:

$$\rho c \frac{\partial T}{\partial \tau} = \nabla \cdot (\lambda \nabla T) \quad (2)$$

with ρ [$\text{kg}\cdot\text{m}^{-3}$] and c [$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$], respectively, the density and specific heat of the material.

Consider the heat transfer in semi-infinite solid which is exposed at the surface $x = 0$ to a sinusoidal temperature variation of amplitude ΔT around \bar{T} and period τ_0

$$T_s = \bar{T} + \tilde{T} = \bar{T} + \Delta T e^{i(\omega\tau - \phi)} \quad (3)$$

The temperature solution is:

$$T_s = T_m + \Delta T e^{i(\omega\tau - \phi) - (1+i)x/d^*} \quad (4)$$

where x [m] is the spatial coordinate, d^* [m] is the penetration depth:

$$d^* = \sqrt{\frac{a\tau_0}{\pi}} \quad (5)$$

where $a = \lambda/\rho c$ the thermal diffusivity [$\text{m}^2\cdot\text{s}^{-1}$]

The heat flux q [$\text{W}\cdot\text{m}^{-2}$] at the surface $x = 0$ can be determined by Fourier's law as follows:

$$\begin{aligned} q &= -\lambda \left. \frac{\partial T}{\partial x} \right|_{x=0} = (1+i) \frac{\lambda}{d^*} \Delta T e^{i(\omega\tau - \phi)} = \\ &= (1+i) b \sqrt{\frac{\pi}{\tau_0}} \Delta T e^{i(\omega\tau - \phi)} = \frac{\tilde{T}}{Z} \end{aligned} \quad (6)$$

$b = \sqrt{\lambda\rho c}$ is the thermal effusivity [$\text{J}\cdot\text{m}^{-2}\cdot\text{K}^{-1}\cdot\text{s}^{-0.5}$]

that indicates the ability of a material to absorb and release heat and Z is the thermal impedance:

$$Z = \frac{d^*}{2\lambda} + \frac{1}{i\omega\rho c d^*} = R + \frac{1}{i\omega C} \quad (7)$$

If the considered thermal process takes place at a node (the environment) that is coupled to the surface of a building component by means of a thermal surface resistance $R_{si} = 1/h_i$ it is possible rewrite the equation (7) as:

$$Z = \frac{1}{h_i} + \frac{d^*}{2\lambda} + \frac{1}{i\omega\rho c d^*} = R + \frac{1}{i\omega C} \quad (7')$$

Where h_i [$\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$] is the surface heat transfer coefficient.

Hence we can conclude that heat flux exchange at surface of semi-infinite slab can be represented by a resistance and a capacitance in series.

2.2 Moisture transfer

In a similar way for the vapour transfer the moisture flux is given by Fick's law:

$$\mathbf{g} = -\delta \frac{\partial p_v}{\partial x} \quad (8)$$

where δ is the water vapour permeability [$\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$] and p_v [Pa] the water vapour pressure.

The general differential equation of diffusion of moisture is :

$$\frac{\partial w}{\partial \tau} = \nabla \cdot (\delta \nabla p_v) \quad (9)$$

with w the moisture content [$\text{kg}\cdot\text{m}^{-3}$]

Further derivation gives:

$$\frac{\partial w}{\partial RH} \frac{\partial RH}{\partial \tau} = \frac{\xi}{p_{vs}} \frac{\partial p_v}{\partial \tau} = \nabla \cdot (\delta \nabla p_v) \quad (10)$$

Where ξ is the moisture capacity [$\text{kg}\cdot\text{m}^{-3}$], RH the relative humidity [-]. The function describing $w(RH)$ is the sorption isotherm (Figure 1).

Notice the similarity with the heat transfer equations (2). Hence, the moisture transfer solutions can be obtained from heat transfer solutions exchanging thermal conductivity λ with the water vapour permeability δ and the volumetric thermal capacity ρc with ξ/p_{vs} .

In the case of sinusoidal moisture variation at the surface with amplitude Δp_v the moisture flux at the surface $x = 0$ is then given by:

$$\begin{aligned} g &= (1+i) \frac{\delta}{d_v^*} \Delta p_{vi} e^{i(\omega\tau-\phi)} = \\ &= (1+i) b_v \sqrt{\frac{\pi}{\tau_0}} \Delta p_{vi} e^{i(\omega\tau-\phi)} = \frac{\tilde{p}_{vi}}{Z} \end{aligned} \quad (11)$$

where d_v^* is called moisture penetration depth [m]:

$$d_v^* = \sqrt{\frac{\delta_v p_{vs}}{\xi}} \sqrt{\frac{\tau_0}{\pi}} \quad (12)$$

The moisture penetration depth corresponds to the depth of the wall that participates to the dynamic moisture exchange between the component and the indoor environment, τ_0 [s] is the period of fluctuation, $\omega = 2\pi/\tau_0$ [s^{-1}] is the pulsation and p_{vs} [Pa] the saturation vapour pressure.

ξ is the so called *moisture sorption capacity* [$\text{kg}\cdot\text{m}^{-3}$] and it is the slope of sorption curve ($\xi = \partial w / \partial RH$, see Figure 1): it shows how much moisture content w (in mass by volume [kg/m^3]) must be absorbed/desorbed by the material per unit change in ambient RH before a new equilibrium has been attained after the ambient relative humidity has changed to a new value. In the following model the hysteresis phenomena

have been neglected.

b_v is the moisture effusivity [$\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-0.5}\cdot\text{Pa}^{-1}$]:

$$b_v = \sqrt{\delta_v \frac{\xi}{p_{vs}}} \quad (13)$$

It measures the ability of a material to exchange moisture across its surface, when the humidity value changes at its surface and Z is the moisture impedance of the wall [$\text{m}^2 \text{ s Pa}/\text{kg}$] defined as follows:

$$Z = \frac{d_v^*}{2\delta_v} + \frac{1}{i\omega \xi \frac{d_v^*}{p_{vs}}} = R_v + \frac{1}{i\omega C_v} \quad (14)$$

with the specific water vapour resistance R_v [$\text{m}^2 \cdot \text{s Pa}\cdot\text{kg}^{-1}$] and the surface hygroscopic capacity C_v [$\text{kg}\cdot\text{m}^{-2}\text{Pa}^{-1}$]

$$R_v = \frac{d_v^*}{2\delta_v} \quad (15)$$

$$C_v = \frac{\xi d_v^*}{p_{vs}} \quad (16)$$

It is possible to conclude that the water vapour flow rate exchange at surface of semi-infinite slab can be represented by a resistance and a capacitance in series.

If a moisture superficial resistance $R_{vs} = 1/\beta_i$ is considered, the RC circuit of moisture transfer at the surface can be represented by an impedance Z due to a specific water vapour resistance R_v and a surface capacitance C_v in series as showed in Figure 2.

Where β_i [$\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$] is the surface water vapour transport coefficient.

Indoor air humidity value is the result of a mass balance among moisture gain, moisture loss and moisture storage. According to the conservation of water mass, water vapour which enters in a room with supply air plus the water vapour produced in that room G_w should equal the water vapour removed with the exhaust air plus the water absorbed by the surfaces of materials in contact

with indoor air plus the water vapour stored in the room air (Figure 3).

The balance can be illustrated by the following equation (17) :

$$\begin{aligned} \rho_{ve} \frac{nV}{3600} + G_w = \\ = \rho_{vi} \frac{nV}{3600} + \sum_n A_n g_n + V \frac{\partial \rho_{vi}}{\partial \tau} \end{aligned} \quad (17)$$

where τ [s] is the time, ρ_{vi} [kg·m⁻³] the water vapour concentration inside, ρ_{ve} [kg·m⁻³] the water vapour concentration outside, n [h⁻¹] the ventilation rate (i.e. the number of room exchanges per unit time), V [m³] the volume of the room, G_w [kg·s⁻¹] the moisture production rate, A [m²] the surfaces available for hygroscopic buffering and g [kg·m⁻²·s⁻¹] the specific water vapour flow rate exchange with absorbing surfaces.

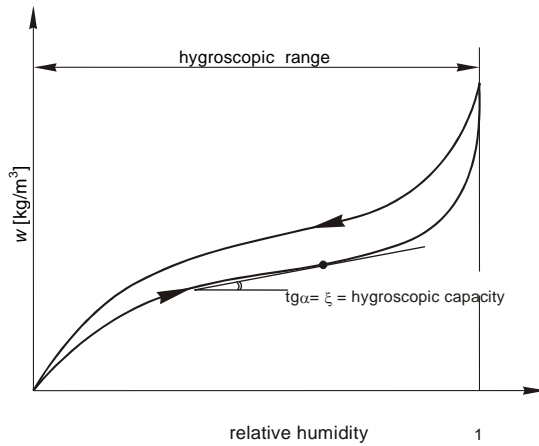


Fig. 1 – Sorption curve. The slope of the curve indicates the moisture capacity ξ .

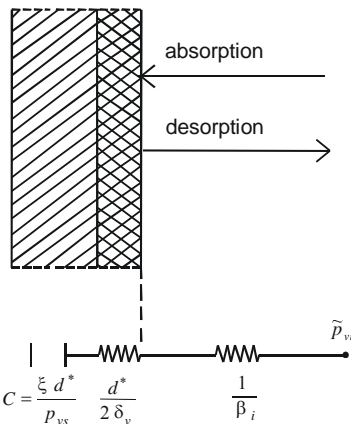


Fig. 2 – The RC configuration simplified model

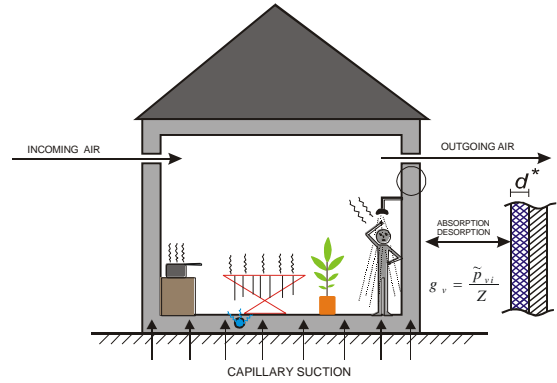


Fig. 3 – Moisture balance of the room

Assuming that the temperature dependency of the vapour concentration is negligible, the moisture balance equation (17) can be rewritten with inside vapour pressure as dependent variable:

$$\begin{aligned} p_{vi} = p_{ve} + \frac{G_w R_w T_i \cdot 3600}{nV} + \\ - \frac{R_w T_i \cdot 3600}{nV} \sum_n A_n g_n - \frac{\partial p_{vi}}{\partial \tau} \cdot \frac{3600}{n} \end{aligned} \quad (18)$$

where p_{vi} [Pa] is the inside vapour pressure, p_{ve} [Pa] is the vapour pressure outside and R_w [J·kg⁻¹·K⁻¹] is the gas constant for water.

The moisture production G_w term includes vapour from people, animals and plants, and released because of housekeeping activities (cooking, washing, cleaning, etc.) [Tenwolde A. et alii, 2001; Viitanen H., 1996].

The moisture production is assumed to have a sinusoidal variation around a mean value $\overline{G_w}$:

$$\tilde{G}_w = G_w - \overline{G_w} = \Delta G_w e^{i(\omega \tau - \phi)} \quad (19)$$

In the simplified model, the water vapour flux exchanged per unit area with the absorbing surfaces can be evaluated by the relation:

$$g_n \cong \frac{\tilde{p}_{vi}}{Z_n} \quad (20)$$

The equation (18) assuming that p_{ve} has a sinusoidal variations around a daily average value with the same frequency then becomes:

$$\tilde{p}_{vi} = \frac{\tilde{p}_{ve} + \frac{\tilde{G}_w R_w T_i \cdot 3600}{nV}}{1 + \frac{R_w T_i \cdot 3600}{nV} \sum_n \frac{A_n}{Z_n} + i \frac{\omega \cdot 3600}{n}} \quad (21)$$

If the computation is performed in a steady state the equation (18) becomes (UNI EN ISO 13788):

$$p_{vi} = p_{ve} + \frac{G_w R_w T_i \cdot 3600}{nV} \quad (22)$$

The difference between inside and outside vapour pressure increases proportionally to moisture production, and inversely to ventilation rate.

The equations of the model above described have been implemented in a Matlab m-file. This file has been used for the numerical simulations of the next section.

3. Numerical examples

We suppose to analyze the hygric response of a room of 65 m³ with a total absorbing area of 100 m². The occupancy and activities lead to a daily sinusoidal moisture variation of amplitude $\Delta G_w = 200$ g/h (i.e. the presence of 4 people). The inside air temperature is 20°C and the starting average relative humidity is $RH = 0.5$.

The surface water vapour transport coefficient is assumed equal to $\beta_i = 1.4 \times 10^{-8}$ [kg · m⁻² · s⁻¹ · Pa⁻¹].

We consider two different cases with different moisture buffering properties of the materials in contact with indoor air. The first case (Table 1): with high sorption capacity of the walls' surfaces and interior surfaces covered with highly permeable paints. The materials adopted in the second case (Table 2) are characterized by low sorption capacity and interior surfaces coated with impermeable paints.

The proposed case study can provide some indications about the hygric capacity of material. Table 1 and Table 2 show the daily indoor water vapour pressure variations Δp_{vi} , the peaks of vapour pressure p_{vi} and relative humidity RH , and the amplitude of relative humidity ΔRH inside the room as a function of ventilation rate n .

The results obtained show how the daily indoor variations of relative humidity can be reduced

starting from around 48% for a room with poor water vapour absorbing surfaces to 17% for a room with high vapour absorbing surfaces and permeable painting. Looking at the evolution of the RH amplitude inside the room, it appears how the moisture buffering properties of the materials can play an important role in the case of lower ventilation rate. Figure 4 shows the values of RH amplitude inside the room as a function of the room ventilation rate n . In order to take into account the effect of surface water vapour transport coefficient the simulations were performed also with $\beta_i = 0.45 \cdot 10^{-8}$ kg·m⁻²·s⁻¹·Pa⁻¹ (low β_i dashed line) and $\beta_i = 4.35 \times 10^{-8}$ kg·m⁻²·s⁻¹·Pa⁻¹ (high β_i dot-dash line). The graphs of Figure 6 show the weak influence of the coefficient and particularly there is no appreciable effect for the low buffering materials case (dashed line and dot dash line are superposed).

n	Δp_{vi}	p_{vi}	RH	ΔRH
h^{-1}	Pa	Pa	%	%
0.	396.40	1564.9	67.0	17.0
0.3	372.06	1540.56	65.9	15.9
0.4	348.31	1516.81	64.9	14.9
0.5	326.56	1495.06	64.0	14.0
0.6	306.76	1475.26	63.1	13.1
0.7	288.78	1457.28	62.4	12.4
0.8	272.45	1440.95	61.7	11.7
0.9	257.63	1426.13	61.0	11.0
1	244.14	1412.64	60.4	10.4

Table 1 – Amplitude of the RH in the room in the case of walls finished with moisture buffer materials ($d^* = 0.0154$ m, $b_v = 11.88 \cdot 10^{-8}$ kg m⁻² s^{-0.5} Pa⁻¹)

n	Δp_{vi}	p_{vi}	RH	ΔRH
h^{-1}	Pa	Pa	%	%
0.2	1122.90	2292.01	98.1	48.1
0.3	947.35	2115.85	90.5	40.5
0.4	802.81	1971.31	84.4	34.4
0.5	689.38	1857.88	79.5	29.5
0.6	600.63	1769.13	75.7	25.7
0.7	530.37	1698.87	72.7	22.7
0.8	473.88	1642.38	70.3	20.3
0.9	427.70	1596.2	68.3	18.3
1	389.39	1557.89	66.7	16.7

Table 2 – Amplitude of the RH in the room in the case of walls finished with low moisture buffer materials ($d^* = 0.0254$ m, $b_v = 65.4 \cdot 10^{-9}$ kg m⁻² s^{-0.5} Pa⁻¹)

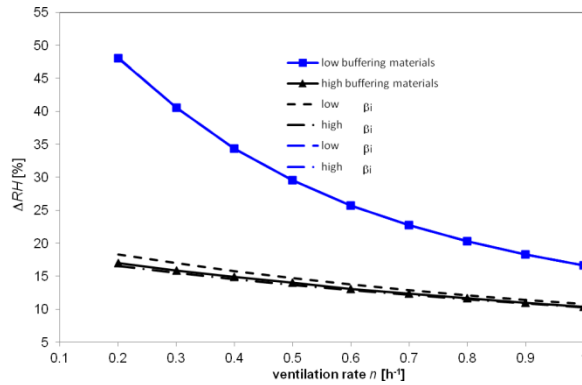


Fig. 4 – Relative humidity amplitude ΔRH inside the room as a function of ventilation rate n .

4. Conclusions

Building materials (i.e. plaster) and material used as furnishings (i.e. carpets,...) and other objects are able to adsorb moisture directly from the indoor air. Using the proposed simplified model, it has been possible to simulate a notable dampening effect on indoor relative humidity variations when moisture buffering materials are used.

The simplified model used in this paper can simulate the dynamic indoor conditions of a room. Moreover, such models can show the order of magnitude of the impact on the indoor humidity variations of the moisture buffering capacity of materials used in the walls, floors, ceiling and furniture.

The obtained data underlines the importance of a correct ventilation rate n in order to avoid indoor RH values that could favour mould growth.

It may be concluded that the use of absorbent plasters on the internal surfaces of the walls and the use of paints of high permeability contribute to dampen the indoor humidity fluctuations.

However, due to the complexity of the transient heat and moisture transfer process these results should be considered preliminary and further analyses should be carried out using more sophisticated heat and mass transfer models.

5. Nomenclature

$\overline{G_w}$ = average moisture production [$\text{kg}\cdot\text{s}^{-1}$];

R_v = specific water vapour resistance [$\text{m}^2 \text{ s Pa kg}^{-1}$];

C_v = surface hygroscopic capacity [$\text{kg}\cdot\text{m}^{-2} \cdot\text{Pa}^{-1}$];

Z = vapour impedance [$\text{m}^2 \cdot \text{s} \cdot \text{Pa}\cdot\text{kg}^{-1}$];

V = volume [m^3];

d^* = penetration depth [m];

τ_0 = the period of fluctuation [s];

b_v = moisture effusivity [$\text{kg} \cdot \text{s}^{-0.5} \cdot \text{Pa}^{-1} \cdot \text{m}^{-2}$];

ξ = moisture sorption capacity [$\text{kg}\cdot\text{m}^{-3}$];

δ_v = water vapour permeability [$\text{kg} \cdot \text{m}^{-1}\cdot\text{s}^{-1} \cdot \text{Pa}^{-1}$];

p_v = vapour pressure [Pa];

n = ventilation rate [h^{-1}];

RH = relative humidity [-];

ρ = concentration [$\text{kg}\cdot\text{m}^{-3}$];

t = time [s]

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