Can Books and Textiles Help in Controlling the Indoor Relative Humidity?

H. Derluyn **H. Janssen, PhD** **J. Diepens** **D. Derome, PhD** *Member ASHRAE* **J. Carmeliet, PhD**

ABSTRACT

Books and textiles can contribute to the moisture buffering capacity of a room, reducing absolute changes in relative humidity (RH). In this paper, the moisture buffering capacity of a magazine-type paper, a newspaper-type paper, and a cotton fabric are measured. A two-scale model is developed to describe the moisture buffering capacity of books. Using a room balance model with moisture buffering, the effect of books and textiles on the RH fluctuations in a room is analyzed and it is found that, for a large number of books, the indoor RH stabilizes (e.g., offices, library room). Textiles, having a limited thickness, only affect the peaks in moisture production. It is shown that the influence of books and textiles may not be ignored when designing the control system for the indoor RH.

INTRODUCTION

The control of the indoor relative humidity (RH) is important with respect to its influence on comfort, indoor air quality, mold growth, durability, and energy consumption. One of the measures to passively control or regulate the indoor RH is using the moisture buffering capacity of finishing materials. Building materials, such as hygroscopic stuccos and untreated wood, can be used for this purpose. In practice, these materials often are treated with a paint, which limits their moisture buffering capacity. As a consequence, not only the finishing building materials but also furnishing materials, books and magazines, cloths curtains, pillows, blankets, etc., may contribute to the moisture buffering capacity of a room. Recent research shows that these materials may have an important impact on the moisture buffering performance of a room and may contribute to the creation of stable microclimates (Svennberg et al. 2004).

In this paper, we focus on the role of books and textiles in regulating indoor RH. Measurements show that moisture buffering of books perpendicular to the fore-edge is higher than for the paper alone because moisture can penetrate deeply into books due to the presence of the thin air layers between the paper sheets. The vapor transport mechanism through the air layer toward the paper is found to substantially increase the possible active area for moisture buffering. In the same way, textiles have to be considered as a bunch of moisture buffering fibers in a loose-air environment showing a large active area but with limited moisture buffering capacity due to the small thickness.

In this paper, we present an approach to describe the dynamic sorption behavior of books and textiles using effective moisture transport properties. Experimental work includes a scanning electron microscopy (SEM) analysis of paper and textiles, water vapor permeability measurements, and sorption curves. Dynamic tests are also used to determine the moisture transport properties of books and textiles. Using a two-scale approach, the effective moisture capacity, permeability, and effusivity of books is determined. Finally, the effect of the presence of books and textiles in a standard room on the indoor RH is examined using a room balance model.

HYGROSCOPIC PROPERTIES OF PAPER AND TEXTILES

Isothermal water vapor transport is described by the following equation:

__H. Derluyn__ is a PhD student and __J. Carmeliet__ is a full professor at the Laboratory of Building Physics, Department of Civil Engineering, Katholieke Universiteit Leuven, Belgium. __H. Janssen__ is assistant professor at the Section of Building Physics and Services, Department of Civil Engineering, Technical University of Denmark, Kongens Lyngby. __J. Diepens__ is a member of the technical staff and __J. Carmeliet__ is a full professor at the Building Physics and Services Group, Faculty of Building and Architecture, Technical University of Eindhoven, The Netherlands. __D. Derome__ is associate professor at the Building Envelope Performance Laboratory, Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Canada.

$$\frac{\partial w}{\partial t} = \nabla(\delta \nabla p_v) \tag{1}$$

where w is the moisture content, δ is the water vapor permeability, and p_v is the water vapor pressure. Further derivation yields the following:

$$\frac{\partial w}{\partial h} \cdot \frac{\partial h}{\partial t} = \xi \cdot \frac{\partial h}{\partial t} = \nabla\left(\frac{\delta_a}{\mu} \cdot p_{vsat} \nabla h\right) \tag{2}$$

where ξ is the volumetric moisture capacity, h is the RH, μ is the water vapor resistance factor, and p_{vsat} is the saturated water vapor pressure. The function describing $w(h)$ is called the *sorption isotherm*.

Moisture effusivity, b_m, is a measure of the ability of a material to exchange moisture across its surface when the humidity changes.

$$b_m = \frac{\delta}{\sqrt{D_w}} = \sqrt{\frac{\xi\delta}{p_{vsat}}} \tag{3}$$

where D_w is the moisture diffusivity.

In the past, several experimental and numerical methods and databases have been proposed to determine the moisture transport properties of building materials (Carmeliet and Roels 2001, 2002; Carmeliet et al. 1999, 2004; Kumaran 1996). However, there is still a need to determine accurate moisture transport properties of magazines, books, newspapers, and textiles.

The moisture transport properties of paper itself may vary, depending on the paper components and the manufacturing process (Derluyn 2006). The density of paper varies from 610–690 kg/m^3 (38–43 lb/ft^3) for newsprint paper to 780 kg/m^3 (48.7 lb/ft^3) for fine paper, and up to 1150 kg/m^3 (71.8 kg/m^3) for coated super calendared paper. Newsprint paper thickness may vary from 60–80 μm(2.36–3.15 mil); office paper is around 105–110 μm(4.13–4.33 mil). The porosity of paper can be as high as 70%.

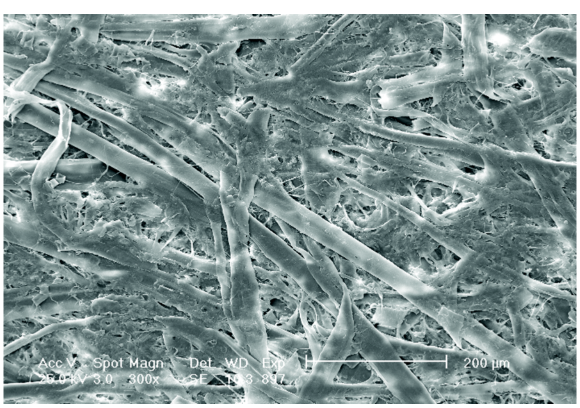
It is reported in literature that water vapor permeability especially may vary due to differences in paper structure and surface treatment. The paper structure is determined by the papermaking process, which consists of pulping, bleaching, and beating. Pulping is the process by which the wood is broken into fibers. We distinguish between mechanical and chemical pulping. Bleaching whitens the pulp, enhances brightness, and eliminates impurities. The structure of the fiber wall and surface is loosened by the beating process in order to ameliorate the mechanical properties of the paper.

Also, every textile fabric has unique moisture properties, depending on the fiber type (e.g., cotton, wool, flax, nylon), the spin and twist of the yarn, the textile fabric weight, and the weave characteristics (Derluyn 2006). The moisture content will be determined mainly by the fiber and yarn properties. For example, the dry density of a cotton fiber amounts 1550 kg/m^3 (96.8 lb/ft^3), while the dry density of a nylon fiber is 1140 kg/m^3 (71.2 lb/ft^3). The moisture transport properties will be determined by the weaving technique and the yarn.

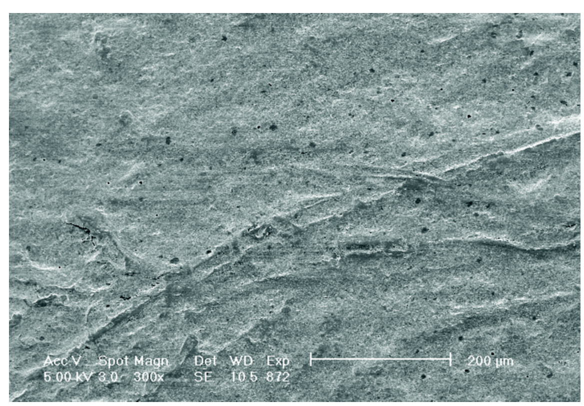
Experimental work was done on two kinds of paper and one kind of textile (Derluyn 2006). For paper, a magazine-type paper and a newsprint-type paper (referred to as *telephone book paper*), were measured. One kind of textile was measured: the fabric of a pillow-case consisting of 100% cotton.

Figure 1a gives an SEM image of the telephone book paper. We clearly see the fibrous structure of paper. The paper is made of 50% to 100% recycled fibers and has a matt finish. Figure 1b gives an SEM image of the magazine paper. The paper has a pulp structure. The paper is made of mechanical and chemical pulp, colors, and fillers such as talc and calcium carbonate, which make the paper smoother. The paper is a machine-finished, glossy-coated paper. The glossy coating gives the paper a more closed surface.

The dry density was determined measuring the dry weight and thickness of a paper or cotton sheet. The dry weight was measured after drying the samples in an oven at 50°C (122°F) and 3% RH. For paper, the thickness was determined using a microme-



(a)



(b)

Figure 1 *SEM images of the top surface of (a) telephone book and (b) magazine paper.*

ter and also from SEM images; for the cotton sheet, microscopic images were used. The data are summarized in Table 1.

Sorption Isotherms

The isothermal sorption curves are determined by conditioning samples in a desiccator with saturated salt solutions at a constant temperature of 23°C (73.4°F). The samples were initially dried in an oven at 50°C (122°F) and 3% RH. First, the main adsorption isotherm was determined by placing the samples in desiccators of 12%, 33%, 53%, 75%, and 94% RH. After attaining equilibrium, the specimens were sequentially placed at lower RHs to determine the primary desorption curves. For paper, samples consisting of several sheets of paper of 10 × 10 cm (3.94 × 3.94 in.) were made. For cotton, samples of 11 × 11 cm (4.33 × 4.33 in.) cut out of a pillow case were used. The adsorption and desorption scanning curves are described by a hysteresis model based on the Mualem model (Mualem 1974; Carmeliet et al. 2005). The Mualem model allows hysteresis modeling based on the main adsorption and desorption curve. In this model, the main adsorption and desorption isotherms are described by the following equations:

$$w_{ad} = w_{max} \cdot \left(1 - \frac{\ln(h)}{A_{ad}}\right)^{\frac{-1}{n_{ad}}} \tag{4}$$

$$w_{de} = w_{max} \cdot \left(1 - \frac{\ln(h)}{A_{de}}\right)^{\frac{-1}{n_{de}}} \tag{5}$$

The primary desorption scanning curves are described by the following equation:

$$w = w_{ad}(h) + [w_{ad}(h_1) - w_{ad}(h)] \cdot A(h) \tag{6}$$

where h_1 is the RH where the primary desorption starts and

$$A(h) = \frac{w_{de}(h) - w_{ad}(h)}{w_{max} - w_{ad}(h)} \tag{7}$$

The values for the parameters are given in Table 1. Figure 2 gives the main adsorption data for the two kinds of paper and the cotton fabric, together with the Mualem (1974) description. We conclude that the volumetric moisture capacity, ξ, the derivative of the moisture content to the RH, is similar for the two paper types, but the volumetric moisture capacity of the cotton fabric is lower.

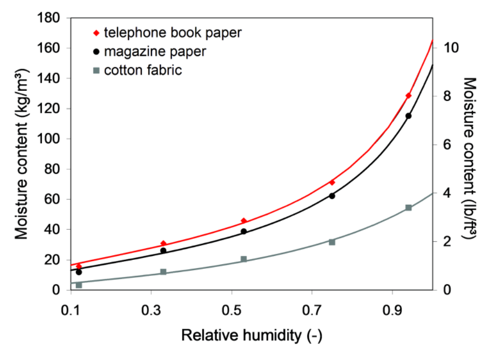


Figure 2 *Data points and Mualem (1974) fit (solid line) of adsorption isotherms for telephone book paper, magazine paper, and cotton fabric.*

Table 1. Material Properties and Sorption Isotherm Parameters for Telephone Book Paper, Magazine Paper, and Cotton Fabric

	Telephone Book Paper	Magazine Paper	Cotton Fabric
General			
Thickness	54 μm (2.1310^{-3} in.)	65 μm (2.5610^{-3} in.)	230 μm (9.0610^{-3} in.)
Dry weight	0.0372 kg/m^2 (7.6210^{-3} lb/ft^2)	0.0545 kg/m^2 (11.1610^{-3}lb/ft^2)	0.110 kg/m^2 (22.5310^{-3} lb/ft^2)
Dry density	690 kg/m^3 (43.1 lb/ft^3)	840 kg/m^3 (52.4 lb/ft^3)	478 kg/m^3 (29.8 lb/ft^3)
Sorption Isotherm			
w_{max}	165.6 kg/m^3 (10.34 lb/ft^3)	151.2 kg/m^3 (9.44 lb/ft^3)	63.9 kg/m^3 (3.99 lb/ft^3)
A_{ad}	0.19	0.20	0.59
n_{ad}	1.12	1.03	0.60
A_{de}	1.66	1.63	1.90
n_{de}	0.45	0.42	0.40

Vapor Resistance Factor

The water vapor permeability of the two paper types is measured for three different RH ranges using the dry/wet-cup test method (12%–54%, 54%–86%, and 86%–97% RH). The specimens consist of a set of paper sheets, which is highly compressed to prevent an additional vapor resistance due to air layers between the sheets. Based on the literature review and a first set of dry/wet-cup test data, the number of sheets was chosen in order to have specimens with an equivalent air layer thickness μd (where d is thickness) larger than 0.2 m (7.87 in.). According to EN ISO 12572 (EN 2001), when meeting this condition, no correction is required for the resistance of the air gap between the sample and the saturated salt solution. As a result, the telephone book specimens have 64 sheets and the magazine specimens have 52.

The water vapor resistance factor is determined from the measured steady-state vapor flow, g_v, given by the following:

$$g_v = -\delta(h)\frac{\partial p_v}{\partial x} \tag{8}$$

Integrating by parts, we get the following equation:

$$\int_0^d g_v \cdot \mathrm{d}x = \int_{h_1}^{h_2} \delta(h) \cdot p_{vsat}\,\mathrm{d}h \tag{9}$$

Expressing the nonlinear water vapor permeability by

$$\delta(h) = \frac{\delta_a}{\mu(h)} \text{ with } \mu(h) = \frac{1}{a + b \cdot e^{ch}}, \tag{10}$$

and knowing that, in steady state, g_v is constant, after integration we get the following equation:

$$g_v d = p_{vsat}\delta_a[a(h_2 - h_1)] + \frac{b}{c}(e^{ch_2} - e^{ch_1}) \tag{11}$$

The parameters a, b, and c can be determined based on the three measurements of the vapor flow (see Table 2). Figure 3 gives the water vapor resistance factor, μ, for telephone book paper and magazine paper. We observe that the magazine paper is about five times more vapor tight than the telephone book paper. This difference can be explained by the higher density of the magazine paper, the pulp paper structure, the lower porosity, and the effect of the finish coating.

The water vapor permeability of the cotton fabric is measured in a dynamic test. The determination of the water vapor permeability is not possible using a stationary dry/wet-cup test due to the high permeability of cotton sheets. The samples are composed of 72 sheets 10 × 10 cm (3.94 × 3.94 in.) of cotton. These are highly compressed so that the influence of possible air layers is negligible. The sides of the sample are taped with vapor-tight aluminium tape, so that a one-dimensional vapor transport in the cotton samples is attained. The dynamic test is performed for two steps in RH: from 8% to 54% and from 94% to 86%. The change in weight of the samples is measured across nine hours. The samples are then kept in the test environment until equilibrium is attained. The vapor permeability, δ, is determined by fitting the measured weights to the following equation:

Table 2. Water Vapor Permeability Parameters for Telephone Book and Magazine Paper

	Telephone Book Paper	Magazine Paper
a	0.00919	0.00167
b	5.62×10^{-5}	5.74×10^{-7}
c	7.12	11

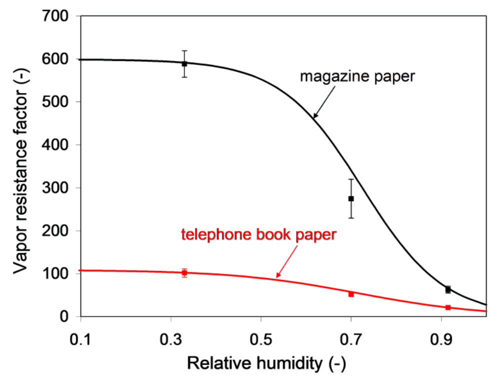


Figure 3 *Data points (squares) with standard deviation and fitted (solid line) curves of the vapor resistance factor for telephone book paper and magazine paper.*

$$m_m(t) = m_{m0} + d \cdot \xi \cdot (h_1 - h_0) \cdot A \cdot \left(1 - \sum_{i=1}^{\infty} \frac{2 \cdot \omega^2}{\gamma_i^2 \cdot (\omega \cdot (\omega + 1) + \gamma_i^2)} \exp(-\gamma_i^2 \cdot \tau)\right) \tag{12}$$

where m_m is the moisture mass, d is the depth of the book, A is the exposed surface of the book, ξ is the volumetric capacity, and h is the RH (Carslaw and Jaeger 1990). The parameter ω is given by the following equation:

$$\omega = \frac{d \cdot \beta}{\delta} \tag{13}$$

where β is the surface coefficient and δ is the vapor permeability. The parameter τ is given by the following equation:

$$\tau = \frac{D_w \cdot t}{d^2} \tag{14}$$

The moisture diffusivity, D_w, is equal to $\frac{\delta \cdot p_{vsat}}{\xi}$. The parameters γ_i are the roots of the function $\gamma \cdot \tan(\gamma) = \omega$. Note that in Equation 12, the vapor permeability, δ, is assumed to be constant over the considered measuring range of RH. The obtained values of the water vapor resistance factor are, therefore, approximate values. In the performed dynamic test, the water vapor resistance factors of cotton fabric at the average RH of 30% and 90% are 2.1 and 1.4, respectively.

HYGROSCOPIC BEHAVIOR OF PAPER AND BOOKS

Definitions, Test Setup, and Measurements

A book is defined as a number of sheets of paper with air layers in between. The total volume of the book is $V_{tot} = V_a + V_p$, where subscript *a* is the air layer and subscript *p* is the paper layer. The paper fractions of the book, Ψ_p and Ψ_a, are defined as follows:

$$\Psi_p = \frac{V_p}{V_{tot}}, \qquad \Psi_a = \frac{V_{tot} - V_p}{V_{tot}} = 1 - \Psi_p \tag{15}$$

The hygroscopic behavior is measured by exposing book specimens to a step change in RH. The experimental setup of the Building Physics and Systems Unit of T.U. Eindhoven is used (Goossens 2003). A book specimen consists of a number of paper sheets (5 × 5 cm; 1.97 × 1.97 in.), which are placed in a sample holder in the form of a small box with five acrylic plastic sides. The open side, with all the sheet edges regularly spaced, mimics the fore-edge of a book. Two paper fractions for magazine paper are used: a high paper fraction ($\Psi_p = 0.86$) and a low paper fraction ($\Psi_p = 0.51$). Also, a telephone book specimen with a paper fraction of $\Psi_p = 0.9$ is measured. After reaching equilibrium at 54% RH, a step change from 54% to 79.5% RH is imposed. Moisture uptake is possible only through the open side, which means uptake parallel to the paper sheets. Figure 4 gives the moisture uptake versus time for the three book specimens. Although the magazine paper is more vapor tight than the telephone book paper, the two book specimens with high paper fraction show a similar uptake behavior. The moisture uptake of the low paper fraction book is lower than that of the high paper fraction book. The low paper fraction book will, however, attain equilibrium faster than the high paper fraction book. This means that, due to the presence of air layers between the paper sheets, the low paper fraction book is characterized by a higher effective permeability and lower effective moisture capacity as compared to high paper fraction book specimens.

In the next section, we formulate a model to predict the effective moisture transport properties of books. We assume the paper to be homogeneous and nonisotropic. The model will then be used to explain the comparable behaviors of the high paper fraction magazine and the telephone book specimens, although the papers of each book show quite different water vapor permeabilities.

Effective Moisture Transport Properties of Books

Effective Density of a Book. The dry density of a book, ρ_b, is given by the following equation:

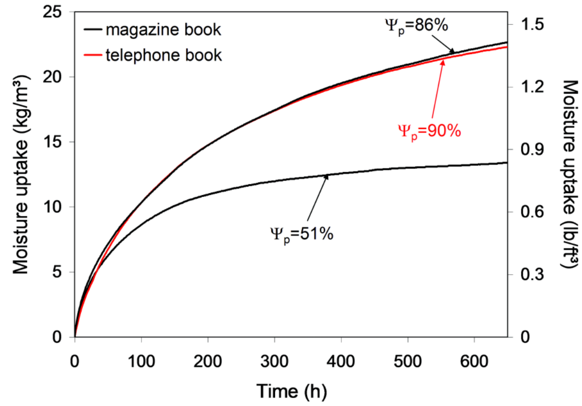


Figure 4 *Moisture uptake by magazine and telephone book for different paper fractions.*

$$\rho_b = \rho_p \cdot \Psi_p + \rho_a \cdot \Psi_a = \rho_p \cdot \Psi_p + (1 - \Psi_p) \cdot \rho_a \tag{16}$$

where ρ_p is the dry density of the paper and ρ_a is the density of air.

Effective Moisture Capacity of Books. The moisture content of a sheet of paper is defined by the following equation:

$$w_p = \rho_l \cdot \phi_0 \cdot S_l \tag{17}$$

where ρ_l is the density of the liquid, ϕ_0 is the open porosity of the paper, and S_l is the degree of saturation. Since the volumetric moisture capacity of air is around 10,000 times smaller than the moisture capacity of paper, the water vapor present in the air layer can be neglected. The moisture content of a book w_b can then be written as follows:

$$w_b = \rho_l \cdot \phi_0 \cdot S_l \cdot \Psi_p = \Psi_p \cdot w_p \tag{18}$$

The effective volumetric moisture capacity of a book, ξ_b, is given by differentiating Equation 18 with respect to RH as follows:

$$\xi_b = \frac{\delta w_b}{\delta h} = \frac{\delta w_b}{\delta w_p} \cdot \frac{\delta w_p}{\delta h} = \Psi_p \cdot \xi_p \tag{19}$$

Effective Water Vapor Permeability of Books. A book is considered a periodic system of paper sheets and air layers. We define a representative elementary volume (REV) consisting of a half layer of paper and a half layer of air (Figure 5).

In this REV, two different paths for water vapor transport exist. The first path describes water-vapor transport in paper perpendicular to the fore-edge of the book. In the second path, water vapor is transported parallel to the paper sheets through the air layer toward the inner part of the book, and then adsorbed by paper in a direction perpendicular to the sheet. Air is characterized by a high water vapor permeability, but very low moisture capacity. This means that the water vapor transported via the air layer is not buffered by the air layer itself, but will be almost immediately buffered by the paper sheets. Due

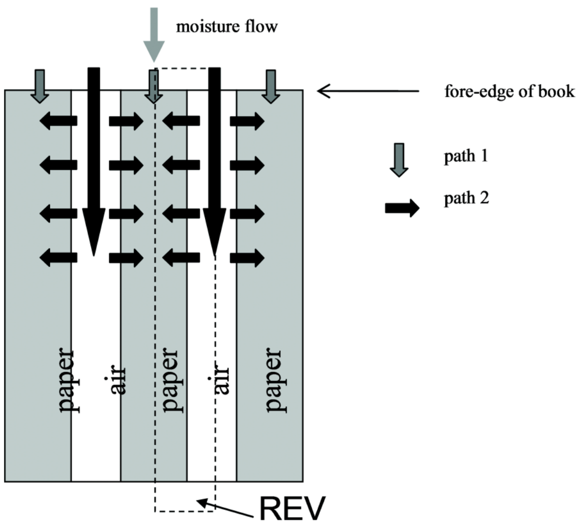


Figure 5 *Representative elementary volume (REV) of a book and moisture transport paths in a book.*

to the limited thickness of paper, the moisture is quickly redistributed over the thickness, and a one-dimensional moisture front is attained in the paper. This means that the moisture front advances parallel to the fore-edge of the book during moisture uptake. Since two different transport paths exist building up a single one-dimensional moisture front in the paper sheet, the water vapor transport in a book can be, in a first approximation, modeled as a parallel system. The water vapor permeability of this parallel system is given by the following equation:

$$\delta_b = \Psi_p \cdot \delta_p + \Psi_a \cdot \delta_a \tag{20}$$

where δ_b, δ_p, and δ_a are the water vapor permeability of book, paper, and air, respectively. We now introduce a factor α, so that

$$\delta_b(h, \Psi_p) = \alpha(h, \Psi_p)\delta_p(h) \ . \tag{21}$$

From Equations 20 and 21, we get the following equation:

$$\alpha(h, \Psi_p) = \mu_p(h) - (\mu_p(h) - 1) \cdot \Psi_p \tag{22}$$

Effective Moisture Effusivity of Books. The effective effusivity of a book is given by the following equation:

$$b_{m,b} = \sqrt{\frac{\xi_b \delta_b}{p_{vsat}}} = \sqrt{\frac{\Psi_p \xi_p \alpha \delta_p}{p_{vsat}}} = \sqrt{\Psi_p \alpha} \cdot \sqrt{\frac{\xi_p \delta_p}{p_{vsat}}} \tag{23}$$

or

$$b_{m,b} = \chi b_{m,p} \tag{24}$$

The factor χ is dependent on RH and the paper fraction.

We remark that, due to the fiber direction of paper and the finishing coating on paper, water vapor permeability may vary with direction. However, the main vapor diffusion path is through the air layers and from the air layer to the paper sheet. Therefore, assuming isotropic behavior by using the water vapor permeability perpendicular to the paper sheet introduces only small errors.

Discussion

The experimental results of Figure 4 can be explained when evaluating the effusivity of magazine and telephone book paper. The effusivity is determined using Equations 23 and 24, given the paper fraction of the dynamic experiment. Figure 6 gives the effusivity as a function of the RH for magazines at two paper fractions of $\Psi_p = 0.86$ and $\Psi_p = 0.51$ and for telephone books at a paper fraction $\Psi_p = 0.9$. We observe that magazine and telephone books at a high paper fraction have comparable effusivities, although magazine paper is much more vapor tight than telephone book paper. The high vapor resistance factor of magazine paper is compensated for totally by the very high vapor permeability of the air layers. This explains the comparable moisture uptake curves as observed in the experiment (see Figure 4). The effusivity of the magazine at a lower paper fraction is higher than the effusivity at a high paper fraction, which explains the faster moisture uptake for the low paper fraction book as observed in Figure 4. However, the total moisture uptake will be lower than for the high paper fraction book, since the total moisture content is dependent on the paper fraction as given by Equation 18.

MOISTURE BUFFERING BY BOOKS AND TEXTILES IN A ROOM

To analyze the role of books and textiles in the moisture buffering of a room, the indoor RH in a standard room is calculated, solving the moisture balance of the room. The moisture balance, taking into account ventilation, moisture sources, and moisture buffering by hygroscopic materials, is given by the following equation:

$$\frac{\partial p_{vi} \cdot V}{\partial t} = (\rho_{ve} - \rho_{vi}) \cdot \frac{nV}{3600} + G_{vp} - \sum_{i=1}^{m} A_i q_{buf,i} \tag{25}$$

where ρ_{vi} is the water vapor concentration inside, ρ_{ve} is the water vapor concentration outside, V is the volume of the room, n is the ventilation rate, G_{vp} is the vapor production inside the room, m is the number of absorbing surfaces, A_i is the surface available for hygroscopic buffering of a certain material, and $q_{buf,i}$ is the water vapor exchange with this absorbing surface. In Equation 25, ideal air mixing conditions are assumed. In this paper, we consider buffering only by one material ($m = 1$), namely, a wall of books or textiles. The ventilation rate is taken 0.5 per hour. For the outside climate, the IWEC meteorological data for Brussels are used (ASHRAE 2001). The inside temperature is taken equal to 20°C (68°F) in

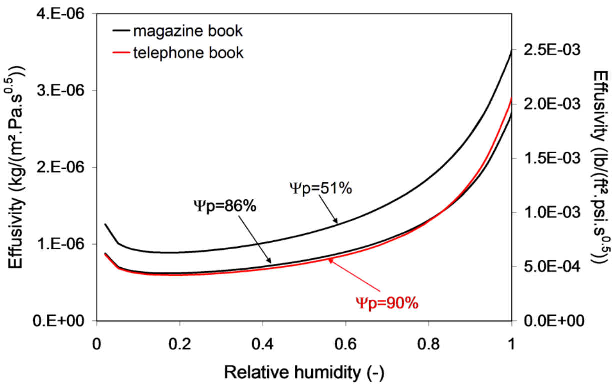


Figure 6 *Effusivity of magazine and telephone book paper in adsorption.*

winter and 24°C (75.2°F) in summer. The initial temperature of the hygroscopic material is taken equal to 20°C (68° F) and the initial moisture content corresponds to 50% RH inside the hygroscopic material.

The water vapor transport at the material surface is given by the following equation:

$$q_{buf} = \beta p_{vsat}(T_s)(h_i - h_s) \tag{26}$$

where β is the interior surface coefficient for vapor, T_s is the temperature at the surface, h_i is the RH in the room, and h_s is the RH at the surface. The interior surface coefficients are 8 W/m^2·K (1.4 Btu/h·ft^2·°F) for heat transport and 2.10^{-8} s/m (8.10^{-4} s/ft) for vapor transport.

The standard room has a volume of 80 m^3 (104.6 yd^3). The values for the buffering surfaces are based on measurements in a living room and in a student room (Derluyn 2006). When assuming that one side wall (2.5 × 8 m[9.2 × 26.2 ft]) of a room of 80 m^3 (104.6 yd^3) is covered with books, as it could be in an office, a value of 15 m^2 (17.9 yd^2) is appropriate. Estimating the paper fraction of a book based on books standing on a book rack gives values between 75% and 85%. For cotton fabric, a buffering surface A of 45 m^2 (53.8 yd^2) is used. The other walls are considered not to have moisture buffering capacity.

The water vapor transport in the books and cotton fabric is calculated using a finite-element model for coupled heat and moisture transport. Books and textiles are modeled as one-dimensional buffering systems characterized by a water vapor permeability and moisture capacity. The books have a depth of 15 cm (5.9 in.) and the cotton fabric has a thickness of 230 µm (9.06 mil). The effective vapor transport properties of book and cotton fabric are determined by Equations 19 and 20 using the measured properties for magazine paper, telephone book paper, and cotton fabric. For cotton fabric, a constant vapor resistance factor of two is used. For the heat transport properties of the materials, standard values are taken. Heat capacity is 1210 J/kg·K (0.289 Btu/lb·°F) for cotton and 750 J/kg·K (0.179 Btu/lb·°F) for paper; heat conductivity is 0.04 W/m·K (0.277 Btu·in./h·ft^2·°F) for cotton and 0.06 W/m·k (0.416 Btu·in./h·ft^2·°F) for paper.

The moisture production varies during the day as given in Table 3 (IEA 1991). Two cases are considered, one with peaks in the moisture production and one with a constant moisture production during occupation.

Simulation Results

The calculated variation of the RH over the course of the year is shown in Figure 7 for the reference room (no buffering material) and for the room with telephone books (A = 15 m^2/ 17.9 yd^2 with a 75% paper fraction). In the figure, the monthly average, daily maximum, and daily minimum RH are shown. We observe that the monthly average does not change due to the buffering effect of the books; the RH is somewhat lower in summer and higher in winter. However, the books are shown to introduce an important stabilizing influence: the difference between daily maximum and minimum RH, called daily change in RH, is substantially lowered. Figure 8 gives the daily change in RH for different cases of moisture buffering as a function of the daily change in the reference room. These results can be approximated by a linear relation. This linear relation suggests that books show moisture transport properties to react sufficiently fast on a daily basis. For the constant moisture production, the slope of the curve is 0.51 for A = 15 m^2 and 0.75 for A = 5 m^2, respectively. This means that the daily changes are reduced by 49% and 25%, respectively. For peak loading, the result is comparable (48%), although higher absolute values (21%–37%) are obtained compared to the constant production case (10%–31%).

Finally, we analyze the daily maximum RH as a function of the daily maximum RH in the reference room (Figure 9). Here, the linear relation is less evident. On average, the maximum is reduced for the constant loading between 10% and 5% for A = 15 m^2 and A = 5 m^2, respectively. For peak loading, the average reduction is 17%.

Figure 10 gives the maximum difference in RH during the last ten days of August for a constant moisture production. The results for the two types of books are given in a function of the buffering surface and for different paper fractions. Figure 10 shows that the surface and paper fractions of books have an important influence on the dampening of the fluctuations in RH. For 100% paper fraction, the telephone book paper, showing a higher water vapor permeability, will dampen the RH variation more than magazine paper. Books with a paper fraction of 75% give approximately the same results as books with a paper fraction of 50%. Also, no difference is observed between the two types of paper. The reason for this is the important influence of the presence of air layers between the paper sheets, resulting in a high water vapor permeability. For peak moisture production, the same conclusions were obtained.

We conclude that daily changes in RH can be reduced substantially by the hygroscopic buffering of books, when sufficient book surface is present with paper fractions of 80% or less. The daily and monthly average RHs are less sensitive

Table 3. Moisture Production in Room

Hour	Moisture Production with Peaks		Moisture Production No Peaks	
	g/h	oz/h	g/h	oz/h
1–5	120	4.2	240	8.5
6–7	360	12.7	240	8.5
8–17	0	0	0	0
18	120	4.2	240	8.5
19–20	600	21.2	240	8.5
21–24	120	4.2	240	8.5

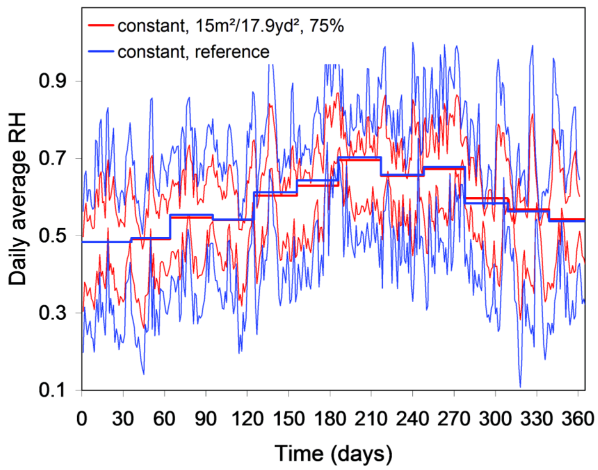


Figure 7 *Variation in RH over a year in a standard room: daily maximum, daily minimum, and monthly average for a constant moisture production (1) with no buffering material in room and (2) with 15 m^2 (17.9 yd^2) telephone book buffering surface (paper fraction of 75%) in room.*

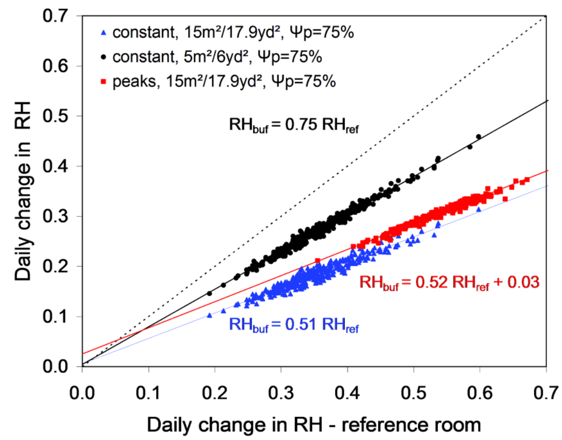


Figure 8 *Daily change in RH in function of daily change in RH in reference room for constant/peak moisture production and moisture buffering by telephone book.*

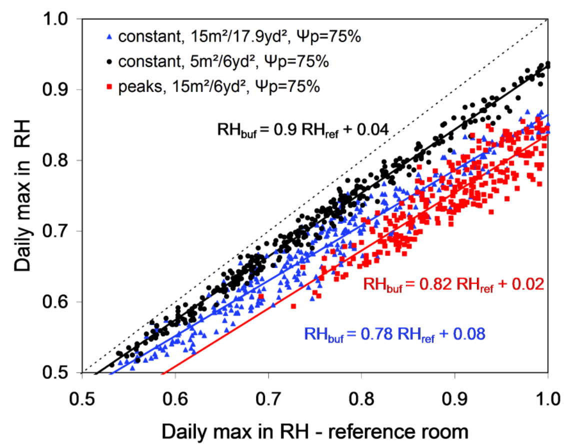


Figure 9 *Daily maximum in RH in function of daily maximum in RH in reference room for constant/ peak moisture production and moisture buffering by telephone book.*

to the moisture buffering by books. The daily maximum RH for peak loading can be reduced to 80% while, for constant moisture production, the influence is more limited.

In Figure 11, we compare the variation of the RH for books and cotton fabric for a peak moisture production during the last five days of February. As already stated, books show sufficient moisture buffering, which lowers the RH variations. Cotton fabric only lowers the RH peak value to a certain level. However, for the constant moisture production case, almost no influence of the buffering of the cotton fabric on the RH in the room was observed. This can be explained by the fact that the cotton sheet, due to its limited thickness (230 μm [9.06 mil]) has a low moisture buffering capacity. During a long constant moisture production, the cotton sheet is completely hygroscopically loaded and no further moisture buffering capacity is present.

Discussion

The simulations illustrate that books can have an important influence on the RH fluctuations in a room if the buffering surface is large enough. Thin cotton sheets aid to dampen peaks in RH. It can be expected that for thicker textile materials (e.g., carpet, curtains, mattress), this buffering effect will be more explicit.

However, the simulation results should be handled with care. In the simulations, we assumed perfect mixing of the air and that moisture production is uniform in the room. The influence of the ventilation pattern, the location of the moisture source, the distance between moisture source and moisture buffering material, the local air movement around

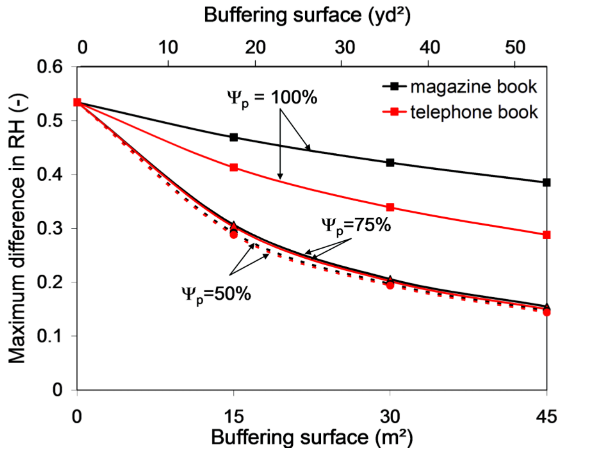


Figure 10 *Maximum difference in RH in a reference room during last ten days of August for a constant moisture production during occupation in function of the buffering surfaces and the paper fractions of telephone books and magazines.*

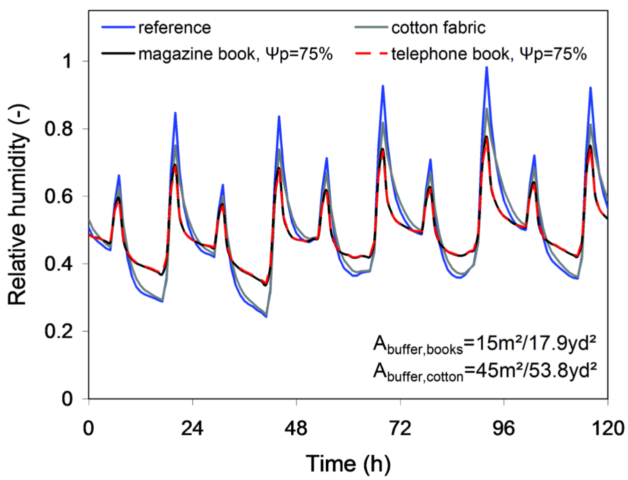


Figure 11 *Evolution of the RH in a reference room for a moisture production with peaks during last five days of February.*

books, and the accessibility of moisture to the edges of the books can have an influence on the RH variations in the room. To understand these effects, experiments in a test room at T.U. Eindhoven are planned.

Finally, the simulations do not take the hysteretic behavior of cotton and paper into account. Future work could include implementing the hysteresis effect in the simulations and adapting the model to calculate the effect of several buffering materials at once in a room.

CONCLUSION

A model to simulate the hygroscopic behavior of books is presented. The model is based on the homogenization of a book as a two-layer material of air layers and paper sheets resulting in effective moisture transport properties. This model is based on the following two characteristic observations:

1. The air has a much lower moisture capacity than the paper and, therefore, this capacity can be neglected.
2. Since a book is a parallel system of air layers and paper sheets, the vapor permeability is determined by the sum of the vapor permeability of the paper and the air layer, weighted with their respective fraction values.

Using the effective moisture transport properties of books, books can be modelled one-dimensionally as a single material.

It is shown that the air layers between the paper sheets greatly determine the rate of the moisture uptake. As the air layer fraction in a book increases, the rate of moisture uptake increases but the effective moisture capacity decreases. The measured vapor transport properties and the developed effective book model were used to simulate the effect of books and cotton sheets on the RH fluctuations in a room. The simulations show that thin cotton fabrics only dampen RH peaks in moisture production. Constant moisture productions will only be buffered a very small amount by thin textile fabrics. Books can significantly buffer peaks in moisture production as well as constant moisture productions when the available buffering surface is large enough (offices, libraries, a library room in an occupied house, etc.).

When designing climatization installations for rooms where a lot of books and textiles are present, the moisture load on the installation will decrease, as well as the energy costs for climatization. This can be important for buildings, such as libraries and museums, which require close attention to their indoor climate because of the importance of good preservation of art objects and books. Fabrics can only help to buffer the peaks in RH, for example, in the form of curtains and walls and floor coverings; the presence of books will lead to a decrease of fluctuations in RH.

NOMENCLATURE

A = surface, m^2 (yd^2)
b_m = moisture effusivity, kg/m^2·Pa·s$^{0.5}$ (lb/ft^2·psi·s$^{0.5}$)
d = depth, thickness, m (in.)
D_w = moisture diffusivity, m^2/s (ft^2/s)
g_v = vapor flow, kg/m^2·s (lb/ft^2·s)
G_{vp} = vapor production, kg/s (oz/s)
h = relative humidity
m_m = moisture mass, kg (lb)
n = ventilation rate, 1/h
p_v = vapor pressure, Pa (lb$_f$/ft^2)
q_{buf} = water vapor exchange with buffering surface, kg/m^2·s (lb/ft^2·s)
S_l = degree of saturation (by liquid)
T = temperature, K (°F)
V = volume, m^3 (yd^3)

w = moisture content, kg/m^3 (lb/ft^3)
β = surface coefficient, s/m (s/in.)
δ = vapor permeability, s
ξ = volumetric moisture capacity, kg/m^3 (lb/ft^3)
μ = water vapor resistance factor
ρ = density, kg/m^3 (lb/ft^3)
ρ_v = water vapor concentration, kg/m^3 (lb/ft^3)
ϕ_0 = open porosity, m^3/m^3 (ft^3/ft^3)

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