Moisture penetration in a chair seat as a response to daily RH variations in the indoor air

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Moisture penetration in a chair seat as a response to daily RH variations in the indoor air

Climatic chamber measurements and calculations

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SUMMARY:
In the indoor environment there are a number of materials with potential to act as moisture buffers including both building materials and furnishing materials. For daily moisture variations in the indoor air furniture with upholstery can play an important role as moisture buffers. Material properties and calculation models describing the response to moisture variations in the ambient climate for these material combinations are limited. In this project the moisture properties for a chair seat with a wool fabric and plastic foam padding were determined. The moisture penetration in the chair seat was measured using small temperature and relative humidity sensors. A numerical calculation model describing the step-response as well as the response to ramp variations is described. A comparison between measurements and theoretical calculations was performed. The difficulties with determination of material properties for highly permeable materials are also discussed as well as suitable methods and special considerations.

1. Introduction

Materials found in the indoor environment form a heterogeneous group with both typical building materials and furnishing materials. Several of the materials exposed to the indoor air have the potential to act as moisture buffers.
There are different ways to categorize the materials in the indoor environment (Martin, 1986) suggested a division into slow and fast materials. (Plathner, 2002) described the furnishing materials as soft and hard. Textiles and upholstery are examples of soft furnishing materials and wooden furniture and hard flooring are examples of hard furnishing materials.
(Svennberg, 2003) suggested that the materials should be divided into different categories depending on their basic moisture properties in varying timescales. These materials may play an important role in buffering the daily moisture variation (Svennberg, 2004).

2. Materials

The measurements as well as the theoretical calculations were performed on a chair seat from an industrially manufactured office chair.
The chair seat consisted of a 5 mm plastic board, 31 mm polyether foam and a 2.5 mm felted wool fabric as a cover. The plastic board was covered underneath with a non-woven synthetic

fabric. The chair seat in cross section with the placing of the RH-and temperature sensors is shown in Fig. 1 and the thickness and density of the materials used are given in Table 1.

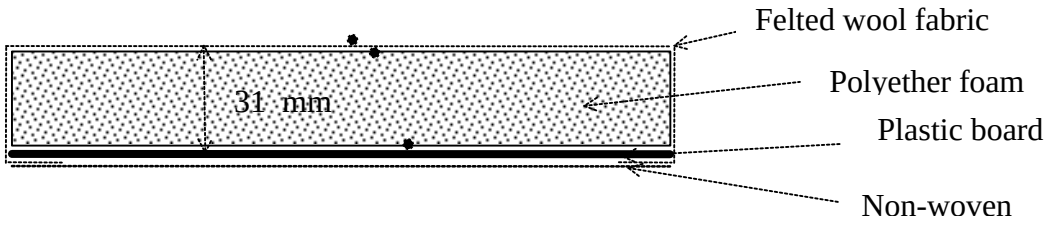

FIG. 1: A schematic drawing showing the structure of the chair seat used for measurements and calculations. The placement of the temperature and RH-sensors is indicated with a (·).

Table 1. Thickness and density

Material	Thickness **(mm)**	Density **(kg/m^3)**
Polyether foam	31	36
Felted wool fabric (100% wool)	2.5	176

3. Methods

3.1 Determination of moisture properties of the materials

The sorption isotherms as well as the water vapor resistances (Z) were determined for the felted wool fabric and the polyether foam.

3.1.1 Sorption balance

The sorption isotherms for the felted wool fabric and the polyether foam were determined using a sorption balance (DVS 1000, Surface Measurement Systems, London, UK (Anderberg, 2004)). The initial weights of the material samples were 57.7 mg and 21.2 mg respectively. The samples were initially dried in the instrument in dry nitrogen. The RH inside the instrument is generated with high precision by mixing dry and water vapor saturated nitrogen gas. Both absorption and desorption were determined in steps of 10 %RH (Svennberg, 2005). The temperature during the experiment was 21 ^{o}C.

The diffusivity for the felted wool fabric was evaluated from the step-change measurements provided by the sorption balance measurements mentioned earlier. The mass change is plotted against the square root of time and gives an essentially linear curve for the initial part of the step. From this the diffusivity, *D*, can be evaluated using an evaluation method based on (Crank, 1975). The method is presented in detail by (Anderberg, 2004). From the diffusivity and the air speed the vapor resistance Z_t of the textile layer can be calculated.

3.1.2 Cup method

The vapor resistance for the 31 mm polyether foam was determined using the cup method according to EN ISO 12572:2001 in two intervals of RH, i.e. 75-49 %RH and 33-49 %RH with the exceptions given below. The cup shown in Fig. 2 was used for the measurements. The specimen was fastened to a plexiglass ring by use of silicone mastic, and the plexiglass ring with the specimen was fastened to the cup by use of rubber sealing as the tightening top was screwed to the cup. Inside the cup a supplementary glass cup containing the saturated salt solution was placed. By use of this supplementary glass cup the air layer thickness inside the cup was 6 mm. The area of cross-section of flow path was 5000 mm^2.

The 75 %RH was generated using a saturated salt solution of NaCl and the RH of 33 %RH inside the cup by using a saturated $MgCl_2$ solution. In both cases the ambient climate outside the cup was held at 23.4 °C and 48.8 %RH, i.e. 49 %RH. The average air velocity above the cups was 2.3 m/s and the average atmospheric pressure was 982 hPa during the measurements.

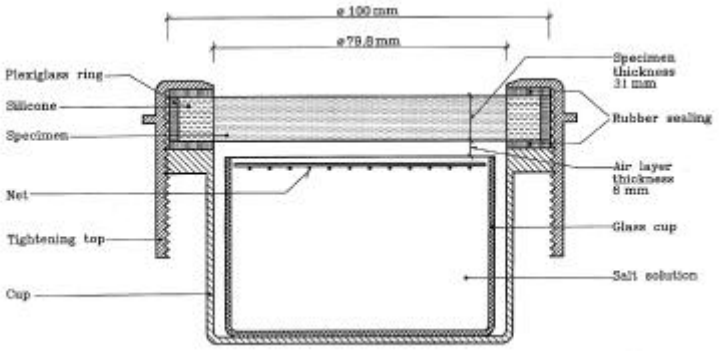

FIG.2: The experimental set-up in the cup method.

The measured water vapor resistance Z_m is primary the resistance in the specimen material itself Z_p, but also the surface resistances at the specimen surfaces Z_1 and Z_2 and the resistance in the air layer inside the cup Z_a must be taken into account. Refer Equation 1, which includes these resistances:

$$q = \frac{\Delta p}{Z_p + Z_1 + Z_2 + Z_a} = \frac{\Delta p}{Z_m} \qquad (1)$$

The surface diffusion resistances Z_1 and Z_2 may be found by Lewis' law, and the diffusion resistance Z_a for an air layer thickness of L_a is $Z_a=L_a/\delta_a$, where δ_a is the water vapor permeability (WVP) in air. An analogy to heat transfer calculations is used to find water vapor pressure p_{1s} and p_{2s} and the corresponding relative humidities ϕ_{1s} and ϕ_{2s} at the specimen surfaces when the different diffusion resistances Z_a, Z_1, Z_2 and Z_p are known (Hansen, 1990). The KOPLYSE 3.0 program (Mullit, 1993) which calculates water vapor resistance Z_m without corrections and the resistance in the specimen material itself Z_p with corrections together with the corresponding relative humidities ϕ_{1s} and ϕ_{2s} at the specimen surfaces was used in the evaluation.

3.2 Chair seat measurements

The penetration measurements of the complete chair seat were performed in a full-scale well-insulated and moisture- and air tight climatic chamber (the PASSYS cell), see Fig. 3. In the climatic chamber the chair seat was subjected to a ramp variation in RH.

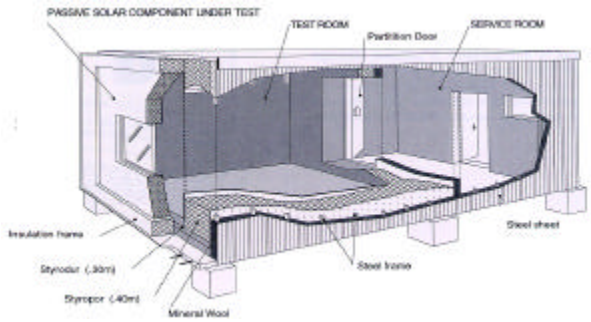

FIG. 3: Drawing of the test cell. The test room is covered with steel sheets on the inside on all sides except the exchangeable facade, which is covered with a polyethylene foil to be moisture tight.

The indoor humidification, that represents the moisture production of an inhabited room, was provided by evaporation of moisture from a reservoir of water heated by an electric coil. Humidity was withdrawn from the air by a dehumidifier draining into the same reservoir. The drying represents the removal of humidity from the room that would normally take place by ventilation. The water reservoir was suspended in a load cell, and the rates of humidification and drying was controlled according to a predefined schedule. Padfield (1998) has used the principle in a small (0.5 m^3) test chamber in the laboratory. The climatic chamber is instrumented with sensors for measuring both the outdoor climate and the indoor conditions. The indoor relative humidity is measured with capacitive moisture sensors with an accuracy of about ± 2 %RH. Two small fans were placed on the floor in both ends of the test cell to ensure a well-mixed airflow.
Three combined temperature and relative humidity sensors were applied on the chair seat for moisture penetration measurements. The first sensor was placed on top of the felted wool fabric. The second sensor was placed on top of the polyether foam but under the felted wool fabric and the third and last sensor was placed under the polyether foam. The sensors were placed somewhat displaced so that interference from the other sensors was minimized, see Fig 1.

3.3 Analytical solution

The measured water vapor content in the textile and at different depth in the polyether foam will be compared to the analytical solution, where the diffusion in the foam is coupled to the textile layer with its moisture capacity and the imposed vapor content in the air above.

3.3.1 Mathematical problem

The water vapor content v(x,t) shall satisfy the diffusion equation. The initial value at $t = 0$ is v_{in}. The moisture flux is zero at the boundary $x = L$. We have

$$0 < x < L: \quad \frac{1}{D_m} \cdot \frac{\partial v}{\partial t} = \frac{\partial^2 v}{\partial x^2}, \quad v(x,0) = v_{in}; \quad \left.\frac{\partial v}{\partial x}\right|_{x=L} = 0. \tag{2}$$

At the boundary $x = 0$, there is a textile layer with the moisture capacity C_{sm}. The moisture flow resistance to the outside air with the prescribed moisture content v_0(t) is Z_s. The moisture balance at the boundary $x = 0$ becomes

$$C_{sm} \cdot \frac{\partial}{\partial t}\left[v(0,t)\right] = \frac{v_0(t) - v(0,t)}{Z_s} + d_v \cdot \left.\frac{\partial v}{\partial x}\right|_{x=0} \tag{3}$$

The two right-hand terms are the moisture fluxes from air and from the underlying material. We may multiply the equation by Z_s. The boundary condition then involves a time $t_0 = C_{sm} \cdot Z_s$, which is the decline time for the textile against air without flux from the underlying material. It also involves a length $L_0 = Z_s \cdot d_v$, which is a measure of the surface resistance Z_s.
The moisture content v_0(t) in the air varies in a “triangular” way between v_{in} and v_1 with a time period t_p, see Fig. 4.

3.3.2 Superposition of ramp solutions

The solution $v(x,t)$ may be obtained from a basic *ramp* solution by suitable superposition. This is described in detail in (Claesson, 2005).Let $v_r(x,t)$ be the solution for a ramp function:

$$v_0(t) = \begin{cases} t & t \geq 0 \\ 0 & t < 0 \end{cases} \qquad v_r(x,0) = 0 \tag{4}$$

The ramp solution starts from zero: $v_r(x,0) = 0, \quad 0 \leq x \leq L$.

We use the transformation

$$v(x,t) = v_{\text{in}} + \frac{v_1 - v_{\text{in}}}{t_{\text{p}}} \cdot v'(x,t) \tag{5}$$

The solution during the first period $0 = t = t_{\text{p}}$ (and for $t < 0$) is now $v'(x,t) = v_r(x,t)$. In the next period $t_{\text{p}} \le t \le 2 \cdot t_{\text{p}}$, we have to subtract two times the ramp solution that starts at $t = t_{\text{p}}$:

$$v'(x,t) = v_r(x,t) - 2 \cdot v_r(x, t - t_{\text{p}}), \qquad t \le 2t_{\text{p}} \tag{6}$$

In the next period, we have to add $2 \cdot v_r(x, t - 2 \cdot t_{\text{p}})$, and so on. In general we have:

$$v'(x,t) = v_r(x,t) + 2 \cdot \sum_{m=1}^{M} (-1)^m \cdot v_r(x, t - m \cdot t_{\text{p}}), \qquad t \le (M+1) \cdot t_{\text{p}} \tag{7}$$

3.3.3 Fourier solution

The basic ramp problem in (5) may be solved by a Fourier series expansion. A detailed report of this is given in (Claesson, 2005). The solution for $t \ge 0$ is given by:

$$v_r(x,t) = t - \frac{LL_0 + D_m t_0 + xL - x^2/2}{D_m} + \sum_{n=0}^{\infty} B_n \cos\left[a_n (1 - x/L)\right] \cdot e^{-a_n^2 D_m t / L^2} \tag{8}$$

Here, the Fourier coefficients are

$$B_n = \frac{2L^4}{D_m a_n^2} \cdot \frac{\cos(a_n)}{L_0 L a_n^2 + \cos^2(a_n) \cdot \left(D_m t_1 a_n^2 + L^2\right)} \tag{9}$$

The eigenvalues a_{n} are the solution to

$$\frac{L}{L_0 \cdot a_n} - \frac{D_m t_1}{L^2} \cdot a_n = \tan(a_n), \qquad 0 < a_0 < a_1 < \ldots \tag{10}$$

The series solution converges very rapidly except for small times. An alternative solution from Laplace transformation is then used. The complete solution is implemented in Mathcad. The result with five-digit accuracy is obtained requiring very little computer time (less than 2 s for the case of Fig.4). All these details are reported in (Claesson, 2005).

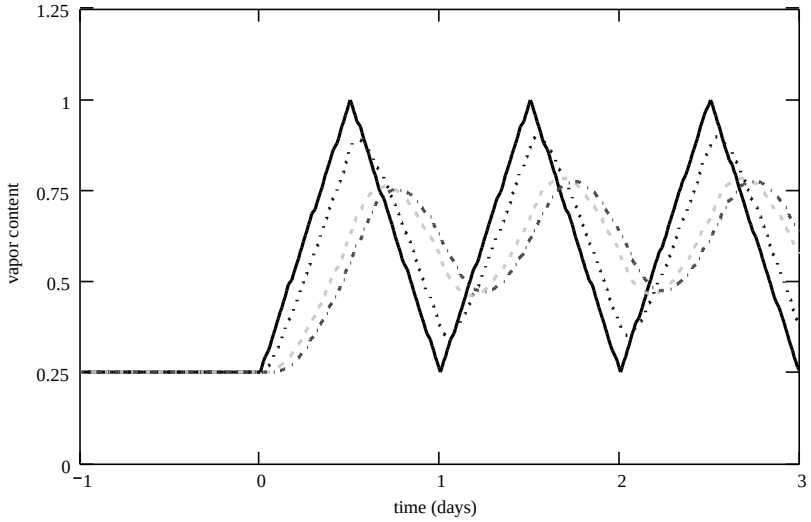

FIG. 4: Water vapor content $v_0(t)$ (solid black line) in the air at the boundary x= 0, normalized values of all parameters was used (all equal to 1). The dashed lines represent different depths in the foam: dotted black – under fabric, light grey - half depth in the foam, medium grey - under the foam.

4. Results

4.1 Determination of material moisture properties

The sorption isotherms for the felted wool fabric and polyether foam shows a great difference in moisture capacity see Fig. 5. The diffusivity for the wool fabric in the range 35-75 %RH was estimated to $450 \cdot 10^{-6}$ m^2/s.

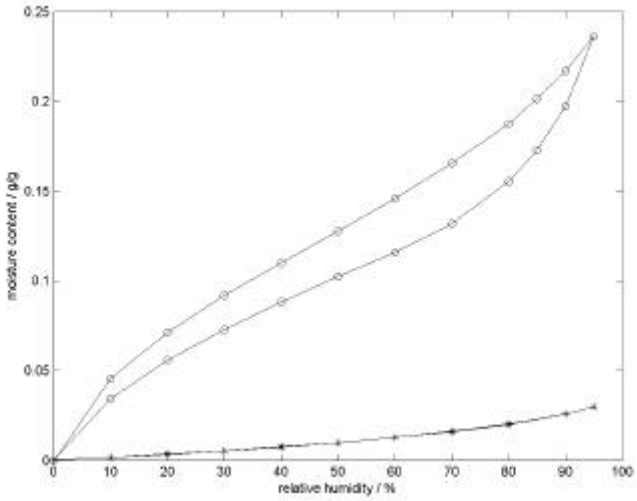

FIG. 5: The sorption isotherm for the felted wool fabric (o) and the polyether foam (∗).

The results of the water vapor resistance Z_m without corrections, and the resistance in the specimen material itself Z_p with corrections for Z_a, Z_1 and Z_2 for the 31 mm polyether foam is shown in table 2.

Table 2. The results of the water vapor resistance Z_m without corrections and the resistance in the specimen material itself Z_p with corrections for Z_a, Z_1 and Z_2 for the 31 mm polyether foam. The RH inside the cups was 75 %RH for cups no. 1-3 and 33 %RH for cups no. 4-6.

	Without corrections		With corrections	
Cup no.	**Z_m** (GPa·s·m²/kg)	**Z_m-average** (GPa·s·m²/kg)	**Z_p** (GPa·s·m²/kg)	**Z_p-average** (GPa·s·m²/kg)
1	0.34	0.34	0.27	0.27
2	0.33		0.26	
3	0.35		0.28	
4	0.35	0.35	0.28	0.28
5	0.35		0.28	
6	0.36		0.29	

The material parameters used in the calculation of the analytical solution is shown in table 3.

Table 3. Material properties used in the theoretical calculations.

Material	Diffusivity **D (m^2/s)**	Moisture capacity x (-)	Surface resistance **Z_{sv} (s/m)**	Surface resistance **Z_{sp} (GPa·s/m²/kg)**
Felted wool fabric	$450 \cdot 10^{-6}$	0.44	100	0.014
Polyether foam	$0.36 \cdot 10^{-6}$	0.025	-	-

4.2 Comparison between chair measurements and analytical solution

The analytical solution uses an ideal triangular variation for the ambient climate (e.g. boundary conditions) and is therefore not capable of taking the small fluctuations caused by

the climatic system. Still the analytical solution provides a good representation of the moisture penetration in the chair seat. An addition of internal resistance in the analytical solution as well as using truer boundary conditions would improve the already satisfactory agreement between measurement and theoretical calculations even more.

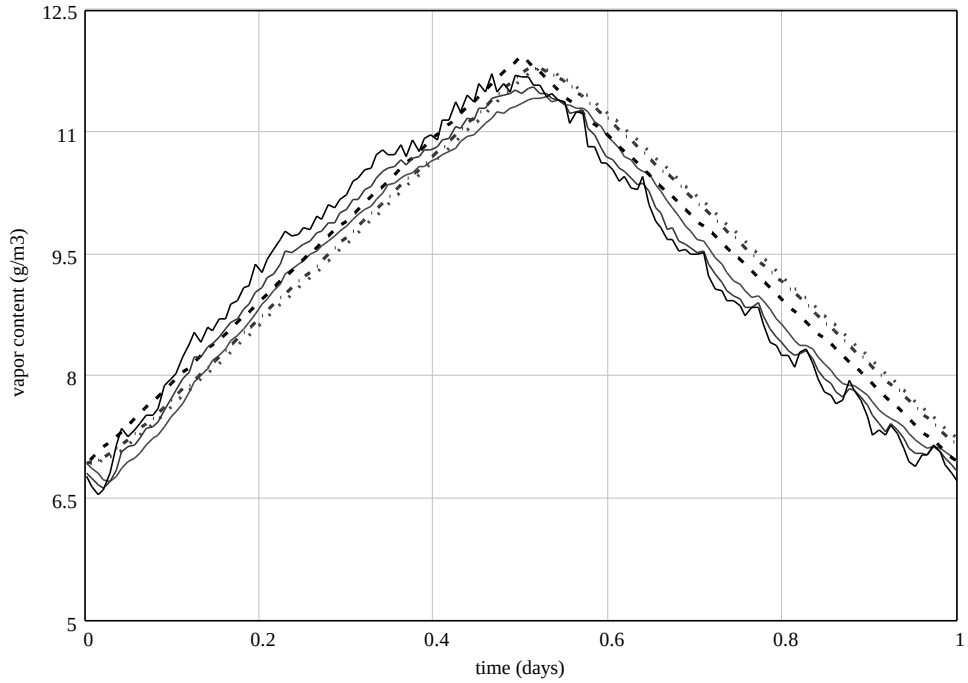

FIG.6: Comparison between the measured vapor content in the chair seat during the climatic chamber experiments (thin solid lines: black – the top surface, medium grey - under the fabric, light grey – under the polyether foam) and the analytical solution (thick dashed lines: black – the top surface, dashed grey- under the fabric, dotted grey – under the polyether foam).

5. Discussion

The results of the water vapor resistance Z_m-average without corrections for the 31 mm polyether foam are in range 0.34-0.35 GPa·s·m^2/kg for the two intervals of RH, which gives the results of the water vapor resistance Z_p-average with corrections for Z_a, Z_1 and Z_2 in the same range 0.27-0.28 GPa·s·m^2/kg for the two intervals of RH. The corrections are in the range 0.07 GPa·s·m^2/kg which is 20 % of Z_m.

In the measurements the air layer thickness inside the cup was 6 mm, while EN ISO 12572:2001 recommends 15 mm air layer thickness. Smaller air space between sorption material and specimen gives higher RH on specimen surface against cup for the interval 75-49 %RH, as resistance of air layer is smaller. But also the overall measured diffusion resistance for the test Z_m for this very porous polyether foam is highly influenced by the air layer thickness. The large influence of the resistance in the air gap makes the traditional cup method unsuitable for thin and permeable textile layers. The method to evaluate the diffusivity from the step measurements made in the sorption balance is promising but need further validation. They also provide simultaneous determination of sorption isotherms and moisture transport properties.

The determination and estimation of surface and internal resistance to the type of multi-layered material combinations that this chair seat represent are also a matter for more investigations since they have a rather large impact on calculated results.

6. Conclusions

The presented analytical solution and measured data commence a better understanding of the moisture dynamics for furnishing such as textiles and soft furniture for daily variations in the indoor climate. More work is needed to find ways to couple this to room or building simulation tools. The methods to assess material properties used in this study showed to be useful for highly permeable materials.

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