Moisture Buffering Effects on Indoor Air Quality—Experimental and Simulation Results

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ABSTRACT

The ability of building materials to control indoor air humidity is studied in this paper. First, moisture capacity and transient response of building materials were investigated in small-scale laboratory experiments. Effects of moisture-absorbing interior wall materials on indoor air humidity were measured in a full-scale room under controlled conditions with known ventilation rates and moisture production schedule. The measured interior surface materials included wood, porous wood fiberboard, gypsum board with hygroscopic insulation, perforated plywood board, and, in a reference case, aluminium foil. Second, numerical simulation tools for hygrothermal performance analyses of building envelope parts and for buildings as a whole were used to assess the impact of hygroscopic mass on indoor air humidity. Two levels of testing and simulation were carried out: First, the moisture capacity of building materials in dynamic conditions was tested in small-scale laboratory tests. Second, the materials were placed in a room with intermittent moisture production. Moisture production and ventilation rates were set to correspond to those typical in residential buildings. Mass transfer between the finishing materials and indoor air affects the humidity both in indoor air and in the building envelope. The effect of coatings and their vapor permeance on the moisture exchange was investigated. A sensitivity study looking at the hygrothermal material properties and their effects on the performance was carried out.

The results show that building materials exposed to indoor air can have a strong effect on the indoor air humidity. Potentials, practical applications, and design concepts for utilizing the moisture-buffering effect of building materials are discussed.

INTRODUCTION

Mechanical (active) heating and ventilation systems try to maintain the indoor temperature and humidity at a comfortable level. Often the systems only consider temperature and the humidity is controlled only indirectly and as a function of the thermal performance of the air-conditioning system. Relative humidity has been shown to affect thermal and respiratory comfort, the perception of indoor air quality (IAQ), and energy consumption. In the efforts to lower energy consumption of buildings, passive systems may be used to aid or even eliminate some parts of the active (mechanical) systems.

The ability of building materials to control indoor air humidity is studied in this paper. When the indoor moisture load increases, the indoor air humidity tends to increase. The increase of the relative humidity level depends on the air change rate, outdoor air conditions, and on the moisture transfer between structures and the indoor air. Many earlier studies (Rode et al. 2001, 2003; Salonvaara 1998; Simonson and Salonvaara 2000; Simonson et al. 2001a, 2001b; Karagiozis et al. 1999; Salonvaara and Karagiozis 2001) have shown that the moisture-buffering effect of hygroscopic structures may have a significant effect on the relative humidity level and variations of the indoor air, which may improve the perceived comfort and quality of the air.

The phenomenon "moisture buffering" has been acknowledged, but information regarding how to design buildings that make use of it is still lacking. A Nordtest project (www.nordtest.org), "Moisture Buffering of Building Materials," was started in the end of 2003. The objective of the project is to define the term "moisture buffering" and suggest how to characterize the material properties. A test method to measure

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the relevant parameters will be developed and tested. The results presented in this paper try to provide answers to those questions.

Simulation models that can take into account the mass transfer between indoor air and building components and that can estimate the effects of moisture buffering on indoor air humidity already exist. However, these models still need more validation in real full-scale environments. The model used in this study is called LATENITE-VTT. The model was validated in an earlier study against field experiments (Salonvaara and Simonson 2000), but the validation included only two cases: one with impermeable walls (polyethylene plastic-covered surfaces) and one with gypsum wallboards in the walls and the ceiling. In a more recent study (Simonson et al. 2002a, 2002b), wood was found to have desirable properties as a moisture buffer material. The results of the study were mainly based on the simulations, and additional validation was therefore necessary. In the second phase of the project, small- and large-scale laboratory and field experiments were carried out including wood and wood-based materials as interior linings of conditioned spaces.

SMALL-SCALE EXPERIMENTS IN LABORATORY

The moisture-related material properties determined with standard test procedures and conditions do not give adequate information about the effective sorption or desorption capacity of building materials. The effect of sorption hysteresis may affect the effective moisture capacity and the moisture transfer under dynamic humidity variations. Also, the performance of multilayered structure components with possible coatings is more complex than that of only one material layer.

There exists no method to experimentally study the moisture-buffering effect of materials or the structural applications to reduce indoor air humidity variations.

An experimental method that could be used to simulate short-term (diurnal) cyclic changes of the indoor air moisture load and relative humidity level is needed. A method to characterize the moisture-buffering performance property of materials or structural systems is briefly presented with results here. The results show how much moisture some typical hygroscopic material layers can absorb from indoor air during peak periods of humidity and transfer it again back to indoor air during the periods of low humidity. The results can be used to complete the sorption properties of materials and also in verification of numerical simulation models. The results can also be used to compare different hygroscopic structure applications and to design such applications so that their effective hygroscopic capacity matches with the indoor humidity loads and cycles.

A similar method has been studied by Reick (2000). Rode et al. (2001) and Mitamura et al. (2001) have also presented results from such measurements.

Test Method

The method is simply to expose the material surface to varying ambient humidity. The material sample is weighed frequently. The size of the square samples was approximately 25 cm × 25 cm. The size depended on the materials and was limited by the ability of the scales to measure weight. The mass flux as a function of time between the material surface and the ambient air can be calculated from the data. Ambient air humidity followed a step change pattern with an 8-hour period in higher humidity conditions and a 16-hour reversion period in lower humidity conditions. The lengths of these humidity variation periods is based on occupancy time in offices or in bedrooms; thus, it is assumed that the moisture load periods represent some real-life conditions.

During the moisture load period, the test structure absorbs moisture, and during the period with a lower humidity level, the structure gives off (some) absorbed moisture to the room air space (reversion period). The effective moisture capacity is determined for both of these periods.

The moisture-buffering capacity of the materials depends mainly on the sorption and vapor permeability properties. These properties are not constants but, instead, may vary a lot depending on the level of humidity; thus, the moisture-buffering capacity of materials is not constant either but a function of relative humidity. Therefore, two different levels of humidity have been used in testing the materials. The two levels selected represent indoor conditions during winter and summer months. The humidity levels were 50/23% RH and 75/50% RH for winter and summer conditions, respectively. For most materials, the moisture buffering-capacity is higher at higher humidity.

Table 1 presents a summary of the moisture capacities determined during the 8-hour period of wetting and 16-hour period of drying period. These figures give an approximation of the applicable buffering capacity in the test conditions.

Pine against the grain and 12 mm gypsum board had about the same moisture capacity under the 50/23% RH test conditions (12 g/m^2 during 8 hours of wetting at 50% RH). Pine along the grain has a very high moisture capacity because of the high vapor transfer permeability in the air of the long "tubes" of wood.

Paint in the surface (two layers of acrylic paint) acted almost as a vapor barrier and effectively limited moisture transfer between the structure and the indoor air to an insignificant level according to the measurements. The diffusion resistance of the paint may vary much depending on the product and on the substrate to which it is applied. More diffusion open paints are available.

Cellulose fiber insulation behind the gypsum and building paper increased the moisture capacity about 50% (24 g/m^2 during eight hours) when compared to a case with similar structure having mineral wool insulation (16 g/m^2 during eight hours). These results also show that the inner material layers behind the gypsum sheathing board can have an effect on the moisture-buffering capacity of the wall during diurnal cycles.

A 12 mm layer of porous wood fiberboard without coating had about 45 g/m^2 moisture buffering capacity.

Table 1. Measured Change in the Mass of Moisture during Eight Hours Wetting Period and 16 Hours Drying Period in 50/23% RH and 75/50% RH Tests

Case	Change in the Mass of Moisture, g/(m^2)	
	Wetting in 8 h	Drying in 16 h
Wood, pine, smooth surface, against the grains	12	10
–"– @ 75/50% RH	22	16
Wood, pine, along the grains	90	70
Gypsum, painted twice	<1	0
Gypsum, unpainted	12	12
Porous wood fiberboard	45	45
–"– @ 75/50% RH	36	32
Gypsum, unpainted + mineral wool insulation	16	15
Gypsum, unpainted + cellulose fiber insulation	24	20

Testing of Simulation Model against Small-Scale Experiments

The transient moisture transfer process between a pine wood sample and the adjacent air space could be simulated numerically relatively well when the total change of the mass of moisture was used as a criterion. During the drying process, the measured moisture flow out of the structure was higher than the calculated flow after the change of the relative humidity of the air (Figures 1 and 2). The difference in moisture mass was the highest one to two hours from the change, but at the end of the period, the measured and calculated moisture levels were about the same.

How well the measured and simulated results match each other depends on many parameters, such as material properties (sorption isotherms, vapor permeability as a function of humidity), and the boundary layer properties, e.g., air flow on the surface. A lot of uncertainty and variation exist in the vapor permeability of wooden materials, even between samples taken from the same lot. Hysteresis (different sorption-desorption curves) can also affect the performance, but the effect seems to be small in these measured results. The simulation model did not include hysteresis effects and only one sorption curve was used. The surface heat and mass transfer coefficients depend on the size of the system, and since the main interest was on full-scale performance, the sensitivity analyses were focused on the full-scale testing.

FULL-SCALE EXPERIMENTS IN TWO IDENTICAL ROOMS

The performance of the materials in small-scale experiments needed to be verified in full-scale experiments. Air movements in a larger room near and far from the material surface and the rate of mixing of air may interfere with the mass transfer and cause differences in the effects found in small- and large-scale experiments. The effects of moisture buffering were investigated in the real-size test rooms at Fraunhofer Institute für Bauphysik's building in Holzkirchen, Germany. The building had two identical rooms that could be used to investigate a room with moisture buffer materials and a room without any moisture storage, being exposed to the same naturally occurring environmental conditions at the same time.

The experiments were carried out in a building erected on the IBP test site in the 1980s designed for energy performance investigations published in Künzel (1984). Two of the five test rooms could be used for our purpose because they have identical walls. The ground plan of the test rooms and the adjacent spaces is plotted in Figure 3. The test rooms have a ground area of 20 m^2 and a volume of 50 m^3. They are heavily insulated (200 mm of polystyrene) toward the ground. In order to avoid moisture flow to or from the ground, the floor has a vinyl covering. The outer surfaces of the ceiling and interior wall sections are surrounded by a conditioned space. The external walls consist of 240 mm thick brick masonry with 100 mm exterior insulation (ETICS/EIFS). On the interior surface 12 mm of standard plaster is applied. The plaster was old and did not have any initial moisture left at the time of testing. The double-glazed windows face south (U-value, 1.1 W/m^{2}K; total solar energy transmittance, 0.57; frame ratio, 30%). Special consideration is given to the airtightness of the rooms. Blower-door tests confirm an n_{50} value below 1 h^{-1}. Following past IBP investigations reported in Hens (1991), the walls and ceiling of one room (test room) were covered with aluminum foil while the other room was left as is (reference room). Since the envelope of the test room has almost no sorption capacity, it can be used to determine the moisture-buffering effect of furniture and specially devised sorptive building components. The reference room with its plastered walls serves as an example of typical construction of German houses.

The rooms are equipped with calibrated heating, ventilating, and moisture-producting systems as well as fans in order to avoid stratification. The indoor air temperature and humidity are measured at different levels above the ground. Temper-

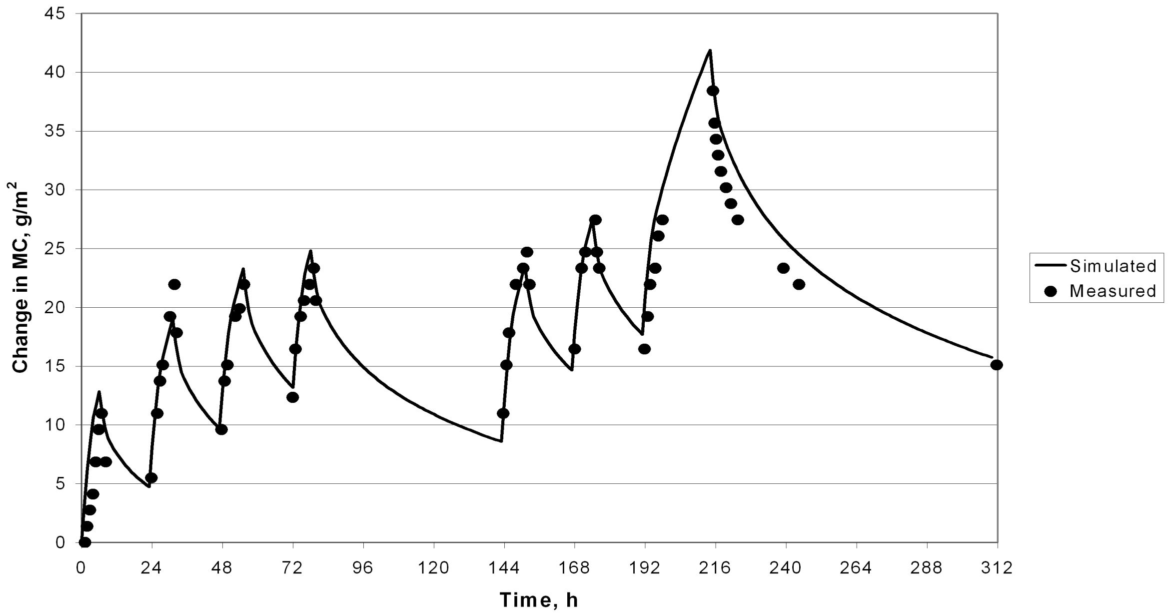

Figure 1 *Comparison results between the small-scale measurements and the numerical simulation.*

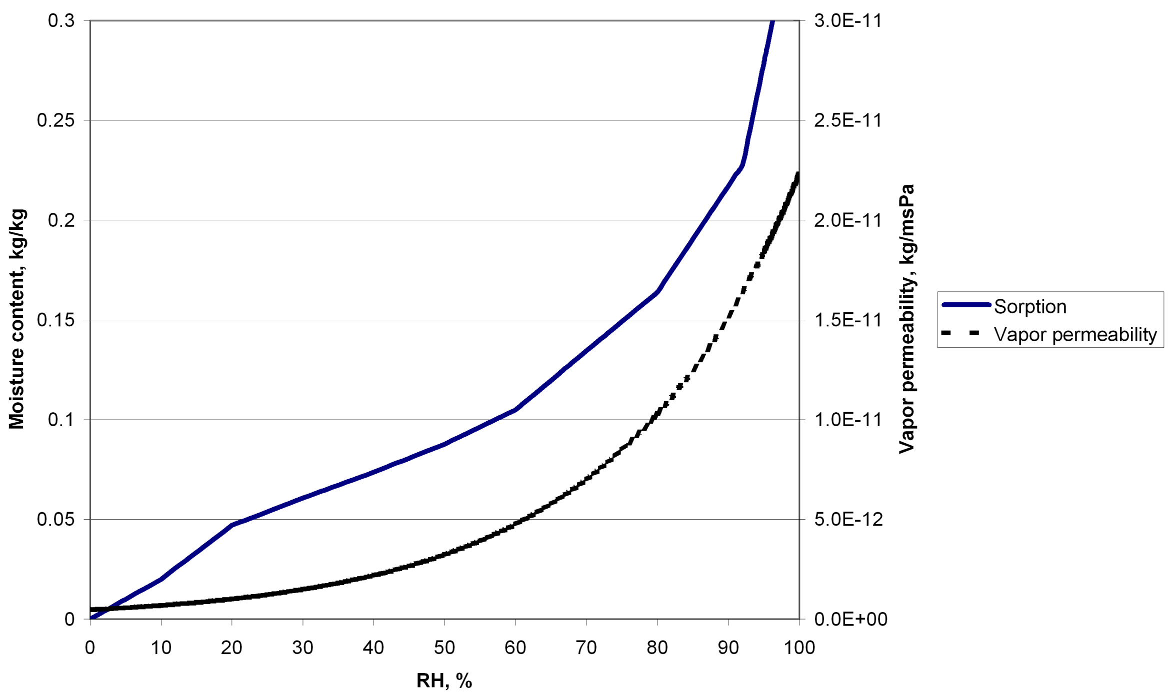

Figure 2 *Material properties of pine used in the small-scale test simulations.*

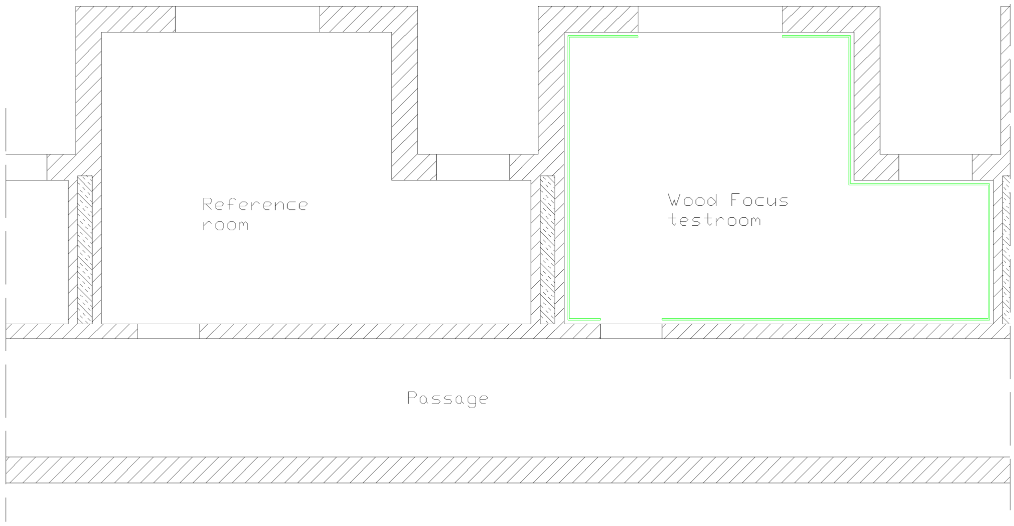

Figure 3 *Ground plan of the test rooms.*

ature sensors and heat flux meters are also fixed to the interior surface of external walls. All values are measured on a five-minute basis and can be analyzed with an Internet-based tool developed by IBP called IMEDAS (see Figure 4).

The first tests are done with a constant air change rate of 0.5 h^{-1}, which is the hygienic minimum rate according to German regulations. The indoor air temperature is kept constant at 20°C controlled by a sensor in the middle of the room. The moisture production is derived from an average moisture load of 4 g/m^3. This means the total amount of water dissipated in the room per day is 2.4 kg or 48 g/m^3. In reality the production rate will not be constant over the whole day. Here a basic production rate of 0.5 g/m^3h is assumed with peaks in the morning and in the evening, i.e., 8 g/m^3h from 6 to 8 a.m. and 4 g/m^3h from 4 to 10 p.m. every day (Figure 5).

RESULTS

The measured values for the relative humidity in both test rooms are plotted in Figures 6-10. The corresponding calculations are based on the assumptions described above concerning indoor temperature, moisture production, and ventilation. They are carried out for the test room in its original form (i.e., covered with aluminum) and the reference room, which is lined with the standard gypsum plaster. The simulations are carried out with a constant air change rate of 0.5 h^{-1}.

The simulated and measured results of the relative humidity in air are compared for the following cases that were measured at the same time in the two adjacent rooms. The cases investigated for this paper are listed in Table 2. The comparisons are made for the measured and simulated data. Cases in set A were measured in December 2002 and cases in set B were measured in January 2003.

Indoor Humidity in a Room with Walls Covered with Unpainted Wood or Painted Plaster

The surfaces of the walls and the ceiling had painted plaster in the reference room when the measurements were carried out for the adjacent room with unpainted wood (spruce) on the walls. The simulations reproduced the measured indoor humidity variations well. The same level of humidity indicates that the ventilation rate is well maintained at the intended set value. Two simulation results for unpainted wood surface are presented in Figure 6 and the difference between them is in the vapor permeability of wood, which was made for sensitivity analysis purposes and is explained more later in the paper. Results for plaster surfaces are presented in Figure 7.

Active Moisture Buffer Capacity. According to the simulations, the wood linings react to the changes in indoor humidity only within a very thin layer below the surface exposed to the indoor air. The changes in relative humidity right below the surface of the wood linings during one full day with intermittent moisture loads and dry periods are shown in Figure 8. Below 50% relative humidity, the vapor permeability of the wood is approximately $2\text{-}3 \cdot 10^{-12}$ kg/m^2s Pa. For a thickness of 1 mm, this gives a permeance of $2\text{-}3 \cdot 10^{-9}$ kg/m^2s Pa, which is close to the mass transfer coefficient between air and the surface.

Indoor Humidity in a Room with Walls Covered with Aluminum or Unpainted Plaster

The room that has its walls and the ceiling covered with aluminium foil does not have any moisture-buffering capacity except the indoor air. The effect of ventilation on the indoor humidity can be seen in Figure 9. An analytical solution for the decay of humidity with constant ventilation rate of 0.5 ach has been plotted in the figure, too. The ventilation module of the simulation model seems to work well and reproduces the analytical behavior of indoor humidity in the aluminium foil-covered room. The analytical solution and the measured data do not match well in one part. The reason for this deviation is yet unknown.

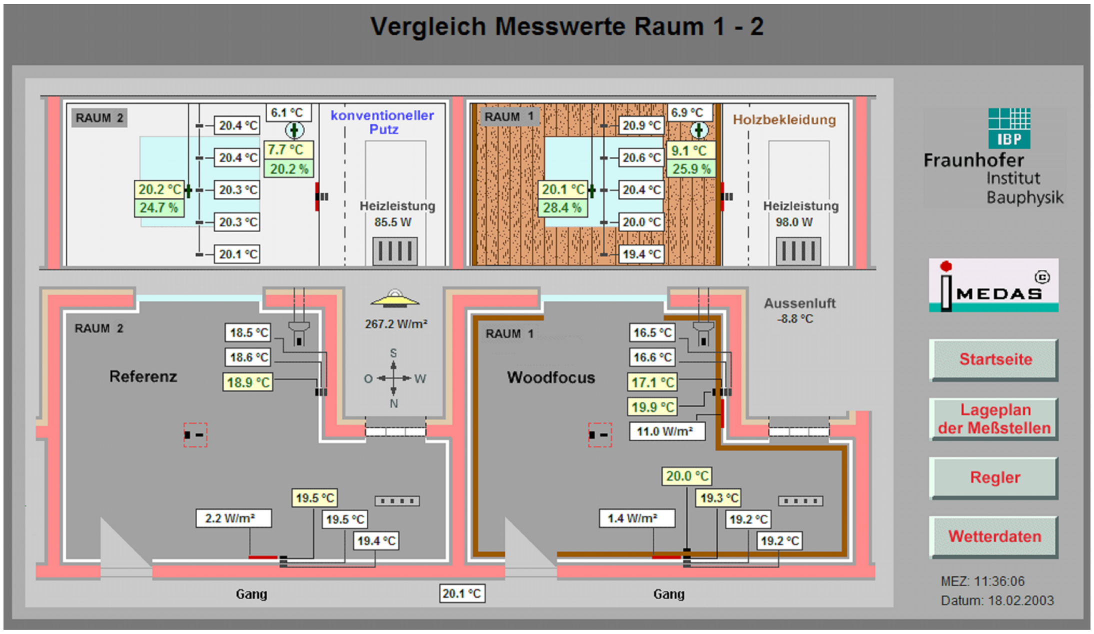

Figure 4 *Screen shot of the internet-based visualization tool IMEDAS.*

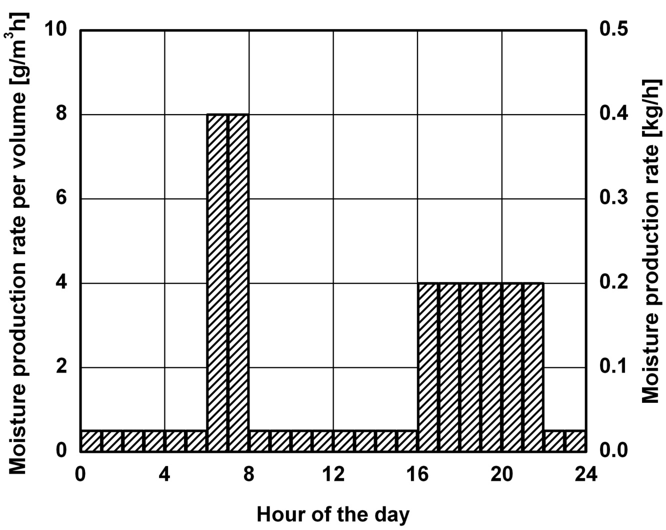

Figure 5 *Daily time schedule of the moisture production rate in the test rooms.*

Table 2. Measured and Simulated Rooms with Different Interior Surface Materials

Set	Reference Room	Test Room
A	Walls and ceiling plastered (unpainted)	Walls and ceiling covered with aluminum
B	Walls and ceiling plastered (painted)	Walls covered with wood (unpainted)

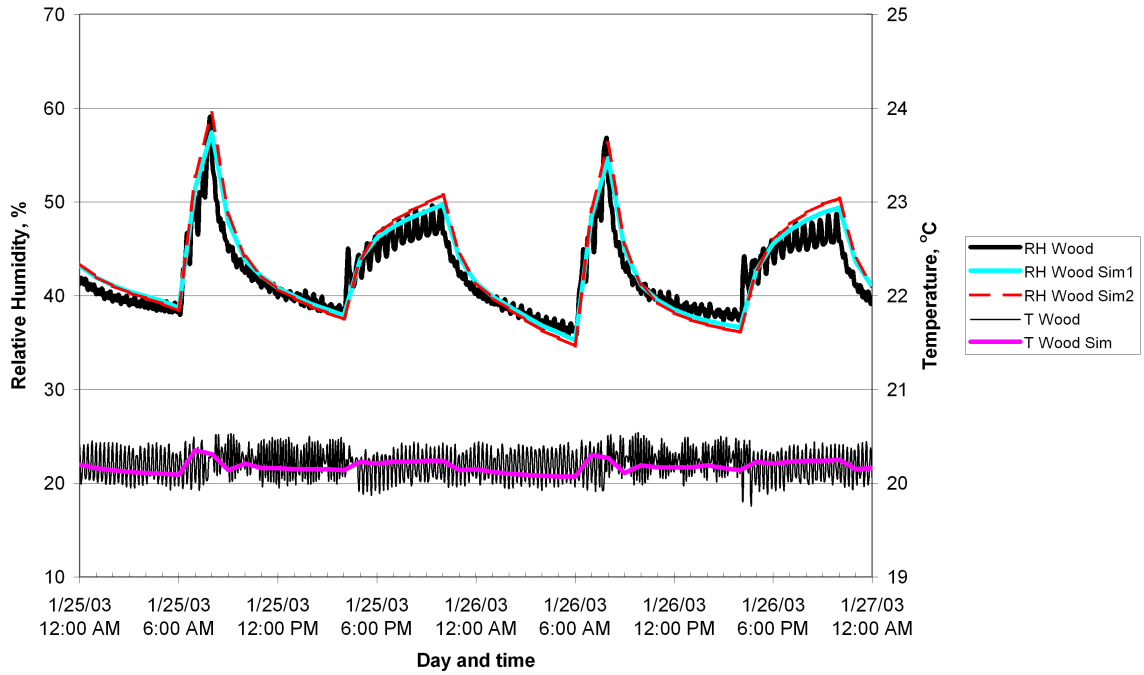

Figure 6 *Temporal behavior of relative humidity in the rooms with wood.*

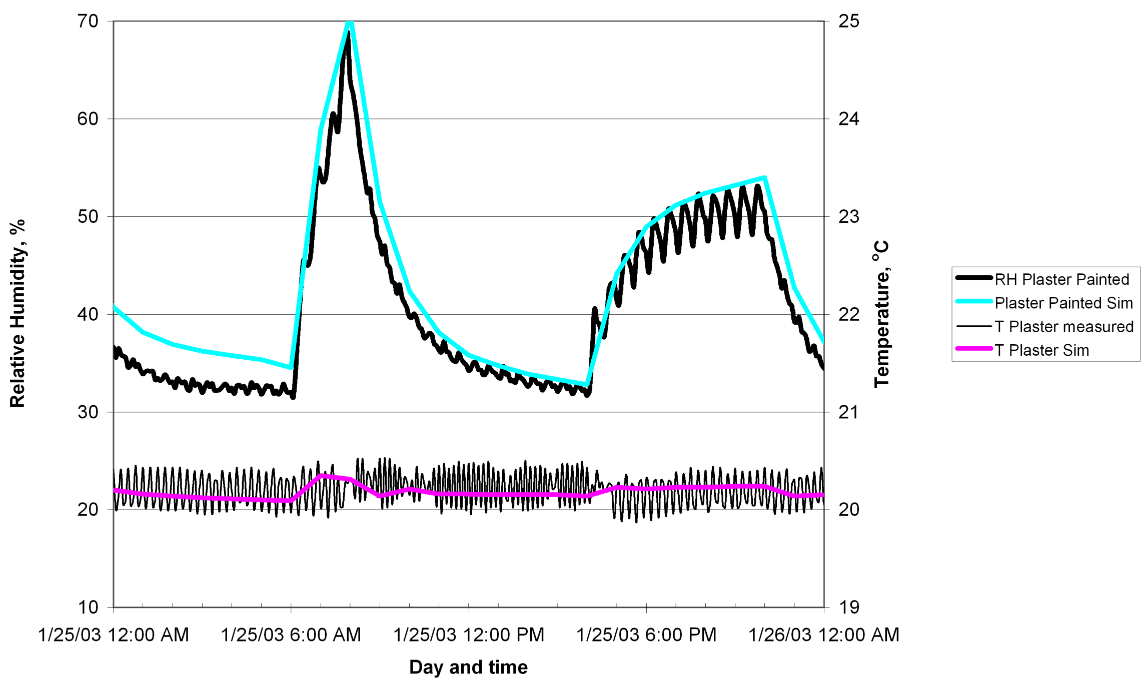

Figure 7 *Temporal behavior of relative humidity in the rooms with painted plaster walls and ceiling.*

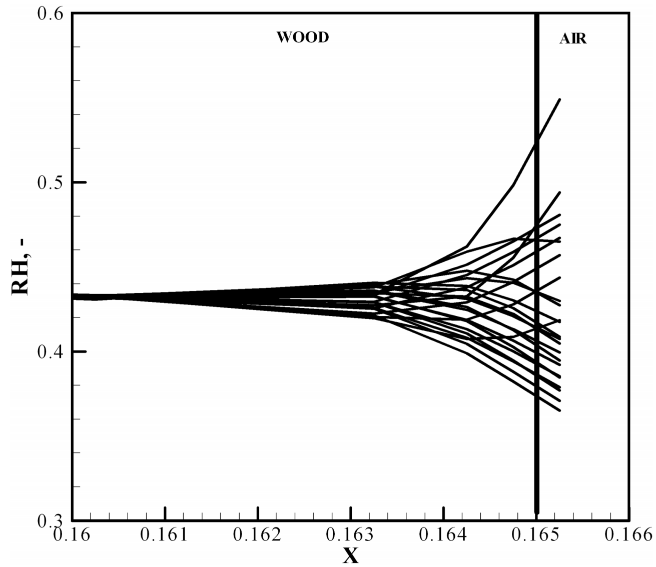

Figure 8 *Relative humidity distribution on the interior surface of the wood lining during 24 hours in the test room. Thick line at location* X = *0.165 m in the wall shows the wall surface at the indoor side. The indoor humidity is shown in the figure at* X = *0.166 m.*

Sensitivity Analysis—Effects of Material Properties and Coatings

Some sensitivity analyses were performed to find out how critical it is to know some of the properties or conditions in the tests and in reality in order to get meaningful results. The sensitivity analyses in the following are not extensive but rather give a feel to the strength of the effects of the parameters.

Vapor Permeability. The effects of wood vapor permeability were investigated by using the simulation model with two different vapor transmission properties for the wood material. The vapor permeability of wood used for “Sim2” in Figure 6 was, on average, approximately half of the vapor permeability used for “Sim1” within the measured relative humidity range 40-60% RH. The effect on indoor air humidity was found to be rather insignificant in this case, which is likely due to the fact that the penetration depth of wood was found to be 1-2 mm for this type of intermittent wetting and drying phenomenon (Figure 8). The vapor transfer resistance from the surface to the active capacity is not significant, and the surface mass transfer coefficient and the moisture capacity of the material play a more decisive role in the performance. Penetration depth describes the active thickness of the material taking part in the moisture-buffering process. The vapor transfer from or to the active moisture capacity of the material is not much hindered by the material’s own moisture transport properties and, therefore, the behavior of the material depended a lot on the surface mass transfer coefficient.

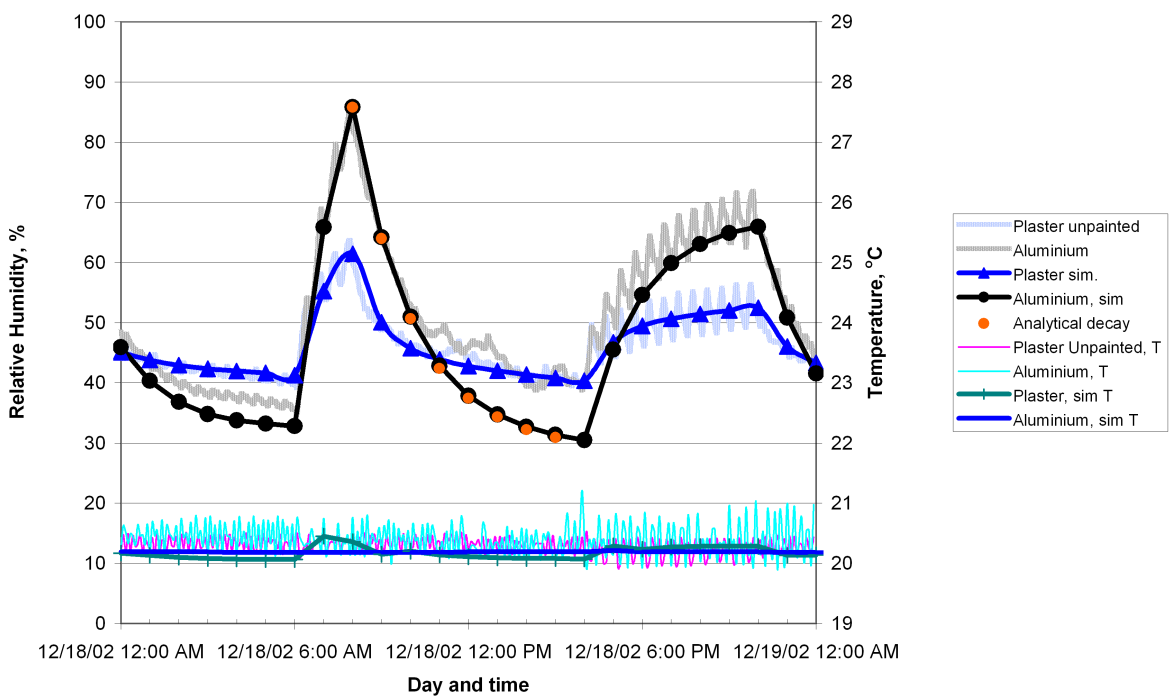

Figure 9 *Temporal behavior of relative humidity in the rooms with plaster or aluminum on the walls and on the ceiling. Measured and simulated room air temperatures are shown for level information only. The temperatures are well within 1 K.*

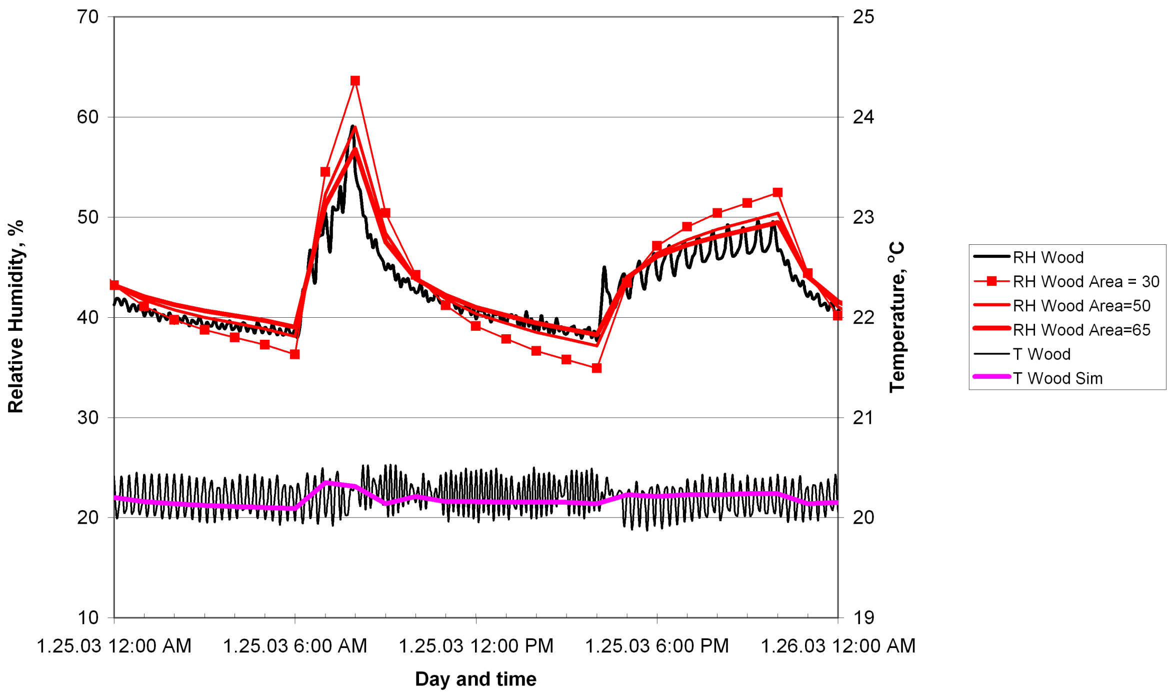

Figure 10 *Indoor air relative humidity in the test room with wood lining. The effects of surface area covered with wood lining have been investigated.*

Surface Mass Transfer Coefficient and Coatings. Coatings or paints will reduce the mass transfer coefficient between the solid surface and the ambient air. The vapor permeability of wood was shown to affect the performance only a little, and instead the mass transfer coefficient was found to be significant, which was likely due to the low penetration depth and high moisture capacity of wood. The surface vapor transfer coefficient $\beta = \alpha \ 1 \cdot 10^{-8}$ m/s was found to produce good results, which value corresponds well with the correlation to estimate mass transfer coefficient from heat transfer coefficient, $\beta = \alpha \cdot 7.4\text{e-}09$, where α is the convective heat transfer coefficient. The surface transfer coefficient is much higher than the permeance of any typical paint used on wall boards or wood. Therefore, paints and varnishes will reduce the moisture transfer rate between the material and air and, consequently, the moisture buffer capacity of the base material will be significantly lower with a coating than without it. This effect can be seen by comparing the cases with plaster unpainted or painted. The sd value[1] of the paint was measured to be approximately sd = 0.15 m and sd = 0.24 m in wet and dry cup conditions, respectively. The sd value represents the thickness of an air layer that has the same vapor permeance as the coating or material with a certain thickness. The paint used in these experiments represents a permeable paint among the variety of paints available. The paint—even a permeable one—reduced the moisture transfer between indoor air and the surfaces to such level that humidity variations in the room with painted plaster were twice (40% RH) as large as in the room with only standard plaster.

Sorption Isotherm. The sorption isotherm was varied by lowering the moisture content of wood by 30%, i.e., the new moisture content was 70% of the original moisture content at the same relative humidity. The change in the sorption capacity did not make a big difference in the results—the magnitude of the change in the performance was as significant as a change in the surface area. A summary of the sensitivity analysis results is shown in Figure 10.

Surface Area. Surface area of the wood linings was 65 m^2 in the test room. Reducing the surface area by 15 m^2 (–23%) made only little difference to the results (Figure 10). Reducing the area to half of the original showed a significant difference in the performance. This indicates that the moisture buffer capacity in the room is already quite adequate in the base case for good buffering, and increasing the surface area will not increase the performance much more.

Ventilation Rate. The ventilation rate was changed from the original 0.5 air change per hour (ach) to 0.6 ach (Figure 11). The effect of ventilation rate is clear on the humidity level, and the average relative humidity is lower with higher ventilation rate, which was, of course, expected. The amplitude of the change in relative humidity, however, does not seem to be much different, especially during the short period of high moisture load.

1. sd value (m) is the vapor transfer resistance of a material layer or a boundary layer described as a thickness of a stagnant air layer that is equal to the resistance.

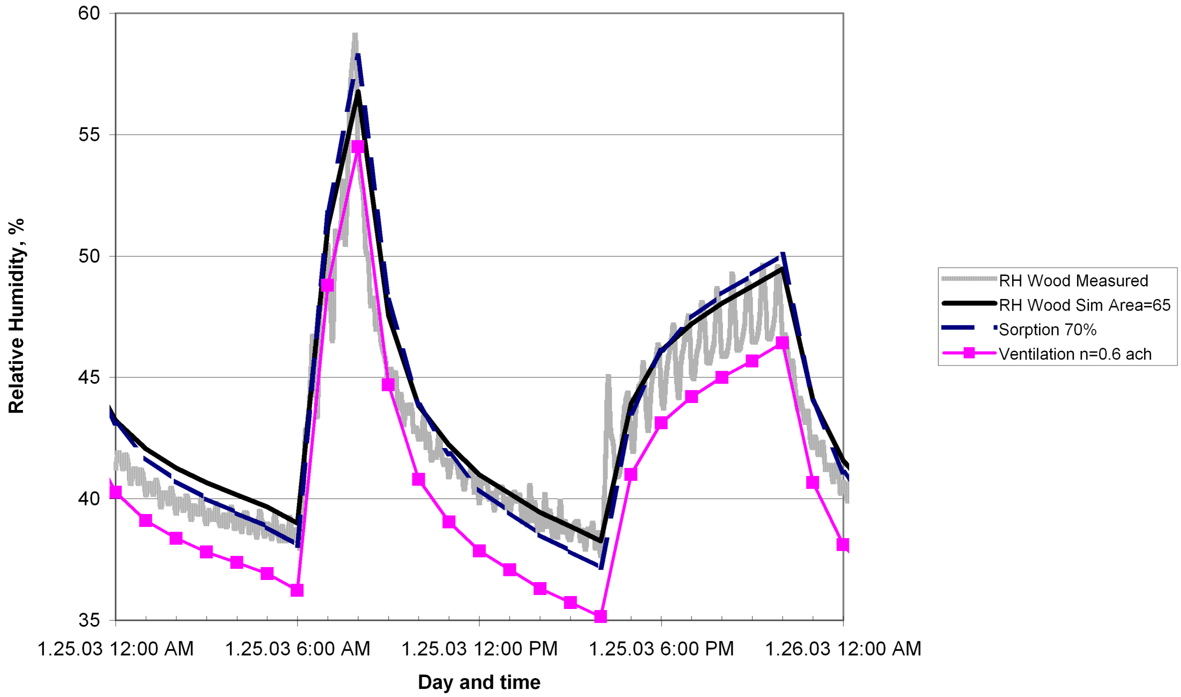

Figure 11 *Indoor air relative humidity in the test room with wood lining. The effects of sorption isotherm and ventilation rate have been investigated. Ventilation rate in the base case was 0.5 ach.*

POTENTIALS AND APPLICATIONS OF BUFFERING MATERIALS

Moisture transfer between indoor air and structures is important and several wood-based materials are appropriate. One of the most important findings is that the vapor resistance of the interior coating and the active area are very important and can be used to compensate each other. This means that in new and retrofit buildings it may be possible to apply surface texturing to increase the active area or small but highly active modules. These modules could employ natural or forced convection and could take up a small fraction of the internal surface area of the room but have an internal surface area that would be comparable to the entire surface area of the room. Since the local airflow and mixing will have a large impact on the performance of very small modules, large rooms with poor mixing may need several modules distributed throughout the room.

Moisture is an important parameter for comfort and indoor air quality, and the comfort and perceived indoor air quality can be improved when applying permeable and hygroscopic materials. It appears possible to provide similar conditions of indoor climate and perceived air quality with a smaller ventilation rate when permeable and hygroscopic materials are correctly applied. To quantify the amount that the ventilation can be reduced when applying wood-based materials in real buildings would be a long and difficult task, but future research in the area of indoor climate and air quality could focus on defining appropriate ways to quantify the effect of humidity on IAQ. It is expected that health affects would create additional arguments for the application of hygroscopic building materials.

It is known that the durability of building materials and the risk of mold growth are affected by moisture. Results show that it is possible to design a permeable envelope with good moisture performance. In fact, a permeable envelope made of hygroscopic materials is less susceptible to condensation and mold growth at the internal surface of thermal bridges because the peak indoor humidity is lower when applying hygroscopic materials.

The commercial application and exploitation of the moisture-buffering effect requires the introduction of the phenomenon with correct argumentation and solid design methods. Demonstration of the designed performance in real and occupied buildings is still needed.

CONCLUSIONS

Small- and full-scale experiments were carried out to produce data for model validation. The direct comparison of measured and calculated indoor relative humidity shows good agreement. A source of error is that the humidifier works in an on/off mode in order to supply the defined moisture load.

The measurements and the simulations carried out show, as expected, greater fluctuation of the indoor air humidity without the sorption capacity of the interior surfaces. For an ach of 0.5 h^{-1}, which is the hygienic minimum rate according to Finnish and German regulations, the peaks during extensive moisture production can be reduced from 70% to about 50% RH. In both cases, the mean relative humidity over the 24-hour period is around 40%, which is a realistic value for indoor air conditions in dwellings during wintertime.

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