

Organic Insulation Materials: Effect on Indoor Humidity and Necessity of a Vapor Barrier

Carsten Rode, Ph.D.

ABSTRACT

Examples of organic insulation products are cellulose fiber, other plant fibers, and animal wool. These materials, which are all very hygroscopic, are associated with certain assumptions about their building physical behavior that need to be verified. Examples are: "A vapor barrier is not needed when using organic insulation materials" and "Organic insulation materials have a stabilizing effect on the indoor humidity."

This paper presents numerical analyses of the hygrothermal behavior of wall constructions and the occupied spaces they surround when an organic insulation material is used. The following problems are analyzed:

- The risk of interstitial condensation in typical building construction with different vapor retarders when either conventional or organic insulation materials are used.
- The influence on diurnal and seasonal indoor humidity variations when using either inorganic or organic insulation materials in the surrounding walls.

INTRODUCTION

The environmental impact of buildings is much in focus these days. As part of this trend, the use of ecological building materials is favored by some building owners and professionals in the building industry. Examples of ecological insulation products are cellulose fiber, other plant fibers, and animal wool. A common assertion when using organic insulation products is that when they are used in walls and roofs, there is no need for a vapor barrier in the form of a plastic foil (e.g., polyethylene) because the materials can "buffer humidity so this can move through the insulation" (a quotation cited by Björk et al. [1997] when investigating similar allegations). A manufacturer of cellulose insulation materials states on its homepage that "the house and the walls will come to breathe as in the old time" and "it will give you a good indoor climate, with regulated moisture" (Eko. 1998). The concept of building envelopes that "breathe" is commonly expressed but not always used with a consistent definition, i.e., does it mean that the building envelope forms part of the building's (natural) ventilation system because it is permeable to airflow, or does

it mean that the materials in the structures are as permeable as possible to water vapor diffusion?

Organic insulation products distinguish themselves from more conventional materials such as mineral fiber and plastic foam. In this paper, plastic foams are not considered as organic—although, chemically, they are. As a researcher, one needs to be both open minded and constructively critical toward alternative ideas, and thus it is important to make an objective evaluation of the hygrothermal properties and behavior of the hygroscopic insulation materials and to use correct physical terms to characterize their performance. Also, it must be recognized that, historically, the materials that are the subject of this paper were used long before well-insulated buildings became common.

Field studies and computational investigations have been carried out in Sweden on ecological buildings and their cellulose insulated constructions (Sikander 1996), and some general recommendations have come out of this work. Sikander indicates that it is possible to calculate the moisture performance of constructions in ecological buildings and recommends the evaluation of such buildings taking an inte-

Carsten Rode is an associate professor in the Department of Buildings and Energy, Technical University of Denmark, Lyngby, Denmark.

gral view of the building system: construction, materials, and ventilation.

In traditional models for hygrothermal analysis of building envelope components, the adjacent climates are typically prescribed as having fixed schedules, and in traditional analysis of occupied indoor spaces, the building envelope is considered without its ability to absorb moisture from the room air. The model used for the analysis in this paper is a model for hygrothermal analysis of building envelopes that will be employed in a new way, such that the hygrothermal conditions both within a wall assembly and in the occupied space behind it are derived from the same calculation while considering the exchange of moisture between the wall assembly and the space.

Scope of Paper

This paper will analyze the necessity of having a vapor barrier that is rather tight to water vapor diffusion on the warm side of insulation, or whether a membrane or material with just a moderate vapor diffusion resistance will be sufficient—a vapor retarder. The constructions analyzed will be exterior lightweight walls. Furthermore, the effect of stabilizing the indoor climate's relative humidity will be analyzed when using either organic insulation or mineral fiber insulation in the walls, with the different possibilities for vapor retarders. The exterior walls that will be analyzed face a moderate Nordic outdoor climate, that is, the climate of Denmark, which has a latitude of 56°N, about 3000 heating degree-days (Celsius based, base 17°C; corresponds to 5400°F-days, base 63°F). The average temperature in the coldest winter months of Denmark is close to the freezing point, the heating season lasts for seven months with an average outdoor temperature of about 4°C (39°F), and the average outdoor temperature in the summer months is around 16°C (61°F). The analysis could be extended to other structures that are adjacent to the room air and to other outdoor climates in the cold zone. However, for the main theme, the necessity of a vapor barrier and its influence on the indoor climate's relative humidity (RH), it is believed that similar conclusions could be drawn as in this paper.

The analysis represents the initial work for participation in a group of Danish projects. With the purpose to promote and further develop insulation products that are both environmentally sustainable and friendly to the labor force, the Danish parliament has reserved what corresponds to about 6 million US\$ over a four-year period. The specific projects, some of which deal with technical clarification, began in early 1998.

Materials Analyzed and Their Properties

The materials analyzed in this paper will be limited to cellulose insulation, representing the organic products, and mineral fiber (rock wool), representing an almost nonhygroscopic insulation material.

The density for rock wool varies from 30 kg/m³ to 190 kg/m³ (Kumaran 1996), where, for example, the lowest density is used in stud walls, whereas the higher densities are used in load-bearing situations such as below ground decks and in warm deck roofs. The density of cellulose insulation varies from 15 kg/m³ to 65 kg/m³ (Kumaran 1996; Björk et al. 1997), with the lowest densities used as loose-fill products in attics and the higher densities obtained after compaction in walls to avoid settling.

The thermal conductivity is the most interesting value for the primary purpose of both materials, and for rock wool it is in the range 0.036–0.040 W/(m·K) (0.25–0.28 Btu·in./[h·ft²·°F]), primarily depending on the density, with an optimum around 70 kg/m³ (4.5 lb/ft³) (ASHRAE 1997). For cellulose insulation, the thermal conductivity is either about the same as for rock wool and not dependent on the moisture content (Heistad and Korneliussen [1995] on cellulose insulation with moisture content between 5% and 24% by weight) or, as stated by other authors, slightly higher and somewhat moisture dependent, i.e., in the range 0.038–0.057 W/(m·K) (0.26–0.040 Btu·in./[h·ft²·°F]) (Kumaran [1996] on cellulose insulation with moisture content between 0% and 24% by weight). However, thermal conductivity is not the most important property for this investigation.

The water vapor permeability for mineral fiber insulation varies between $0.7 \cdot 10^{-10}$ kg/(m·s·Pa) (50 perm inch) to about the same vapor permeability as that of still air, $1.8 \cdot 10^{-10}$ kg/(m·s·Pa) (120 perm inch), or perhaps even slightly higher (Kumaran 1996; ASHRAE 1997; ASTM 1994). The highest numbers are measured with the wet-cup method. The vapor permeability for cellulose insulation has been tabulated neither by ASHRAE nor by ASTM. Heistad and Korneliussen (1995) have collected results from Scandinavian sources in the range from about $0.7 \cdot 10^{-10}$ kg/(m·s·Pa) (50 perm inch) to $2.2 \cdot 10^{-10}$ kg/(m·s·Pa) (150 perm inch), where the highest value was reported for the range 90%–100% RH and is slightly higher than the value for still air. It may be concluded that there is no significant difference in water vapor permeability between the two categories of materials and that it varies between 40% and 100%–120% of the vapor permeability of still air.

The sorption isotherm for rock wool shows a low ability of this material to absorb humidity from the ambient air. The absorbed moisture content in the highest end of the hygroscopic regime, RH > 95%, is around 1% by weight (according to the sorption isotherm catalog by Hansen [1986]). Hansen does not report the sorption isotherm for cellulose insulation, and neither are these curves given by ASHRAE (1997) or ASTM (1994). Heistad and Korneliussen (1995) quote five different sources of sorption isotherms for cellulose insulation and find quite some deviation between them, especially for high RH values. Their conjecture is that the way of drying during measurement of the sorption isotherm is not always the same. If drying takes place at too-high temperatures, crystal water from the fire-retarding and fungicide salts will be dried out. However, since all the quoted sorption curves show about

the same absorbed moisture content at moderate RH levels, i.e., around 50%, the author of this paper suspects that a lack of consensus on how to measure sorption values in the high RH regime could be the reason for the discrepancy. But still, there could be some differences between raw materials (recycled newspaper or others) and the additives (salts) used in the different products to explain the difference in sorption characteristics at high RH regimes. Figure 1 shows the sorption isotherms for rock wool (Hansen 1986) together with a high (Zarr et al. 1995) and a low (Salonvaara 1992) variation of the curves for cellulose insulation. The different curves for cellulose insulation will be used for parameter variation in the analysis that follows later.

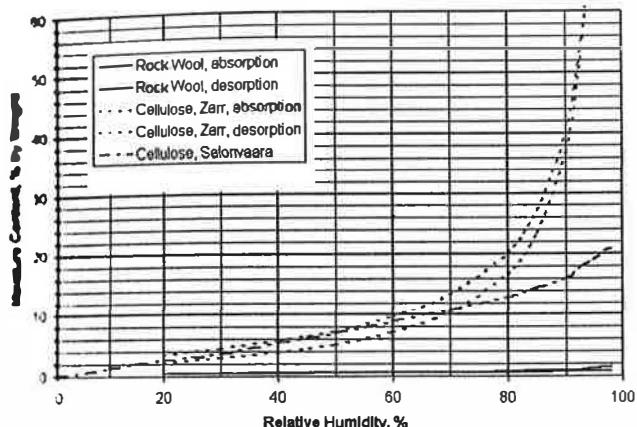


Figure 1 Sorption isotherms for different variations of mineral fiber and cellulose insulation.

Tool and Limitations for the Analysis

The analytical tool used in this paper is a one-dimensional computer program for combined heat and moisture transport that was developed in a Ph.D. thesis in the late 1980s (Rode Pedersen 1990a). The program has been verified, not only as part of the original development, but also by comparison with other programs and experimental results in the International Energy Agency (IEA) Annex 24 of the Energy Conservation in Buildings and Community Systems research program (Hens 1996) and by comparison with experimental results (Rode and Burch 1995). The program is capable of performing hourly based, transient calculations of moisture transfer by vapor diffusion and capillary suction for composite constructions of homogeneous plane layers. In the normal execution of the program, the indoor and outdoor environments are given. The outdoor climate is read from a weather data file with air temperature, solar radiation, wind speed, and humidity (in the form of a Test Reference Year or similar data), and the indoor climate is specified by the user as typical monthly values for temperature and indoor humidity (RH or difference in indoor and outdoor vapor concentration). As part of the analysis for this paper, these descriptions of the adjacent climates will be modified so that the humidity part of the indoor climate is a

result of the simulation. That is, rather than letting the hydrothermal conditions within the structure be determined solely by the adjacent environmental conditions, the situation is changed so the building materials influence the internal boundary condition. See the description below on how this is done.

The analytical procedure has the following limitations:

- The calculation is one-dimensional.
- Although the program has some capabilities to consider moisture flow by convection, e.g., exfiltration and infiltration, it has been decided not to let this feature be part of the analysis for this paper. That is, for this analysis, it is assumed that the wall assembly contains an effective air barrier that excludes air infiltration and exfiltration.
- The properties for liquid moisture flow are not known for most of the materials in this analysis, and capillary suction, therefore, plays no role in the computational analyses. Before liquid flow takes place in insulation products, it is necessary to have high rates of condensation, and when that happens, gravity often plays a major role in further distribution of the moisture. Liquid moisture flow is not considered for this analysis.

EXAMINATION OF A PROCEDURE TO EVALUATE THE INTERACTION BETWEEN SPACE AND MATERIAL

As a first step, a procedure has been devised to use the existing computer program to analyze the interactive flow of vapor between the materials of the wall and an adjacent space. Results of the procedure will be compared with measurements conducted under isothermal conditions. The experiments have been carried out as part of a Ph.D. study that was completed in 1998 (Padfield 1998a), the results of which were not available at the time of this writing. The results of already published experiments have been made available for the analysis of this paper (Padfield 1998b).

The Experimental Setup

A climate chamber has been developed that makes it possible to control vapor flux into and out of the air volume, as opposed to the usual control of the chamber's RH. The volume of the airtight chamber is 0.5 m^3 (18 ft^3), and it consists mainly of stainless steel plates so that the inside of the chamber is both vapor tight and inert to accumulation or release of vapor. The chamber's humidity is controlled by a device that evaporates or condenses water in a reservoir whose temperature is controlled by a thermoelectric cooler and heater. Programmed evaporation or condensation rates are continually compared against results of weighing the water reservoir with calibrated strain gauges to adjust the evaporation or condensation of water in the reservoir. For the experiments used in this analysis, 24-hour periods with humidification

rates of 1 g/h (0.0022 lb/h) alternated with equally long periods with the same rates of dehumidification.

Within the chamber is located a rack for positioning a wall of 30 mm (1.2 in.) thick homogenous material sealed at the back. The exposed surface area of the material is 0.36 m^2 (3.9 ft^2). Thus, the ratio between the chamber's volume and the surface area of the wall is $1.39 \text{ m}^3/\text{m}^2$ ($4.6 \text{ ft}^3/\text{ft}^2$), a typical ratio for occupied rooms. For the comparison that will be shown in this paper to justify the numerical procedure, a wall of cellular concrete was used (dry density 720 kg/m^3 , 45 lb/ft^3). Cellular concrete is a quite homogenous material and has from previous investigations some rather well-known hygrothermal properties. The experiments were conducted at the constant temperature 25°C (77°F) with the variation kept within a 0.5°C (1.0°F) band. During the tests, the chamber's humidity varied between approximately 45% and 70% RH. Due to latent heat effects, the measured surface temperature of the specimen was up to about 0.5°C (1°F) colder or warmer than the chamber air depending on whether the specimen was drying or absorbing moisture.

The Calculation Procedure

The experimental setting of the test wall in the climate chamber was modeled in the one-dimensional computer program as outlined in Figure 2. The 30 mm of cellular concrete was divided into 40 control volumes of varying thickness from 0.1 mm (0.004 in.) in the surface layer next to the chamber air to 2 mm (0.08 in.) deeper in the material. The program calculates everything per m^2 wall area, so the chamber air should be represented as a volume of 1.39 m^3 (4.6 ft^3) at the fixed temperature of 25°C (77°C). The density of air at this temperature is 1.185 kg/m^3 (0.0741 lb/ft^3), and the saturation humidity ratio is 0.0201 kg/kg (0.0201 lb/lb). In the calcu-

lation, the air space was given a thickness of 1 mm (0.04 in.) and density of 1647 kg/m^3 (103 lb/ft^3) to achieve the same weight as the real air volume. The sorption isotherm is a straight line from zero at 0% RH to 0.201 kg/kg at 100% RH. The reason for compacting the volume to the small thickness, 1 mm, is to almost exclude the possibility of having temperature gradients across the air layer. As in the almost isothermal experiment, the simulation also registered some small temperature changes due to the latent heat of condensing or evaporating moisture in the material.

The boundary conditions for the calculation on the rear side of the wall are a normal thermal surface resistance of $0.13 \text{ m}^2\cdot\text{K/W}$ ($0.74 \text{ ft}^2\cdot\text{h}\cdot^\circ\text{F/Btu}$) and a large vapor diffusion resistance to simulate impermeable conditions. At the intersection between cellular concrete and the air volume are inserted single resistances normal for an internal surface—a thermal resistance of $0.13 \text{ m}^2\cdot\text{K/W}$ ($0.74 \text{ ft}^2\cdot\text{h}\cdot^\circ\text{F/Btu}$) and a vapor diffusion resistance of $0.051 \text{ GPa}\cdot\text{m}^2\cdot\text{s/kg}$ (same as Figure 2's 0.051 Gm/s , corresponding to a permeance in IP units of 340 perm). To maintain an air temperature of 25°C (77°F), a boundary condition of this temperature was defined at a position next to the air volume (the right-hand side of Figure 2), and a thermal resistance of zero was defined to establish a good contact between this boundary condition and the air temperature.

Finally, a special feature of the program was applied to simulate the additional humidification or drying of the air space by the vapor flux controller. The humidifying/drying rates of 1 g/h for the actual wall in the experiments correspond to 2.8 g/h (0.0052 lb/h) for the 1 m^2 wall in the simulation. These rates were entered in a file that the program would read for every hour simulated in the calculation.

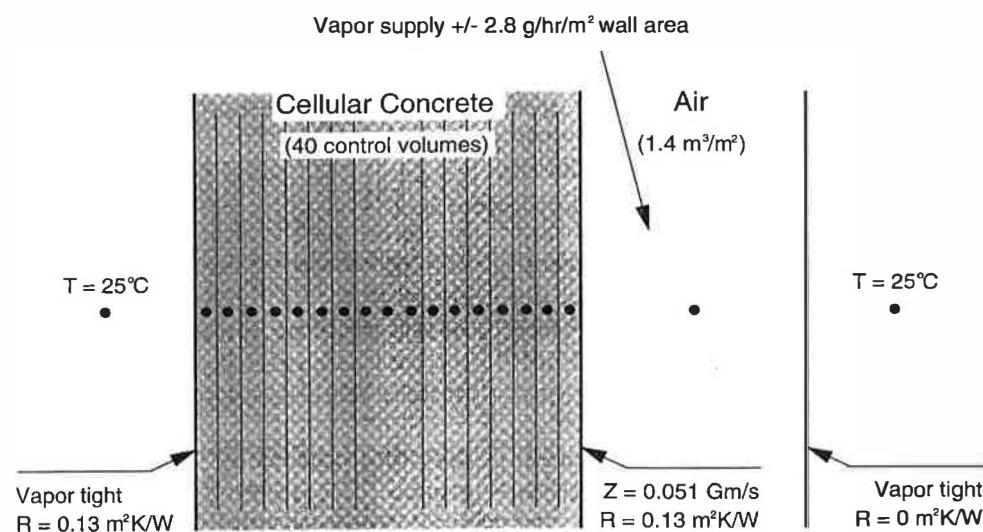


Figure 2 Model for the calculation of humidity exchange between a monolithic slab of cellular concrete and a climate chamber with controlled supply and removal of water vapor. The chamber air is modeled as one of the layers of the otherwise homogenous slab.

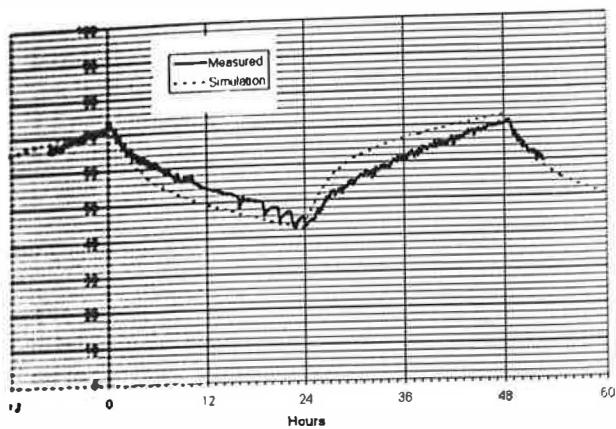


Figure 3 Measured and simulated relative humidity in the climate chamber of Figure 2 during a two-day cycle when the chamber had a controlled supply of moisture for 24 hours followed by 24 hours of moisture removal.

Results of Comparison

The results of the experiment and the numerical simulation are shown in Figure 3 for a sequence of about two days, well away from the initial stabilization at quasi-constant levels. The qualitative correspondence is not too bad, although quantitatively it is far from perfect. Parametric variations around the above-mentioned surface resistances and the properties of the cellular concrete have revealed the following:

- The surface resistances have only a small influence on the results. Reducing the thermal surface resistance of the surfaces of the cellular concrete to zero has no visible influence on the results. Doubling the water vapor resistance of the cellular concrete's surface to the air space increases the amplitude of the daily RH variation only by about 1% RH.
- There is some moderate influence of the vapor permeability of cellular concrete on the results. Doubling the water vapor permeability of cellular concrete reduces the amplitude of the daily RH variation of the air space by a few percent RH.
- An equally important property is the shape of the sorption isotherm. The slope of the sorption isotherm signifies how much moisture a material needs to absorb (or dry) per change of RH in the surroundings to maintain equilibrium, i.e., it depicts the moisture capacity of the material. A low slope of the sorption isotherm in the active RH regime (midrange RH values) causes a large daily variation of indoor RH in the space, whereas a steep sorption isotherm in the active RH regime has a stabilizing effect on the indoor RH. In this case, a different numerical representation of the otherwise same sorption curve, e.g., from curve fitting of measured points, had a significant influence on the results. To

generate the results shown in Figure 3, the program was run with a model that simulates the hysteresis between the curves for absorption (humidification) and desorption (drying) of cellular concrete (Rode Pedersen 1990b).

It will be concluded that this way of simulating indoor humidity levels is qualitatively correct and can be used to compare the humidity buffering effect of different materials if their sorption isotherms are known with as much precision as possible, preferably in the form of both an absorption and a desorption curve.

INFLUENCE OF MATERIALS AND VAPOR RETARDERS WHEN CALCULATING UNDER NONISOTHERMAL CONDITIONS

The analysis described in the previous section was extended to simulations of rooms that were subjected to more natural conditions. The model of a room as one of the layers in a one-dimensional homogeneous structure was extended by allowing the contribution of humidity to the room air to simulate the release from processes or occupants and by subjecting the room to ventilation with outdoor air. The monolithic and isothermal wall from the previous section was replaced in the computer model by a lightweight wall consisting of exterior siding and sheathing, insulation, and the possibility of an internal vapor retarder and interior drywall. In the simulations, the wall was exposed to the outside climate as described by the weather data of the Test Reference Year of Copenhagen, Denmark. The following hourly climatic characteristics were defined: dry-bulb air temperature, dew-point temperature, solar irradiation, wind speed, and cloud cover. The calculation model predicts longwave radiation to the surroundings based on the available climatic data. In this way, the nonisothermal hygrothermal processes within the composite wall structure were predicted. The materials in the wall, the simple representation of the room behind the wall, and an outline of the grid spacing for the numerical analysis are illustrated in Figure 4.

The rates of ventilation with outdoor air and moisture release in the "room" are adjusted on an hourly basis to give the humidity increases shown in Figure 5. The humidity increase for a particular hour is understood to be the moisture release in that hour divided by the air change volume. This would be the same as the difference between indoor and outdoor vapor concentration if there were no accumulation of moisture in the building materials that surround the room, i.e., conditions are steady state. The daily average of the humidity increase was set to 3.5 g/m^3 (1.5 g/ft^3) during the months November to March, 3.0 g/m^3 (1.3 g/ft^3) in April and October, 2.5 g/m^3 (1.1 g/ft^3) in May and September, and 2.0 g/m^3 (0.9 g/ft^3) in June, July, and August. These are rather normal figures for a dwelling under normal use without devices that control the humidity levels. The daily profile shown in Figure 5 was made up for the purpose of this paper and was meant to

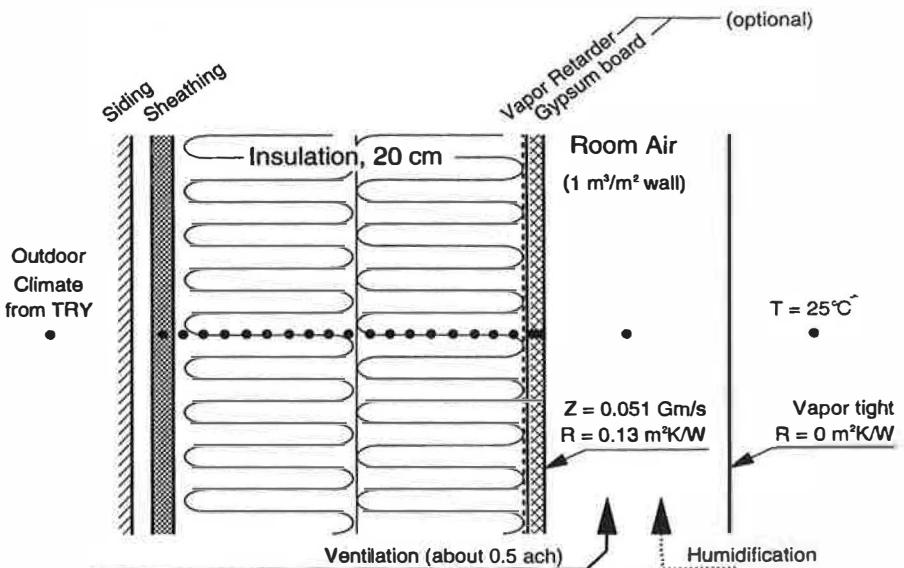


Figure 4 Model for the calculation of humidity exchange between an exterior insulated wall and the indoor climate of a room with ventilation by outdoor air and moisture release from indoor activities. The room air is modeled as one of the layers of the multi-layered structure.

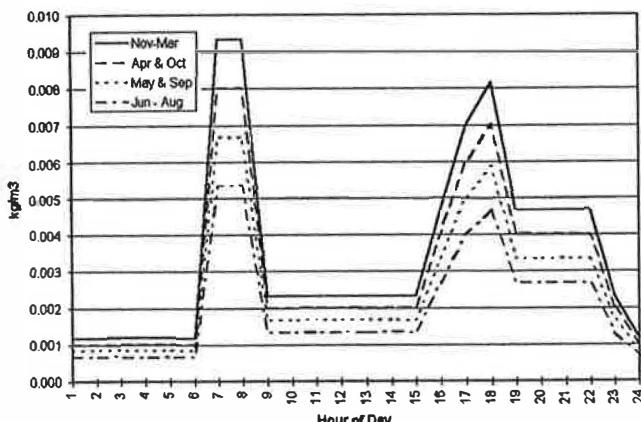


Figure 5 Daily scheme for humidity increase of the room air. The humidity increase is regarded as a steady-state parameter found as the hourly vapor release divided by the hourly volume of air change.

simulate normal activity in a dwelling (human transpiration, bathing, cooking, washing, etc.). The profile was purposefully made to show variation over the day so that moisture buffering effects would be apparent.

The volume of the room was one cubic meter per square meter of wall, a rather normal ratio for rooms in dwellings and office buildings. The model did not consider moisture absorption in surfaces other than the exterior construction; that is, inside walls and furnishings are neglected. The justification for this neglect is that the purpose of the analysis is to compare the moisture performance of different insulation materials.

The following variations of the materials in the wall were analyzed:

- **Insulation material:** Either cellulose insulation or rock wool insulation was used (200 mm, 8 in.). The sorption curve chosen for the cellulose insulation was the one by Zarr et al. (1995) for a material with a density of 56 kg/m^3 (Figure 1). Furthermore, a run with the sorption curve for the less hygroscopic cellulose insulation according to Salomvaara (1992) was carried out to test the sensitivity to hygroscopicity.
- **Vapor retarder:** Four different variations were analyzed.
 - (1) The wall had no vapor retarder or internal cladding, that is, the insulation material was in direct contact with the room air.
 - (2) A 13 mm (0.5 in.) drywall (a gypsum board) separated the insulation from the room air. There was no vapor retarder. To analyze a rather inert situation with just a small vapor diffusion resistance between the room air and the insulation material, the drywall had no cardboard facing, wallpaper, or paint; that is, the hygroscopically rather inactive gypsum material was in direct contact with the room air. The vapor diffusion resistance, Z , of the drywall was $0.55 \text{ GPa/m}^2 \cdot \text{s} \cdot \text{kg}$ (corresponding to a vapor permeance in IP units of 32 perm), that is, rather permeable.
 - (3) Same as (2), but between insulation and drywall was used a vapor retarder with moderate vapor diffusion resistance of $Z = 5.0 \text{ GPa/m}^2 \cdot \text{s} \cdot \text{kg}$ (vapor permeance = 3.5 perm).
 - (4) Same as (2), but between insulation and drywall a vapor barrier of polyethylene was used with a vapor diffusion resistance of $Z = 250 \text{ GPa/m}^2 \cdot \text{s} \cdot \text{kg}$ (vapor permeance = 0.070 perm).

- **Exterior sheathing:** Either 9 mm (3/8 in.) of gypsum board was chosen as a rather vapor permeable sheathing, $Z = 0.38 \text{ GPa/m}^2 \cdot \text{s} \cdot \text{kg}$ (vapor permeance = 46 perm), or 3.5 mm (1/8 in.) oil-tempered wood fiberboard was used as a less permeable sheathing, $Z = 4.5 \text{ GPa/m}^2 \cdot \text{s} \cdot \text{kg}$ (vapor permeance = 3.9 perm).

Other conditions for the calculations were the following.

- The insulation was simulated with 26 control volumes varying in thickness between 0.16 mm (0.006 in.), closest to the room air, to 46 mm (1.8 in.) in the deeper layers. The drywall was simulated with ten control volumes 0.2 mm to 3.3 mm thick (0.008 in. to 0.13 in.). Less accuracy was required for the exterior layers, so the sheathing was simulated with only two control volumes, and just one control volume was used to represent the siding.
- A vapor diffusion resistance of $Z = 0.5 \text{ GPa/m}^2 \cdot \text{s} \cdot \text{kg}$ (vapor permeance = 35 perm) and thermal resistance of $0.2 \text{ m}^2 \cdot \text{K/W}$ ($1.1 \text{ ft}^2 \cdot \text{h} \cdot ^\circ\text{F/Btu}$) were used for the exterior siding. The rather low vapor resistance (high permeance) was meant to reflect the limited ventilation behind the siding (as also suggested in an example by Ten Wolde in ASTM's handbook on *Moisture Control in Buildings*, 1994). For the same reason, the somewhat low solar absorptance, 0.4, and long wave emittance, 0.5, were chosen for the exterior surface, which was facing west.
- The calculation periods were 2½ years long, starting October 1 in the first year and continuing through the second year as an initialization period, before calculating the third year from which results were taken for presentation and analysis.

The analyses have the following uncertainties, which should be observed before drawing decisive conclusions from the results:

- The analyses are carried out for constructions that would typically have a two- or three-dimensional character, e.g., stud walls. However, the walls are only modeled one-dimensionally.
- There is a great risk of convective moisture flow in such walls, which would either distribute moisture from the adjacent climates or internally in the walls. Such moisture flow can be very significant in comparison with diffusive flow when it occurs. Although the model used can analyze the effect of homogeneous one-dimensional exfiltration or infiltration through a structure, this option has been left out since the severest flow is the intense flow that might occur through cracks and irregularities, which cannot be estimated by the model used. Thus, concerning the condensation risk, the results are possibly too optimistic.
- The analysis is limited to the set of parameters for which it has been run. That is, an exposure to the outside climate of Denmark, an indoor climate that approximates a dwelling at 21°C year-round, and hygrothermal material properties within the ranges outlined above. The results might not be readily extrapolated to other situations or constructions other than lightweight exterior walls.

Thus, the intention is to give an example of a qualitative comparison of the hygrothermal performance of two different insulation materials and to demonstrate the use of a tool that was originally prepared solely for the analysis of constructions, now used to investigate the interaction between a space and a construction.

RESULTS AND DISCUSSION

Indoor Humidity Variation

Figures 6 through 9 show the hourly variation of simulated indoor relative humidity during the first week of January

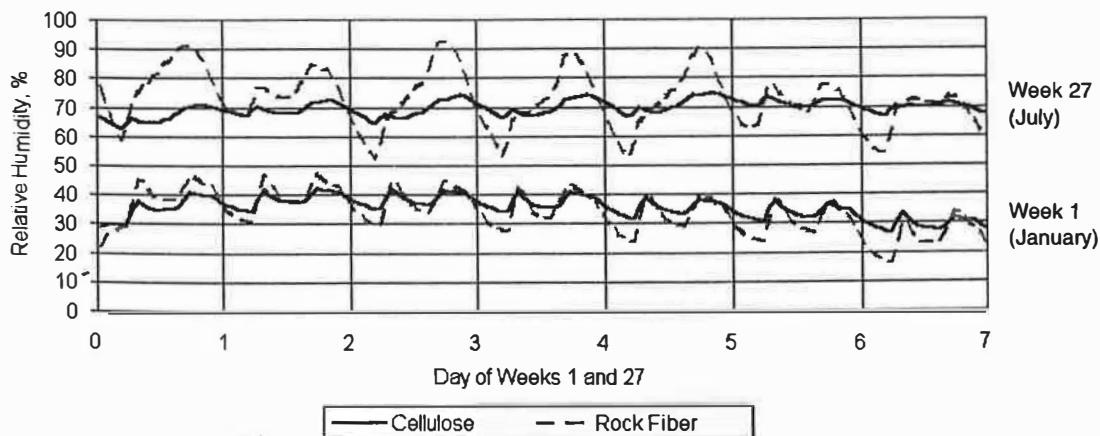


Figure 6 Simulated indoor relative humidity for the first week of January (lowest two curves) and the first week of July (top curves) when there is no membrane or cladding on the inside of the insulation.

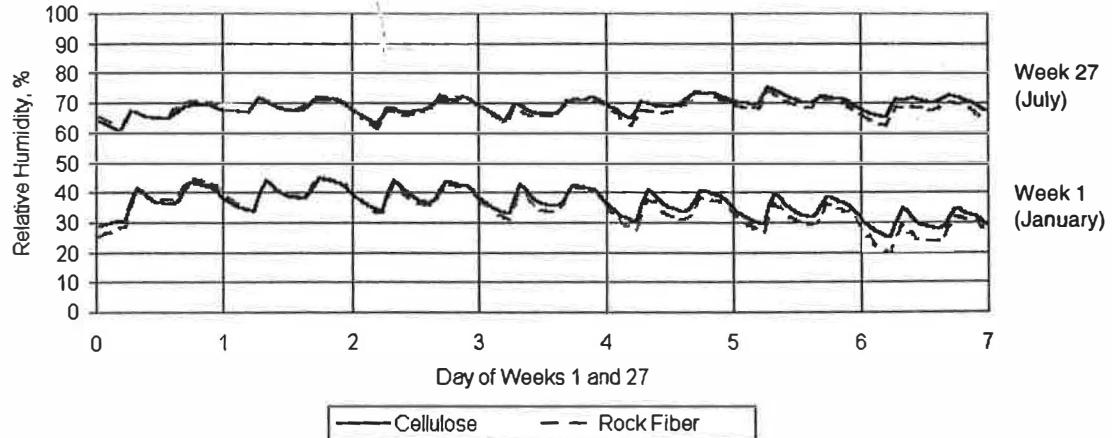


Figure 7 Simulated indoor relative humidity in January and July when there is only a bare board of 13 mm (0.5 in.) drywall on the inside of the insulation.

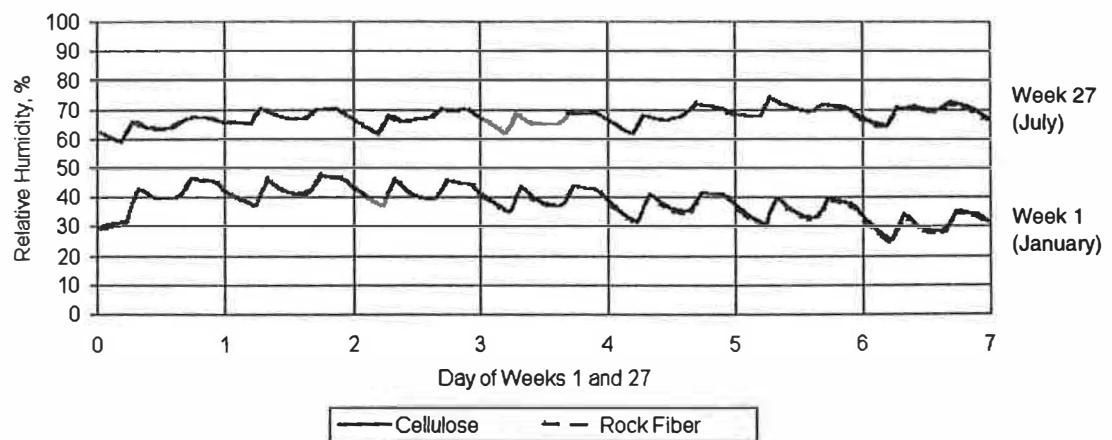


Figure 8 Simulated indoor relative humidity in January and July when there is a somewhat permeable vapor retarder and a drywall on the inside of the insulation.

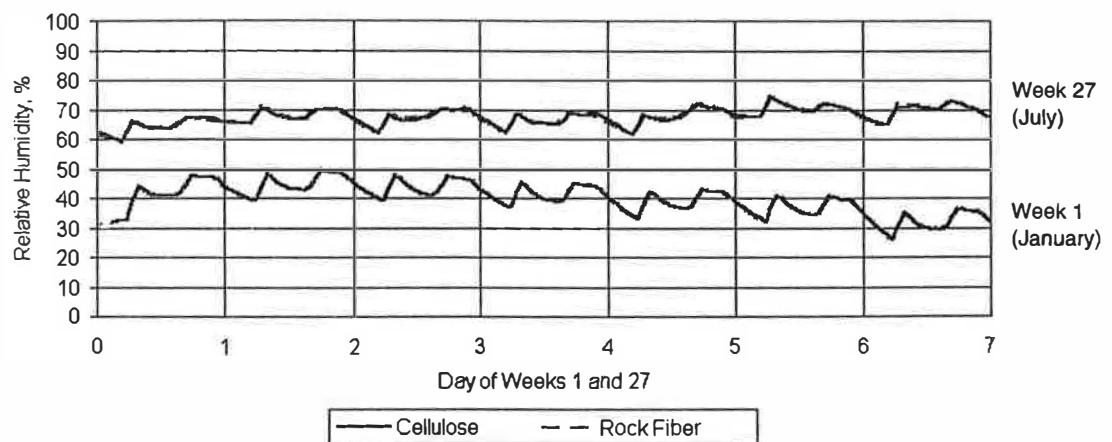


Figure 9 Simulated indoor relative humidity in January and July when there is a polyethylene vapor barrier and a drywall on the inside of the insulation.

("Week 1") and the first week of July ("Week 27"). The figures show two bundles of curves, where the lower bundle is for the week in January and the other bundle is for July. Each graph represents one of the choices of vapor retarder. As would be expected, the indoor relative humidity varies around 40% in January and around 70% in July. The results are shown for the cases with oil-tempered wood fiberboard as exterior sheathing.

As Figure 6 (no vapor retarder) shows, there is some possibility of stabilizing the daily variation of indoor relative humidity by using an insulation material with a large moisture capacity such as cellulose. The lack of moisture capacity of rock wool results in a large daily variation of RH, particularly during summer, probably because of the almost unobstructed contact with the vapor pressure behind the exterior sheathing when there is no vapor retarder. The vapor pressure of the exterior sheathing is somewhat controlled by the outdoor temperature.

However, as the comparison with Figures 7 through 9 shows, the insulation's moisture buffering effect on the indoor climate vanishes as soon as the vapor admittance to the insulation materials is hindered by the vapor diffusion resistance of a material that is closer to the room air. Even 13 mm (0.5 in.) of drywall is enough to practically eliminate the effect of the insulation material's moisture capacity on the diurnal indoor RH variation. It seems that for short oscillations, all that matters is the moisture capacity of the thin layer of material that is in immediate contact with the indoor air. This corresponds well with Olsson (1996), who for periodic diurnal humidity variations finds the moisture penetration depth for gypsum to be 5 mm. None of the curves for the indoor climate seems to reveal any buffer effect that stretches over longer periods than diurnal variations.

However, the indoor RH level is slightly lower in winter, when there is a somewhat permeable vapor retarder or none at all, than when there is a vapor-tight polyethylene barrier in the wall. The reason can only be the easy access to the cold parts of the wall, where moisture will accumulate and to some extent migrate to the outdoors when there are only permeable

layers on the warm side of the wall. In this case, one could see that diffusion open structures might have a (small) influence on regulating the indoor humidity level. However, as analyzed by, for instance, Elmroth et al. (1996), one could compare possible vapor diffusion rates into a wall against the rate of moisture exchange by normal infiltration of indoor spaces to see that in most cases the room ventilation will dominate. The next subsection will reveal whether the desiccating effect of diffusion will endanger other parts of the wall.

Relative Humidity Behind the Exterior Sheathing

Figures 10 through 13 show the daily average values of RH immediately behind the exterior sheathing during the whole of the third calculation year.

Figures 10 and 11 show that entirely without vapor retarders, or when there is only a drywall on the inside, the relative humidity behind the exterior sheathing will be unacceptably high during the winter months. There is a high risk of fungal growth, particularly since the high humidity levels extend long into the spring months when the temperature of the exterior parts of the wall rises and, thus, aggravates the risk. The generally bad situation is slightly better when gypsum is used as a permeable exterior sheathing material, as opposed to oil-tempered wood fiberboard, because drying to lower RH levels, e.g., to a condition below 90% RH on the interior of the sheathing, is one to two months ahead and typically lasts around three months longer. The results do not favor one insulation material over another. The condensation risk may seem to be a little worse when rock wool is used, since RH is closer to 100%, but when drying sets in, the critical part of the construction dries to safe RH levels within a very short time.

The maximum moisture content of the cellulose insulation immediately behind the wood sheathing is less than 70 kg/m^3 (4.4 lb/ft^3). Consequently, the potential for liquid suction is normally minimal and limited to the area close to the outside of the insulation. The maximum moisture content is somewhat

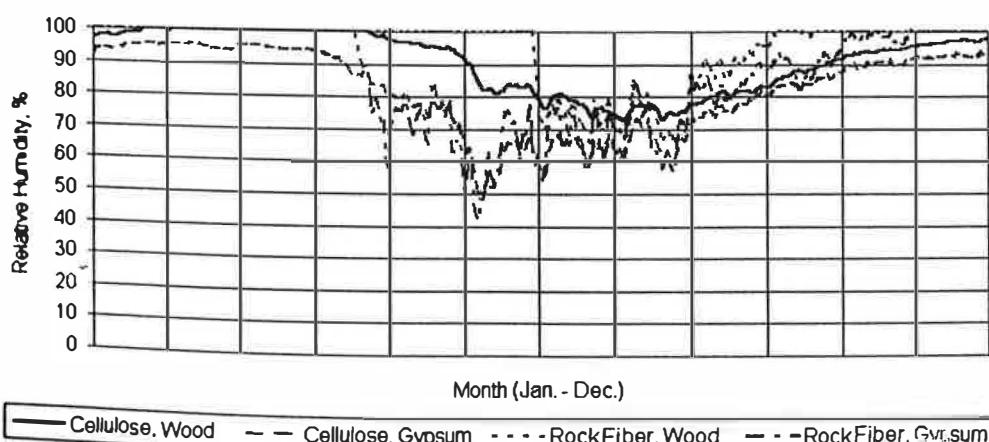


Figure 10 Annual course (January to December) of simulated relative humidity on the inside of the exterior sheathing when there is no vapor retarder or other material between the insulation and the indoor air. The legend refers to the choice of insulation material and material used for the exterior sheathing.

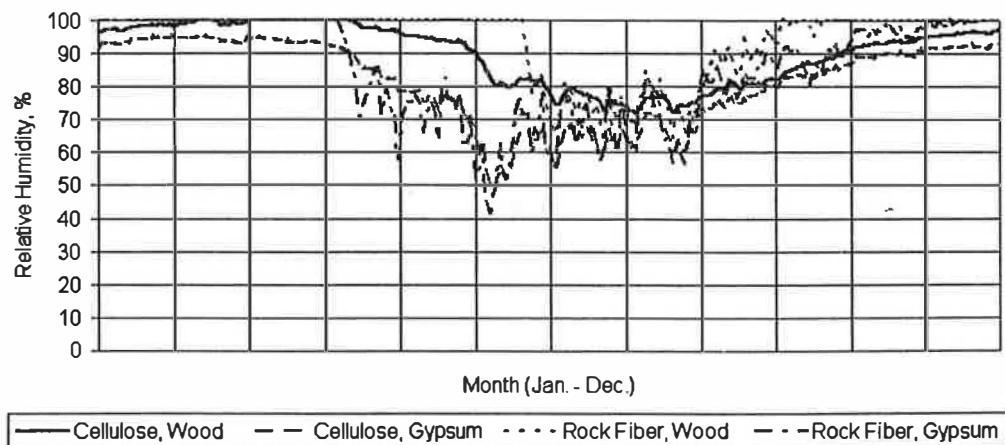


Figure 11 Annual course of simulated relative humidity on the inside of the exterior sheathing when there is only a bare board of 13 mm (0.5 in.) drywall between the insulation and the indoor air.

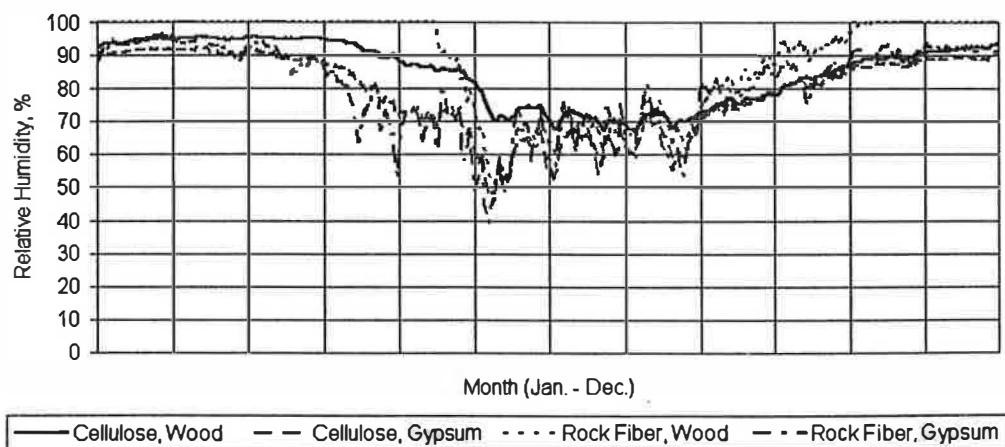


Figure 12 Annual course of simulated relative humidity on the inside of the exterior sheathing when there is a somewhat permeable vapor retarder and a drywall between the insulation and the indoor air.

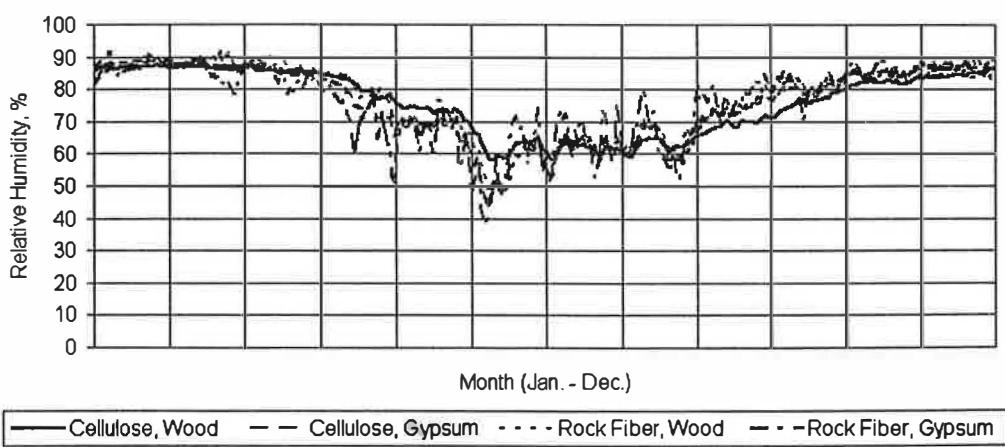


Figure 13 Annual course of simulated relative humidity on the inside of the exterior sheathing when there is a polyethylene vapor barrier and a drywall between the insulation and the indoor air.

higher when less hygroscopic insulation material is used, but even if this renders a potential for liquid movement, it is judged that this will only be a local phenomenon occurring behind the exterior sheathing.

Figure 12 indicates that with a vapor retarder with a moderate vapor diffusion resistance, the RH levels behind the exterior sheathing become lower, except for the case with rock wool and wood sheathing. However, from these calculations, it does not seem to be sufficient to eliminate the risk of fungal growth since the relative humidity is higher than 90% during the winter.

All the calculations in Figure 13 for a polyethylene vapor barrier show almost the same result. In this case, the exterior part of the wall adjusts to the RH of the outdoor climate, which usually means that the risk of fungal growth is minimal if there are no other moisture sources present. There are only small variations between the curves, which indicates the difference in how readily the materials can adjust to the outdoor environmental conditions.

Effect of Sorption Curve for Cellulose Insulation

Figure 14 shows the indoor relative humidity in January and July when either Zarr et al.'s (very hygroscopic) or Salonaara's (less hygroscopic) sorption isotherms are used for cellulose insulation. The calculations are for the case completely without vapor retarder on the inside and oil-tempered wood fiberboard as exterior sheathing. The results cannot be distinguished. An obvious suggestion for an explanation is the similarity of the sorption curves in the central region of the hygroscopic interval, the 40%-70% RH, in which the indoor humidity varies. Both moisture content and moisture capacity (slope of the sorption isotherm) are almost identical in this RH region.

Figure 15 shows, for the same calculations, the annual course of the RH profile immediately behind the exterior sheathing. There is a clear difference. While Zarr et al.'s material is at 100% RH during only the severest winter months, Salonaara's material experiences condensation behind the exterior sheathing during the whole winter and long into the spring season. Again, the shape of the sorption isotherms may

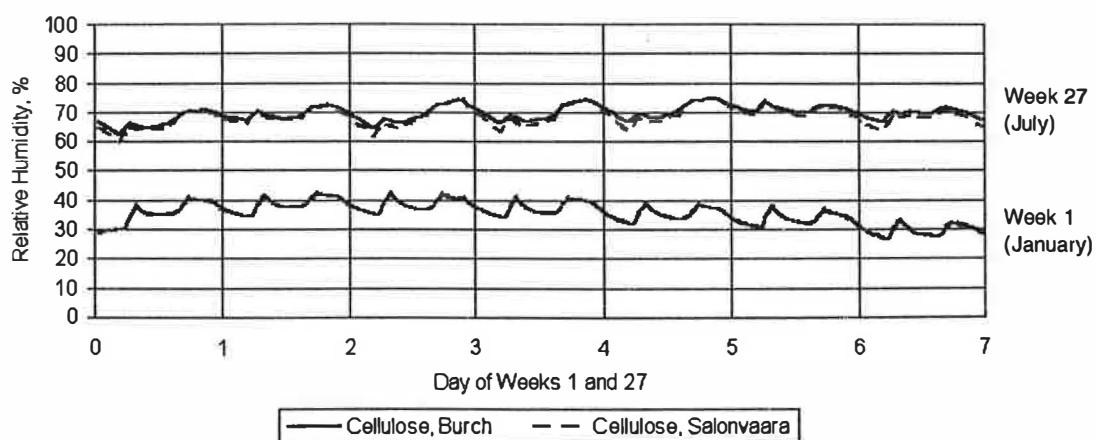


Figure 14 Simulated indoor relative humidity in January and July when there is no membrane or cladding on the inside of the insulation, which consists of cellulose with sorption curves either according to Zarr et al. (1995) or according to Salonaara (1992).

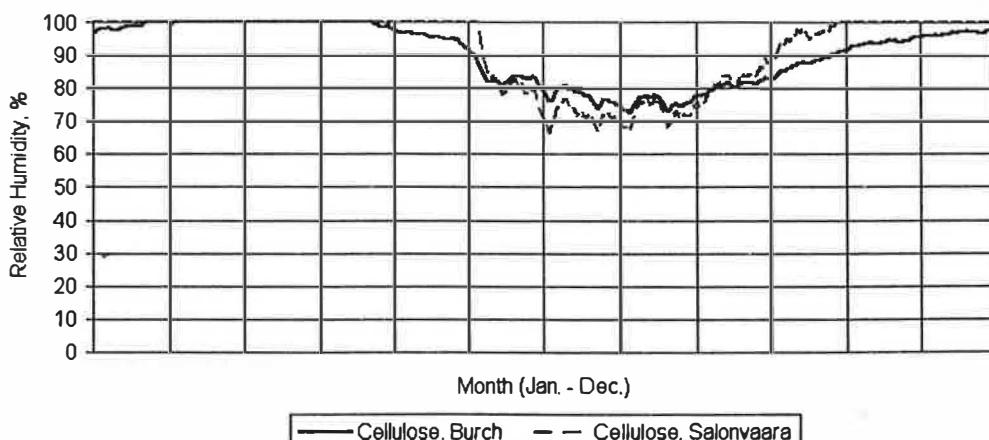


Figure 15 Annual course of simulated relative humidity on the inside of the exterior sheathing when there is no vapor retarder or other material between the insulation and the indoor air and the insulation, which consists of cellulose with sorption curves either according to Zarr et al. (1995) or according to Salonaara (1992).

explain the results. The relative humidity behind the exterior sheathing is always at the highest end of the hygroscopic regime. This is the area in which the two curves differ quite significantly. Zarr et al.'s material can absorb large quantities of water before the material experiences real condensation (100% RH) because the sorption curve becomes still steeper as the saturation point is approached. In contrast, it is quite noteworthy that the moisture capacity of Saloavaara's material does not increase significantly at the high end of the hygroscopic regime, and, therefore, condensation is inevitable in a situation where moisture accumulates in the material over a long period.

CONCLUSION

A procedure has been proposed on how to use a tool that was originally developed to analyze transient hygrothermal conditions in constructions in a different way so that it is able to analyze the interaction between the occupied interior space and a wall assembly. The space is modeled as one of the layers in the composite structure. However, some limitations still exist, mainly since the space has only one adjacent structure.

The analysis seems to indicate some possibility to predict qualitatively and under isothermal conditions the course of relative humidity variation in a space that exchanges moisture with a homogenous material and is subjected to an auxiliary addition or removal of humidity.

The procedure has been extrapolated to analyzing the hygrothermal performance of a wall with cellulose or mineral fiber insulation material under nonisothermal conditions when there is moisture production and ventilation with outdoor air to the room that is adjacent to the wall. The analysis seems to indicate that, unless there is no vapor retarder or other material between the insulation layers of the wall and the adjacent space, the hygroscopic capacity of the insulation material will not act as a buffer for the indoor relative humidity level. If there is little or no vapor diffusion resistance between the insulation layer of a wall and the indoor space, diffusion through the wall might desiccate the room by a small amount under winter conditions in a Nordic climate. However, the same conditions may cause high humidity levels in the exterior construction parts, which could result in fungal attack on wood-based materials that are in contact with the insulation. Vapor permeable conditions on the outside may not be sufficient to prevent such damage. Provided there is no possibility for harmful convective moisture flow, a vapor barrier with high diffusion resistance seems to render the safest moisture conditions in the wall structure.

ACKNOWLEDGMENTS

Doctoral candidate M. A. Tim Padfield from the Conservation Department of the National Museum of Denmark is gratefully acknowledged for his contribution of experimental

data for the comparison in the second section as well as for contributing fruitful discussion on the outlines of the paper.

REFERENCES

- ASHRAE. 1997. *1997 ASHRAE handbook—fundamentals* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASTM. 1994. *Moisture control in buildings*. ASTM Manual Series, MNL 18. Ed.: Heinz R. Trechsel. American Society of Testing and Materials.
- Björk, F., D. Lundblad, and K. Öden. 1997. Transport of air tracer gas and moisture through a cellulose fibre insulated structure. *Nordic Journal of Building Physics*, Vol. 1.
- Eko. (Ekofiber). 1998. Quotation from a cellulose insulation manufacturer's product information. <http://www.ekofiber.se>
- Elmroth, A., C.-E. Hagentoft, and K. Sandin. 1996. Plastfolie—behövs den i väggar och tak? *Byggforskning*. Vol. 2.
- Hansen, K.K. 1986. *Sorption isotherms—A catalogue* Building Materials Laboratory, Technical University of Denmark, Technical Report 162/86.
- Hens, H. 1996. *Heat, air and moisture transfer in insulated envelope parts*. Final Report, Volume 1, Modelling IEA, Annex 24. International Energy Agency, Energy Conservation in Buildings and Community Systems research programme. Katholieke Universiteit, Leuven Belgium.
- Heistad, H., and T. Korneliussen. 1995. Cellulosefiber som isolasjonsmateriale. Sivilingeniørutdanningen i Narvik. Master's thesis.
- Kumaran, M.K. 1996. *Heat, air and moisture transfer in insulated envelope parts*. Final Report, Vol. 3, Material Properties. IEA, Annex 24. International Energy Agency, Energy Conservation in Buildings and Community Systems research programme. Katholieke Universiteit, Leuven, Belgium.
- Olsson, M. 1996. Houses built with ecological aspects. *Proceedings of the 4th Symposium on Building Physics in the Nordic Countries*. VTT, Espoo, Finland. September.
- Padfield, T. 1998a. The role of absorbent buffering materials in moderating changes of relative humidity. Doctoral thesis. Department of Structural Engineering and Materials, Technical University of Denmark.
- Padfield, T. 1998b. A climate chamber that controls water vapour flux. *Third International Symposium on Humidity and Moisture*, National Physical Laboratory, Middlesex, United Kingdom.
- Rode, C., and D.M. Burch. 1995. Empirical validation of a transient computer model for combined heat and moisture transfer. *Thermal Performance of the Exterior Envelope of Buildings VI*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

- Røde Pedersen, C. 1990a. Combined heat and moisture transfer in building constructions, Ph.D. thesis. Report no. 214, Thermal Insulation Laboratory, Technical University of Denmark.
- Røde Pedersen, C. 1990b. Transient calculation of moisture migration using a simplified description of hysteresis in the sorption isotherms. *Proceedings of the 2d Symposium on Building Physics in the Nordic Countries*, Norwegian University of Science and Technology, Trondheim, August, 1990.
- Salonvaara, M. 1992. The effects of vapour transfer on heat flows through cellulose insulation. Laboratory of Heating and Ventilation, Technical Research Centre of Finland.
- Sikander, E. 1996. Fugtsäkerhet hos några typer av byggnadskonstruktioner. SP Report 1996:34, Swedish National Testing and Research Institute.
- Zarr, R.R., D.M. Burch, and A.H. Fanney. 1995. Heat and moisture transfer in wood-based wall construction: Measured versus predicted. NIST Building Science Series 173, National Institute of Standards and Technology.