Moisture Content of Indoor Air and Structures in Buildings with Vapor-Permeable Envelopes

Carey J. Simonson, Ph.D.
Associate Member ASHRAE

Mikael H. Salonvaara
Member ASHRAE

Tuomo Ojanen

ABSTRACT

It is known that a vapor-resistant layer on the inside of an insulated envelope in cold climates is needed to prevent excessive diffusion of water vapor from indoor air into the building envelope. However, the required magnitude of this vapor resistance has been debated in recent years. In this paper, the moisture transfer between indoor air and the building envelope and the moisture performance of a building envelope that has no plastic vapor retarder is analyzed with field measurements and numerical simulations. The results show that the diffusion resistance of the internal surface should be greater than the diffusion resistance of the external surface for a structure safe from moisture but that the vapor resistance of the vapor retarder can be significantly below that provided by polyethylene, even in cold climates. Meanwhile, the moisture transfer between indoor air and the building envelope can moderate the indoor humidity, which improves indoor climate and comfort.

INTRODUCTION

Conditioning indoor air is very important because research has shown that both the indoor climate and indoor air quality (IAQ) can influence comfort, health, and productivity (Wargocki et al. 1999; Seppänen et al. 1999; Wyon 1996). Therefore, buildings with a good indoor environment are necessary for a healthy, productive, and prosperous society because people spend 90% of their time indoors. An important, but often neglected, indoor environmental parameter is humidity, and often indoor humidity is considered to be of small importance for a successful design because temperature is easier to sense, quantify, and control. Nevertheless, research has shown that the indoor relative humidity can significantly affect

- thermal comfort (Toftum et al. 1998a, 1998b; Berglund 1998; ASHRAE 1992; Fanger 1982),
- the perception of IAQ (Fang et al. 1998a, 1998b),
- occupant health (Clausen et al. 1999; Cooper-Arnold et al. 1997; Dales et al. 1991; Green 1985),
- the durability of building materials (Viitanen 1996; Ojanen and Kumaran 1996; ASTM 1994), and
- energy consumption (Besant and Simonson 2000; Harriman et al. 1997).

Well-designed heating, ventilating, and air-conditioning (HVAC) systems add or remove heat and moisture from the occupied spaces of buildings and provide an acceptable indoor environment in many climates. However, in many hot and humid climates, conventional air-conditioning units are unable to meet the latent load and the indoor relative humidity exceeds the often recommended value of 60% to 70% RH (ASTM 1994; ASHRAE 1992; ASHRAE 1989). This has led to the growing application of heat and moisture transfer devices that can reduce the latent load on air-conditioning units (Besant and Simonson 2000; Harriman et al. 1997; Rengarajan et al. 1996). With these devices, it is possible to provide an acceptable indoor climate even in hot and humid climates. Nevertheless, there is a desire to develop more passive and less energy-intensive methods of moderating the indoor environment. The passive method investigated in this research uses the moisture storage capacity of building structures to damp occupant-induced moisture. The main focus will be on moisture transfer between indoor air and building struc-

Carey J. Simonson and Tuomo Ojanen are senior research scientists and **Mikael H. Salonvaara** is a research scientist at VTT Building and Transport, Espoo, Finland.

tures and the resulting effect on indoor climate, air quality (IAQ), and building durability.

Passive methods of moderating the indoor environment are gaining popularity because they are energy conscious and environmentally friendly. In moderate climates, where air conditioning is seldom or never used, passive methods may make it possible to provide an acceptable indoor climate during hot periods without the need of air conditioning. In cold climates, such as Finland, passive methods could help control the occupant-induced diurnal variations in indoor humidities, which are often moderated by providing outdoor ventilation air. By appropriately utilizing moisture transfer between indoor air and building structures, the needed ventilation rate could possibly be reduced because the perception of IAQ is closely linked to the humidity of indoor air (Toftum and Fanger 1999; Fang et al. 1998a, 1998b). Furthermore, the ability of buildings to damp changes in temperature is much greater than their ability to damp changes in humidity (Padfield 1998) even though humidity control can be extremely important. These factors indicate that there is a great need for research and development before buildings with greater hygroscopic mass will be realized, even though many materials have the potential for exploitation (Simonson et al. 2001a; Virtanen et al. 2000).

Moisture transfer between indoor air and building materials can improve the moisture performance of indoor air, but the moisture performance of the envelope is important and must be addressed as well. Moisture accumulation in building envelopes due to the convection and diffusion of water vapor from indoor air is an important issue, especially in cold climates (ASTM 1994). Moisture accumulation can degrade building materials through mold growth, rotting, corrosion, and other physical or aesthetic damage. To minimize convective moisture transfer, the building envelope should be made airtight and any exfiltration airflow should be very small (Ojanen and Kumaran 1996). An airtight layer (often called air barrier) reduces air leakage through the building envelope, thereby improving the moisture performance, energy consumption, ventilation performance, and thermal comfort. Even with an airtight building envelope, the diffusion of water vapor may be significant and, therefore, it is important to have a layer that is resistant to vapor diffusion on the warm side of an insulated envelope in cool climates. The purpose of this layer (often called vapor barrier or vapor retarder) is to reduce the diffusion of moisture from indoor air into the building envelope to such a level that it does not cause problems. Naturally, in cold climates, a very high vapor resistance is safer than a very low resistance and often polyethylene vapor retarders are recommended and applied in practice. Polyethylene also has a very low air permeance and therefore functions as both an air and vapor barrier. Because of its dual function, polyethylene is often specified and the safety of envelopes with air and vapor barriers other than polyethylene is often questioned. Therefore, one of the purposes of this paper is to present research that illustrates the level of vapor resistance required to keep water vapor diffusion from causing a moisture problem in a cold climate such as Finland's.

FIELD EXPERIMENTS

CONSTRUCTION AND INSTRUMENTATION

The house monitored in this study is a two-story wood-frame house located in Helsinki, Finland, with a gross floor area of 237 m^2 and an internal volume of living space of 470 m^3. The insulation material is wood-fiber insulation and the thickness is 250 mm in walls and 425 mm in the roof, giving a wall U-factor of 0.16 $W/(m^2 \cdot K)$ and a roof U-factor of 0.10 $W/(m^2 \cdot K)$. To permit the diffusion of water vapor between indoor air and the envelope, diffusion permeable paints are applied and no plastic vapor retarder is used. The ratio of the internal to external vapor resistance is about 3:1 or 4:1 (1.5 - 3 x 10^9 to 0.5 - 1.0 x 10^9 $m^2 \cdot Pa \cdot s/kg$ depending on the outdoor relative humidity). District heat and a wood-burning fireplace provide heating, while a natural ventilation system provides outdoor ventilation. The thick insulation is intended to keep energy consumption low, whereas the porous envelope and natural ventilation systems are examples of passive methods of controlling the indoor climate and IAQ.

Moisture Transfer Test

The moisture transfer between the building structure and the indoor air was studied in a second floor bedroom shown in Figure 1. The bedroom is nearly square and has two windows and two doors and a volume of 29 m^3. The north and west walls are exterior walls (250 mm wood-fiber insulation), and the south (100 mm wood-fiber insulation) and east walls are interior walls. The east wall and the small support wall are made of 140-mm-thick brick and coated with plaster and primer. All other walls and the ceiling (425 mm wood-fiber insulation) are of wood frame construction and, at the time of the test, were finished with 13 mm of gypsum board that was plastered and coated with a single coat of primer. The floor has 125 mm of wood-fiber insulation and the wooden floor board is 32 mm thick. The door leading to the interior of the house was not in place at the time of the test but was covered with 5-mm-thick wood fiberboard. As a comparative test, the ceiling, floor, and walls of the test room were covered with 0.2 mm polyethylene vapor retarder (except for the external windows and door) to represent a room with vapor-tight sealing and to directly show the influence of diffusion moisture transfer between the indoor air and the porous building envelope.

During the test, water vapor was generated and monitored with an electric humidifier located on an electronic balance. Ventilation airflow was provided with a variable speed fan that drew air out of the room through the interior door (Figure 1). To replace this air, outdoor ventilation air entered the room through a ventilation channel located above the balcony window. The ventilation flow rate was measured with a calibrated orifice plate and a digital pressure transducer with a precision of 0.1 Pa. The uncertainty in the measured ventila-

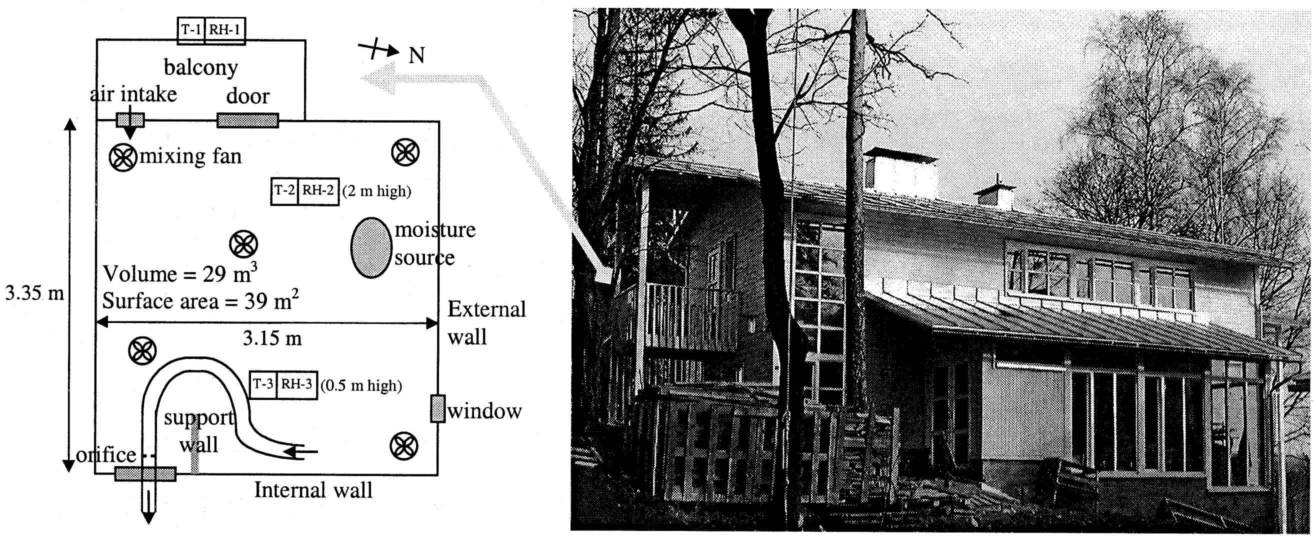

Figure 1 *Schematic diagram of the test room showing dimensions, instrumentation, and its location in the test house.*

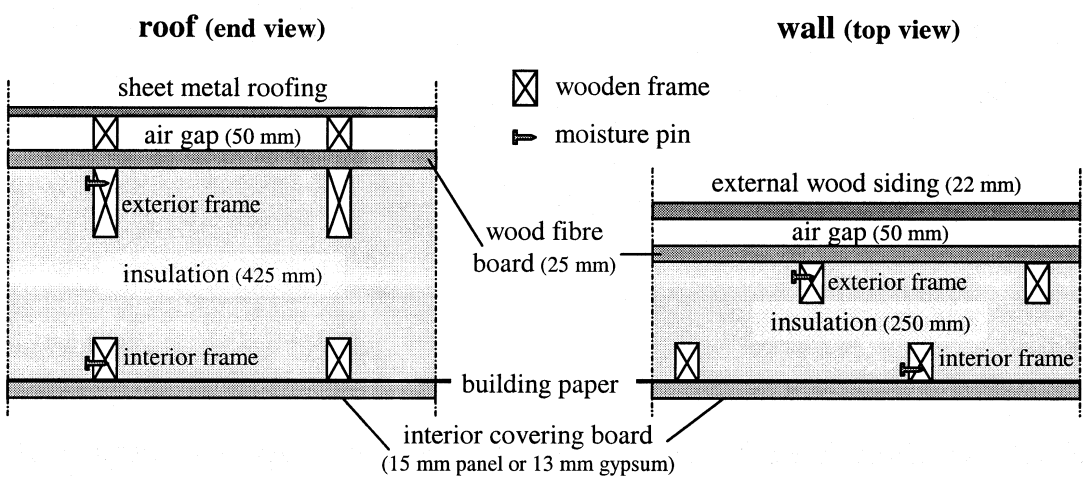

Figure 2 *Roof and wall construction showing the location of moisture pins.*

tion flow rate was ±4%. Five fans were used to continuously mix the air in the room and the locations of the temperature and relative humidity sensors are shown in Figure 1. The difference between the different sensors in the room was quite small (on average less than 0.1°C and 5% RH), indicating good mixing. The temperature sensors were thermistors with radiation shields and the relative humidity sensors were capacitance-type sensors that were calibrated after the test against salt solutions. The accuracy of the temperature and humidity sensors is expected to be within ±0.3°C and ±3% RH, respectively.

Performance of the Building Envelope

The moisture content of the wooden frames in the walls and roof was measured using moisture pins near the interior and exterior sides of the envelope as shown in Figure 2. To obtain the greatest spread in moisture content, the moisture pins were located as close as practical (≈ 15 mm) to the internal and external covering boards. The moisture content of the roof was measured on the north and south sides of the sloped roof (1:3) and in the north, south, and east walls. The moisture content of the walls was measured near the top (200 mm from the ceiling) and near the bottom (200 mm from the floor). Only the walls on the first floor were measured. In all, 32 moisture pins were monitored, and the uncertainty of the measured moisture content is expected to be ±0.02 kg/kg.

BUILDING TIGHTNESS

A building with poor airtightness may have uncontrolled airflow through the building envelope, which can lead to problems related to moisture, thermal comfort, energy consumption, ventilation performance, and noise. Therefore, it is important to construct buildings with minimal airflow through the building envelope. The intention in constructing the test house was to build a house that allows mass transfer by molecular diffusion but not by convection (airflow). To minimize convective mass transfer (airflow) through the envelope, the house was well sealed with building paper and the tightness of the building envelope was measured. In addition, the airtightness of the test room was measured to confirm that the air leakage through the envelope was small during the moisture transfer test. The tightness of the envelope is important because the purpose of the moisture transfer test is to investigate diffusion mass transfer between indoor air and structures rather than convective mass transfer.

The airtightness of the whole house and the test room was measured with a lower pressure indoors than outdoors, resulting in infiltration airflow (Charlesworth 1988). A variable-speed fan was ducted through 5-mm-thick high-density wood fiberboard that was sealed in a basement window during the tightness measurement of the whole house and in the door connecting the test room and the house during the tightness measurement of the test room. A calibrated orifice plate was used to measure the flow rate of air exhausted from the house and test room. In all the tests, the natural ventilation supply vents were removed and sealed with tape. During the test of the whole house, the chimney and exhaust vents were sealed with polyethylene plastic and tape on the roof. All windows and external doors were closed during the pressure tests, but typically were not sealed with tape to represent the conditions during the moisture transfer test and actual use. Measurements were also performed in the test room with the balcony door and windows sealed to determine their leakage characteristics. During the pressure test, it was noticed that the main leakage paths were the front door of the house and the balcony door in the test room.

During the tightness measurement of the whole house, the pressure difference across the building envelope was measured on both the first and second floors. The measured pressure differences on the first floor were only slightly higher (usually less than 3 Pa) than the pressure difference on the second floor, indicating good mixing. During the measurement in the test room, the main door of the house was kept open to minimize pressurization of the house. The pressure difference between the house and outdoors was typically less than 1 Pa. The results of the airtightness test are summarized in Figure 3 and show that the house is moderately airtight and that the test room has less air leakage than the whole house, especially when the balcony door is sealed with tape. At an underpressure of 50 Pa, the air infiltration through the building envelope is estimated to be 3.1 ach, while the air infiltration into the test room is 2.2 ach and 1.5 ach when the balcony door and windows are unsealed and sealed, respectively. This tightness is in the lower range of normal houses in Finland according to the classification of Laine and Saari (1998), which is good (1 to 2 ach), normal (3 to 4 ach), and leaky (> 5 ach). The airtightness is also in the range of 1 to 3×10^{-5} $m^3/(s \cdot m^2 \cdot Pa)$ (0.5 to 1.5 $L/(s \cdot m^2)$) at 50 Pa as recommended by Uvslokk (1996) and Ojanen (1993).

The airtightness results for the test room show that nearly half of the infiltration air comes through the seals in the balcony door, which was also confirmed with smoke tests. (Sealing the windows with tape had little effect on the leakage.) The exact location of other leakage points was difficult to quantify with smoke because of the low velocities and flow rates. Because the balcony door, windows, and ventilation channels are not taped during the moisture transfer test, these results indicate that most of the ventilation air will be from outdoors during the moisture transfer test, which is desired.

MOISTURE PERFORMANCE OF INDOOR AIR

In the study of the mass transfer of water vapor between the indoor air and the building structure, water vapor was generated during the night using an electric humidifier and an electric timer. The average moisture generated during the night (87 g/h) is equivalent to two occupants producing 30 W/occupant of latent energy for 8 hours every night. This is most likely slightly higher than expected for a sleeping adult because ASHRAE (1997) indicates that 30 W of latent energy would be produced, for example, by a person seated at a theater. No values for sleeping adults are presented in ASHRAE (1997), but the metabolic rate for sleeping people (0.8 met) is 80% of the metabolic rate for seated and quiet people (1.0 met) (ASHRAE 1992).

During the moisture transfer test, which was undertaken from May 14 to May 31, 1999, the outdoor temperature varied between 0°C and +20°C (one night had a temperature of –10°C) and the average was 11°C. The indoor temperature was quite high due to the heat gain from equipment. The average value during the test was 27°C and the range was 24°C to 30°C.

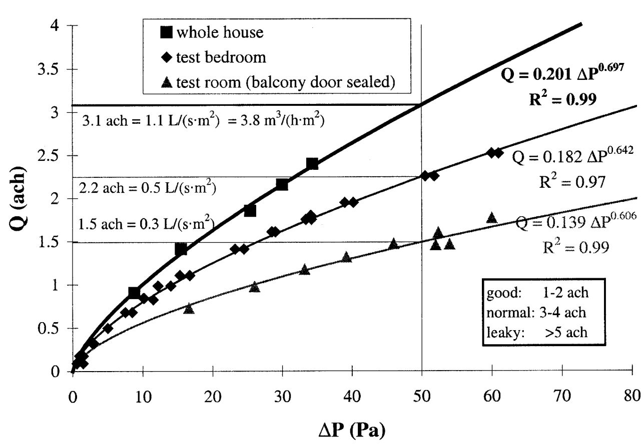

Figure 3 *Airtightness of the test house and the test bedroom.*

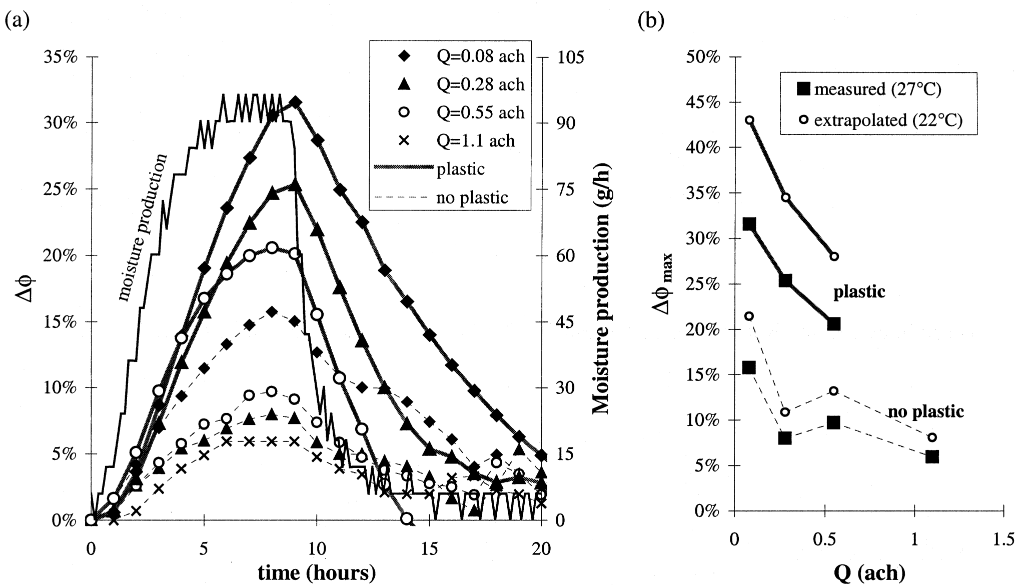

Figure 4 *Change (a) and maximum increase (b) in relative humidity in the test room after the start of humidity generation for various outdoor ventilation rates.*

To compare the effects of outdoor ventilation and moisture transfer between indoor air and structures, Figure 4 contains the change in humidity of the room ($\Delta\phi$) as a function of time after the onset of humidification for two cases. One case is where the interior coating of the room is permeable (base case with vapor-permeable paint) and the other case is where the interior coating is impermeable (i.e., the interior surface of the room is covered with a plastic vapor retarder). The change in humidity is defined as

$$\Delta\phi = \phi - \phi_o \qquad (1)$$

where ϕ is the average indoor relative humidity and ϕ_o is the initial indoor relative humidity, which is the relative humidity in the room when the humidity generator is turned on. The results show that the increase in relative humidity is significantly greater when there is plastic than when there is no plastic. In fact, the increase in relative humidity is greater for the 0.55 ach test with plastic than for the 0.08 ach test without plastic. This shows that, for these test conditions, the sorption of water vapor in the porous envelope has a greater effect on the indoor humidity than ventilating the room with 0.55 ach, which is close to the typical design value of 0.5 ach in Finland (national building code of Finland—D2 1987). For comparison, the proposed ASHRAE Standard 62.2P, Ventilation and Acceptable Indoor Air Quality in Low-rise Residential Buildings, specifies a ventilation rate of about 0.4 ach for the test house studied in this paper (Sherman 1999). With no forced ventilation (expected ventilation of 0.08 ach), the maximum increase in humidity ($\Delta\phi_{max}$) is twice as large when the room is covered with plastic ($\Delta\phi_{max}$ = 32% with plastic and $\Delta\phi_{max}$ = 16% without plastic). The average difference between $\Delta\phi_{max}$ with and without plastic is 15% at 27°C, which corresponds to 21% RH at 22°C based on the ratio of absolute humidities at saturation.

Most of the results in Figure 4 show, as expected, that $\Delta\phi$ decreases as the ventilation rate increases. When the room is not covered with plastic, however, $\Delta\phi$ is greater for a ventilation rate of 0.55 ach than for a forced ventilation rate of 0.28 ach. The reason for this is that the humidity ratio of the outdoor air is greater than the humidity ratio of the indoor air during the 0.55 ach test, and, therefore, the ventilation air is actually increasing the humidity in the room rather than decreasing it, as is the case with the other ventilation rates. Since the conditions are not exactly the same for each test, the data in Figure 4 are somewhat limited. Therefore, to supplement these measurements, a numerical model will be applied in the modeling section to compare different ventilation rates and to extrapolate these results to other test conditions.

Measurements During Occupation

In the controlled moisture transfer experiment, the room was unfurnished and the doors were always closed except to enter the room to adjust and inspect equipment. Therefore, to verify these experimental results, the indoor temperature and relative humidity were measured during normal occupation of the house. The temperature and relative humidity of the indoor air were monitored for about two months in the winter (February 8 to March 31, 2000) and summer (May 9 to July 8, 2000). The average indoor temperature and humidity (including standard deviation) were 21.4 ± 0.5°C and 21 ± 3% RH in the winter and 23.4 ± 1.1°C and 30 ± 7% RH in the summer. During the winter measurements, the absolute humidity in the test room was, on average, 1.9 g/m^3 (standard deviation of 1 g/m^3) greater than the outdoor absolute humidity, while the humidity in the open hallway was, on average, only 0.7 g/m^3 greater than the outdoor humidity. In the summer, the average indoor and outdoor absolute humidities were nearly equal and the difference between the indoor and outdoor humidity showed greater fluctuations than in the winter.

The most important aspect of the measurement is the diurnal fluctuation of humidity, which can be seen in Figure 5 for a two-week period in the winter and summer. During the summer, the humidity sensor was located in different bedrooms with open or closed doors, and the concentration of CO_2 is also included in Figure 5b to show when the bedroom door is open or closed. When the peak concentration of CO_2 exceed 1200 ppm, the door is closed, and when the peak concentration is lower than 1200 ppm, the door is open. The maximum increase in humidity during the night ($\Delta\phi_{max}$) is nearly the same in the winter and summer, but it is clearly influenced by the position of the bedroom door. For comparison, the humidity measured in an open hallway near the test room is presented in the winter.

The diurnal fluctuations in indoor humidity are evident in Figure 5 and show that the fluctuations are greater in the bedrooms than in the open hallway, especially when the bedroom doors are closed. In the bedrooms, the relative humidity increases during the night and decreases the following day. The maximum increase in humidity during the night

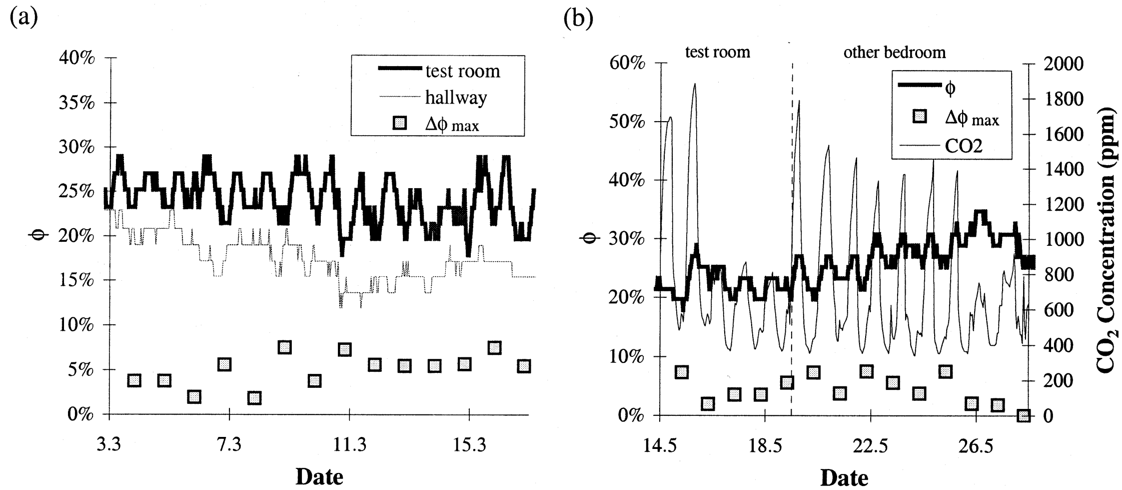

Figure 5 *Indoor relative humidity during two weeks of occupation, showing the increase in relative humidity during the night for winter (a) and summer (b) conditions. The measured CO_2 concentrations are shown in the summer to indicate when the bedroom doors are open (low peak concentration) and closed (high peak concentration).*

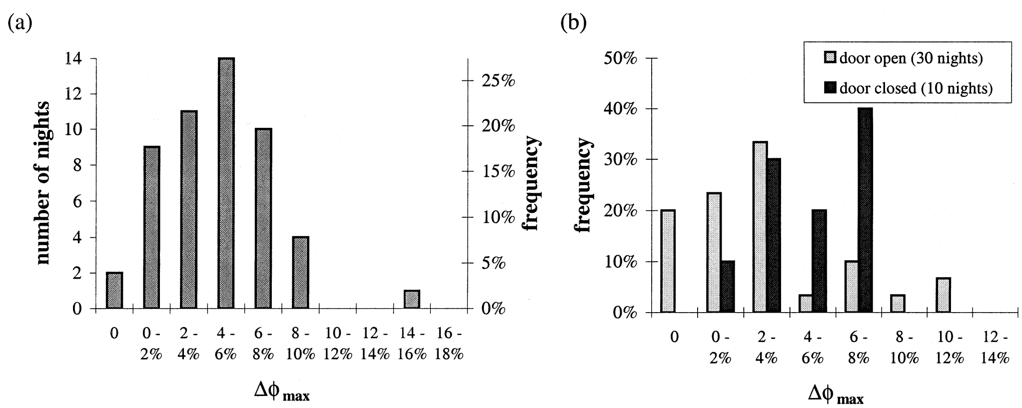

Figure 6 *Frequency distribution of the maximum increase in relative humidity during the night in the winter (a) and summer (b). The winter measurements (February 8 to April 4, 2000) are from the test room and the summer measurements (May 13 to July 7, 2000) are from all of the bedrooms in the house.*

is presented as a frequency diagram in Figure 6 where the indoor humidity at 20:00 is used as ϕ_o.

Figure 6a shows that during two nights, the increase in humidity during the night was 0% RH (i.e., there appeared to be no occupant in the room or the outdoor humidity decreased significantly). The maximum value of $\Delta\phi_{max}$ is 14.6% RH, but $\Delta\phi_{max}$ is greater than 10% RH during only one night. The most common value of $\Delta\phi_{max}$ is between 4% and 6% RH, which occurred 14 out of 51 nights or 27% of the time. The average value of $\Delta\phi_{max}$ is 5.1% RH and the standard deviation is 2.8% RH. To compare the results in Figure 6a to those measured during the controlled experiments in Figure 4, the ventilation of the test room must be estimated. Simonson (2000) estimated the ventilation rate in the test room to be about 0.25 ach. From Figure 4, the value of $\Delta\phi_{max}$ is about 10% to 15% RH at a ventilation rate of 0.25 ach and an indoor temperature of 22°C. Considering that there is only one occupant in the furnished bedroom during normal occupation (in the experimental results in Figure 4, two occupants were simulated in the unfurnished room), the experimental results are quite comparable to the results measured during occupation.

Since the humidity sensor was moved between bedrooms in the summer, the frequency distribution for a single room is not meaningful; however, the summer measurements can be used to show the difference between having the bedroom door open or closed. In Figure 6b, the value of $\Delta\phi_{max}$ has been normalized by the number of people in the room. The average value of $\Delta\phi_{max}$ is 3.4% RH (standard deviation of 3.1% RH) when the bedroom door is open and is 5.2% RH (standard deviation of 2.2% RH) when the bedroom door is closed.

MOISTURE PERFORMANCE OF THE BUILDING ENVELOPE

The moisture performance of the envelope was monitored during the construction and occupation of the house. The moisture performance was assessed considering mold growth to be the most critical moisture concern, where the risk of mold growth depends on the temperature, humidity, and time of exposure. Mold growth can occur at temperatures as low as 0°C (requires 100% RH) and humidities as low as 80% RH (requires temperatures greater than 15°C), but it requires at least six weeks exposure to these conditions (Hukka and Viitanen 1999). For pine wood, the moisture content is about 0.16 kg/kg at 80% RH and the maximum hygroscopic moisture content is about 0.28 kg/kg.

Construction Moisture

Simonson (2000) and Simonson and Ojanen (2000) demonstrate that the moisture content in the envelope was quite high (> 20% by mass) when the moisture pins were installed in April 1998 after construction of the frame. Most of the structures dried below the mold threshold (80% RH, 0.16 kg/kg, and 15°C) during the first summer, but the exterior frame of the north wall and the interior frame of all walls had moisture contents as high as 0.19 kg/kg. Heating began in October 1998 and the interior frames dried to about 0.10 kg/kg during the first winter. The maximum moisture content of the external frames were between 0.18 kg/kg and 0.22 kg/kg during the first winter, but the house was not occupied. During the second summer, all the measurements were below the mold growth threshold (80% RH at 15°C) and the maximum moisture contents were between 0.13 kg/kg and 0.10 kg/kg. These results show that the initial construction moisture dries after about two years.

Moisture Accumulation During Occupation

The results from the second winter (1999/2000) are important because the house is occupied. Here only the maximum moisture content at each location (Table 1) is presented (Figure 7) because this is the most important value when assessing moisture performance and the risk of mold growth. When analyzing the data, it was noticed that the moisture content was most significantly affected by whether the moisture pins were in an internal or external frame. The moisture contents on the north and south sides of the roof were very similar and are not presented separately. The exterior frame in the north and south walls, on the other hand, had slightly different moisture contents, which are shown separately.

The results in Figure 7a show that, during the winter, the internal frames remain dry, while the external frames accumulate moisture such that the maximum moisture contents in the roof, north wall, and south wall are 0.19 kg/kg, 0.17 kg/kg, and 0.15 kg/kg, respectively. Since these maximum moisture contents are between the 15°C and 5°C mold thresholds, the temperature at the measurement points is critical. Figure 7b shows that the temperature at the location of the maximum moisture content was between 0ºC and 6°C greater than the outdoor temperature and did not exceed the threshold for mold growth at the time of the moisture content measurements. The temperature sensors positioned near the other moisture pins were 2ºC to 12°C greater than the outdoor temperature, depending on the solar radiation. Nevertheless, the moisture contents at these locations were correspondingly lower and did not exceed the threshold for mold growth during the measurements. Since the moisture content must exceed the threshold for six to eight weeks before mold growth begins, these measurements show that the envelope is performing

TABLE 1
Measurement Locations and Nomenclature

Structure	Location	Nomenclature	Number of moisture pins
Roof	external frame	Roof, *e*	8
Roof	internal frame	Roof, *i*	8
North wall	external frame	Wall, *e* (N)	4
South wall	external frame	Wall, *e* (S)	2
All walls	internal frame	Wall, *i*	8

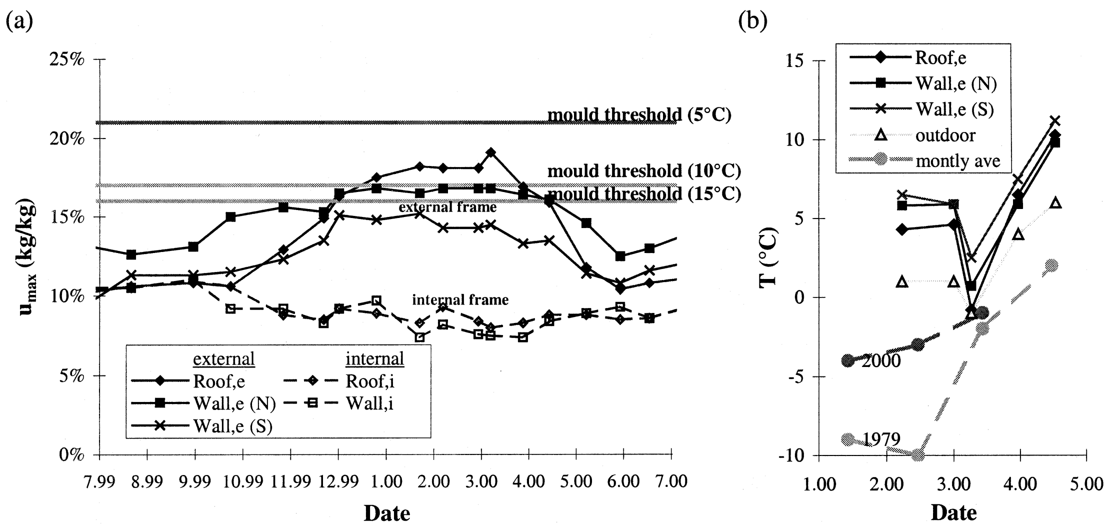

Figure 7 *Maximum moisture content of the interior and exterior frames in the roof and walls (a) and corresponding temperature in the external frame at the time of measurement (b). The monthly average temperatures in Helsinki during the winters of 2000 and 1979 are included.*

well. It is important to note that the temperatures in Figure 7b are the measured temperatures at the time of the moisture content measurement, which was always during the day. Therefore, these values do not reflect the average temperature for the measurement period. Considering that the average temperature in Helsinki was about –3°C when the moisture content was above the mold threshold (January to March), the average temperature at the points of maximum moisture content will be below 5°C and mold growth is unlikely. The average temperature in Helsinki during January to March of the typical year used for energy calculations (1979) is –7°C. This indicates that the winter of 1999/2000 was slightly milder. The moisture content will be slightly higher during a colder winter, but the temperature of the structure will be lower as well. The results in Figure 7 are specific to the investigated house that had a reasonably low indoor humidity (average humidity of 21% RH and an average indoor moisture content in the test bedroom 1.9 g/m^3 greater than outdoors in the winter). A higher moisture content of indoor air would increase the risk of mold growth, which could be reduced by moderately increasing the water vapor diffusion resistance on the warm side of the insulation.

Figure 7a also shows the effect of solar radiation because the moisture content of the external frame in the south wall is almost always a few percentage points lower than the moisture content of the north wall. The moisture content of the east wall (not presented) is nearly always between the moisture content of the north and south wall and is quite close to the values for the south wall. It is also important to note that the roof has a slightly lower maximum moisture content than the walls during the summer but a slightly higher maximum moisture content during the winter. These results show that the critical moisture point is likely the exterior frame in the north wall or the exterior frame in the roof.

Numerical Results

Simonson and Ojanen (2000) present numerical results for an ideally airtight and well-insulated wall (250 mm insulation) that supplement the measurements presented in Figure 7. The numerical results show that the rate of moisture accumulation in the winter and the rate of drying in the spring depend on the internal vapor diffusion resistance. To keep mold growth to a minimum, the internal vapor diffusion resistance should be greater than the external vapor diffusion resistance. However, increasing the vapor diffusion resistance of the indoor surface beyond seven times the outdoor resistance had essentially no effect on the risk of mold growth for the airtight structure. As mentioned previously, the test house has a value of three to four times.

MODELING MOISTURE TRANSFER BETWEEN INDOOR AIR AND STRUCTURES

Measured data are an important part of quantifying the moisture performance of structures and indoor air, but such data are difficult to quantify and extrapolate because there are many uncontrolled variables. Numerical data, on the other hand, can be obtained with ideally controlled conditions but are limited by the assumptions and accuracy of the numerical model. This section briefly describes the modeling of heat and mass transfer between indoor air and structures and uses the model to extrapolate the measured results from the short-term field tests.

The model used for the simulations was developed starting from an existing model that is primarily used for the hygrothermal simulation of building envelope parts (LATENITE). The model combines the heat, air, moisture, and contaminant balance of indoor air with the hygrothermal performance of the building envelope. The model has been presented previously by Salonvaara (1998), and model validation has been done by Salonvaara and Simonson (2000) and Salonvaara (1998).

An overview of the LATENITE version 1.0 hygrothermal model is given by Hens and Janssens (1993) and a more detailed description is given by Salonvaara and Karagiozis (1994). The moisture transport potentials used in the model are moisture content and vapor pressure. The porous media transport of moisture (vapor and liquid) through each material layer is considered strongly coupled to the material properties (i.e., the sorption-suction curves). The corresponding moisture fluxes are decomposed for each phase and are treated separately. The heat and moisture transfer equations, including liquid and vapor transfer, are

$$q_M = -\delta_p(u,T)\nabla P_v - \rho_m D_w(u,T)\nabla u + v_a\rho_v + K\rho_w g \text{ and} \quad (2)$$

$$q = -\lambda(u,\mathrm{T})\nabla T + v_a\rho_a h_g + q_{M,v}Cp_vT + q_{M,w}Cp_wT \quad (3)$$

where the symbols are defined in the nomenclature. The most important term in the moisture transfer equation, for the conditions in this paper, is the first term. Here the moisture transfer is assumed to follow Fick's law, which states that moisture transfer is proportional to the vapor pressure gradient. Even though this is not strictly correct for some materials, the results should be quite accurate and give a reasonable estimation of the moisture transfer in real materials. The energy transfer equation uses temperature as the transport potential and includes the energy transfer resulting from air and moisture flow. The energy and moisture conservation equations are coupled via the latent heat of phase change as follows:

$$\rho_m\frac{\partial u}{\partial t} = -\nabla\cdot q_M + S_M \text{ and} \quad (4)$$

$$\rho_m Cp_m\frac{\partial T}{\partial t} = -\nabla\cdot q + S - \nabla\cdot q_{M,v}\Lambda \quad (5)$$

The energy released/absorbed during adsorption/desorption, condensation/evaporation, and thawing/freezing is included and the latent heat of sorption is assumed equal to the latent heat of vaporization.

The indoor air model, which has been added to the LATENITE model, is fully coupled with the building envelope solution. The coupling is made possible by using the delta-form equations and by deriving the equations in such a way that changes in the building envelope affect the solution already during the solution of the discretized equations. The building envelope components are modeled one-dimensionally when coupled to the indoor air model. The indoor air model is a multizone model with the limitation that the airflow rates between zones are known a priori (i.e., the air flow rates due to forced or natural ventilation are not calculated but instead given as input). The airflow may come from different zones, directly from outdoors or through a heat exchanger with a known thermal efficiency. Walls may exist between the zones, and interior hygroscopic mass within a zone may be included in the form of walls with an adiabatic and impermeable exterior surface.

Indoor air is handled by assuming perfect mixing within each zone and the conservation of moisture and energy in zone *i* are

$$\rho_{a,i}V_i\frac{\partial W_i}{\partial t} = \sum_{j=1}^{zones}\dot{m}_{j,i}(W_j - W_i) + \sum_{n=1}^{surfaces}\beta^*_{p,n}A_n(P_{v,s,n} - P_{v,i}) + S_{M,i}V_i \text{ and} \quad (6)$$

$$\rho_{a,i}V_i\frac{\partial h_{g,i}}{\partial t} = \sum_{j=1}^{zones}\dot{m}_{j,i}(h_{g,j} - j_{g,i}) + \sum_{n=1}^{surfaces}\alpha_nA_n(T_{s,n} - T_i) + S_iV_i. \quad (7)$$

The model allows time-dependent heat and moisture (and contaminant—not discussed in this paper) sources to be given as input. The moisture source term (S_M) is positive for moisture sources (most common) and is negative if there are known moisture sinks in the room, such as a dehumidifier, that are known to remove a certain amount of moisture per unit time. The moisture sources are currently defined and scheduled through user input and the moisture source term (S_M) can represent all types of moisture sources (and sinks). The currently used moisture sources include constant moisture sources from occupants (according to occupancy schedule), heated or unheated water surface, or known release of vapor from a humidifier.

The heating and cooling systems are modeled with the source term (S) and the heating system can be controlled based on the indoor or outdoor temperature and humidity (e.g., known heat source as a function of outdoor temperature), or the heating system can be controlled by a proportional controller (e.g., 100% heat output at T ≤ 20°C, proportional control between 20°C and 22°C, and 0% heat output at T ≥ 22°C). The heating is assumed to affect only the indoor air enthalpy (no radiative heating). Solar gains through windows can be taken into account by evenly distributing the heat gain on an interior surface of the zone, but solar radiation is neglected in this paper.

VALIDATION

The measured data used to validate the model are obtained from the moisture transfer test in the test bedroom described previously. The property data of the building materials listed in Table 2 were taken mainly from the database of property data included in the LATENITE simulation program (Karagiozis et al. 1994) and are detailed in Simonson (2000). In addition to the envelope parts, a thermal conductance of 2

TABLE 2
Envelope Areas and Material Layers of the Test Room

Envelope part and boundary condition	Area, m^2	Material layers (inside to outside)
Ceiling (external)	11.1	13 mm gypsum board, building paper, 425 mm wood-fiber insulation, 25 mm porous wood fiberboard
Supporting wall (impermeable and adiabatic conditions at mid-plane)	3.8	140 mm brick with plaster
East wall (interior)	6.8	140 mm brick with plaster
North wall (external)	6.3	13 mm gypsum board, building paper, 250 mm wood fiber insulation, 25 mm wood fiber board
West wall (external)	5.4	13 mm gypsum board, building paper, 250 mm wood-fiber insulation, 25 mm wood fiberboard
South wall (interior)	9.4	13 mm gypsum board, 100 mm wood-fiber insulation, 13 mm gypsum board
Floor (interior)	10.6	32 mm wooden floor board, 125 mm wood-fiber insulation

W/K is used to represent the heat transfer through the two windows and the balcony door. The boundary condition for the exterior walls is convective heat and mass transfer to the outdoor air. The temperature and relative humidity of the outdoor air were measured during the test, and hourly values are used as input for the simulation. Due to lack of information, the conditions inside the rest of the house, which was under construction at the time of the test, are simplified, and a constant temperature (21°C) and relative humidity (32%) are set to represent the rooms that border the test room (32% at 21°C corresponds to the average vapor pressure outdoors, approximately 800 Pa).

In the moisture transfer test, about 90 g/h of water vapor was generated in the room for eight hours to represent two sleeping adults, and the measured moisture production in the room was used as input to the numerical model. To compare different ventilation rates with and without a plastic vapor retarder, Figure 8 shows the humidity of the room (vapor pressure in Pa) as a function of time for the whole measurement period. Each day shows an increase in humidity during the night followed by a decrease during the day. On some days, the measured results show additional peaks and valleys due to inadvertent moisture production or temporarily higher ventilation rates and the simulation results track these well. The results clearly show that the increase in humidity is significantly greater for the tests with plastic than for the tests without plastic. The measured and calculated results match each

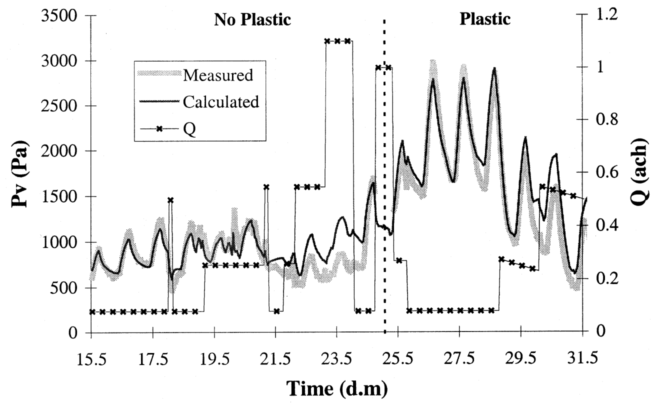

Figure 8 *Measured and calculated vapor pressure in indoor air during the moisture transfer test and the corresponding outdoor ventilation rate.*

other very well except for the two-day period just before adding the plastic on the interior surfaces. The difference is likely due to inadequate mixing in the room at the higher ventilation rates or other measurement errors because the outdoor humidity became much higher than the indoor humidity during these days. For example, one difficulty that was noticed when measuring the outdoor humidity was that when the humidity sensor was exposed to saturation conditions, it took a few hours for the sensor to dry and give reliable results again. Another difficulty in comparing the measured and calculated results arises from the fact that the heat sources in the room during the test (mixing fans, computer, and gas analyzers) were not measured and, as a result, the indoor temperatures of the room could not be matched. In addition, solar radiation was not included in the simulations because the local solar radiation resulting from the local shading was not measured. Despite these limitations, 60% of the simulated temperatures were within ±1.5°C of the measured temperatures and the average difference was slightly less than 1°C. To alleviate the effect of temperature, the results are presented as vapor pressure, but the temperature level will have a moderate effect on the results as well.

In the case when the room was covered with polyethylene foil, some sorption of moisture was found to exist. When the relative humidity increases in the room, the surfaces covered with plastic adsorb moisture and the effect is noticeable. The values for surface adsorption were taken from IEA (1991) where surface adsorption on polyethylene foil was found to be 0.0021 kg/m^2 (in the range of 0% to 100% RH) in an experimental study.

EXTRAPOLATION

In order to expand the results to other weather conditions, the thermal and hygric performance of the test bedroom is calculated for a winter (January) and summer (July) month in Helsinki, Finland. The weather in January is cold and dry and the average and standard deviation of temperature and absolute humidity are –8.5 ± 6.1°C and 1.8 ± 0.9 g/kg. The weather in July is warmer and more humid with monthly average and standard deviation values of 16.0 ± 4.5°C and 6.6 ± 1.5 g/kg. Because the time to reach steady-state conditions is quite long for the walls with hygroscopic mass, the simulations were started three months before the investigated period in order to eliminate the influence of the assumed initial moisture content. The bedroom is occupied by two adults (producing a total of 90 W of sensible heat [ASHRAE 1997]) for nine hours per night. The total moisture production rate is 60 g/h, which is slightly lower than in the field experiments. In the simulations, the mid-plane of interior walls is assumed impermeable and adiabatic, representing the case where the rest of the house has a similar ventilation rate and moisture and heat sources as the bedroom. The room is heated to about 21°C in January, but there is no heating or cooling in July.

The calculated results presented in this section compare the case where the interior paint is vapor tight and allows essentially no moisture transfer to the structure (solid lines) with the case where the paint is vapor permeable and has a very limited effect on the moisture transfer to the structure (broken lines). The purpose of these simulations is to compare the case where moisture transfer occurs between indoor air and the building envelope with the case where no moisture transfer occurs. It is important to note that the simulations do not represent the effect of real paints. In addition, the ventilation rate was kept constant in each simulation, which is not exactly the case in real buildings—opening or closing doors and windows would temporarily increase or decrease the outdoor ventilation rate and air exchange with the rest of the house.

Figure 9 shows that the average indoor relative humidity is significantly lower in January than in July, but it is only moderately affected by the moisture transfer to the structure. Typically, the average humidity is slightly higher in the case where an impermeable paint prevents moisture transfer between the indoor air and the structures. At a ventilation rate of 0.1 ach, the difference between the permeable and impermeable case is 9% RH in January and 16% RH in July, while the difference reduces to 1% RH in January and 3% RH in July at a ventilation rate of 0.5 ach. The fluctuation of indoor humidity is greater in the impermeable case, as indicated by the larger standard deviations, but the fluctuation of indoor temperature is greater in the permeable case. The fluctuations in temperature are due to the coupling of heat and moisture transfer. When moisture is adsorbed in the structure, heat is released and the room temperature will increase slightly, and, similarly, when moisture is desorbed from the structure, the room temperature will decrease slightly. The indoor temperature is generally warmer during the night and cooler during the day in the permeable case than in the impermeable case. The average temperature in January is the same in both cases, but the average temperature in July is 0.5ºC to 1.5°C higher in the permeable case depending on the ventilation rate. The higher temperature in the permeable case is due to moisture transfer from indoor air to the structure, which manifests itself in a lower average indoor relative humidity. Based on the average temperatures and relative humidities in the permeable and impermeable cases, it is estimated that 3 kg of water accumulates in the structure during July when the ventilation rate is 0.1 ach. This moisture transfer would increase the indoor temperature by 3°C if all the phase change energy was delivered to the indoor air.

The ventilation rate also affects the level of indoor temperature and humidity. As Q increases, ϕ and T both typically decrease, but, in July, ϕ sometimes increases as Q increases, and in January, the indoor temperature is nearly

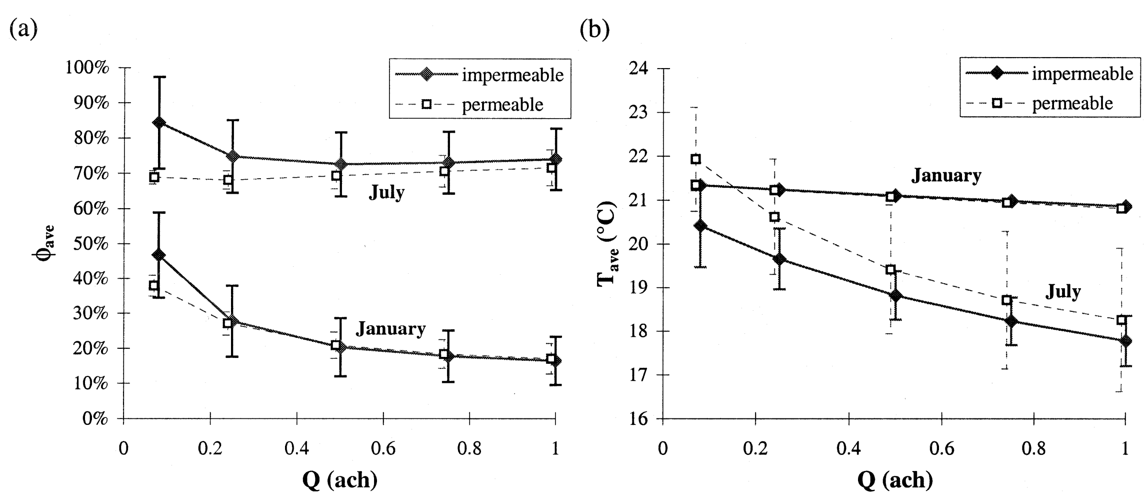

Figure 9 *Monthly average and standard deviation of relative humidity (a) and temperature (b) in July and January as a function of ventilation rate for an impermeable and permeable paint. The permeable and impermeable cases have the same ventilation rate but are plotted with a slight offset to distinguish the standard deviation bars.*

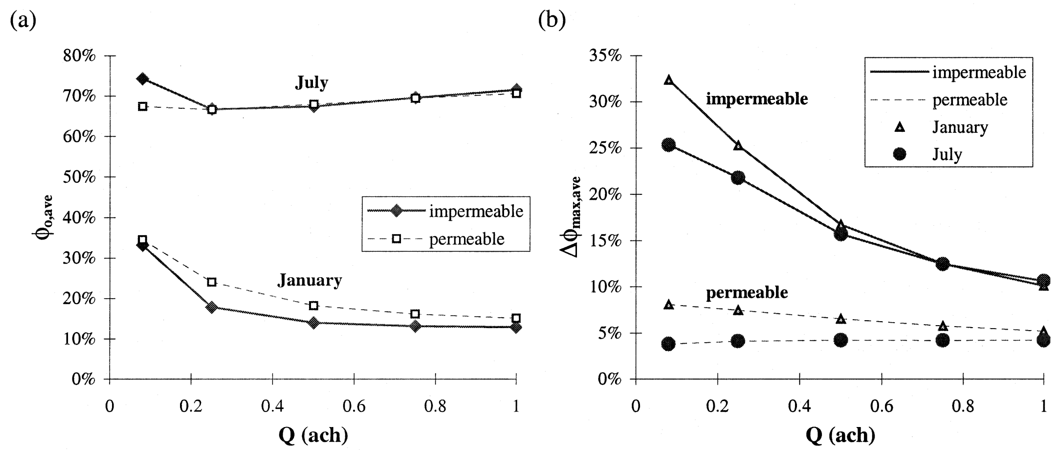

Figure 10 *Monthly average relative humidity when the occupants enter the room (a) and the monthly average increase in humidity during the night (b) as a function of ventilation rate for an impermeable and permeable paint.*

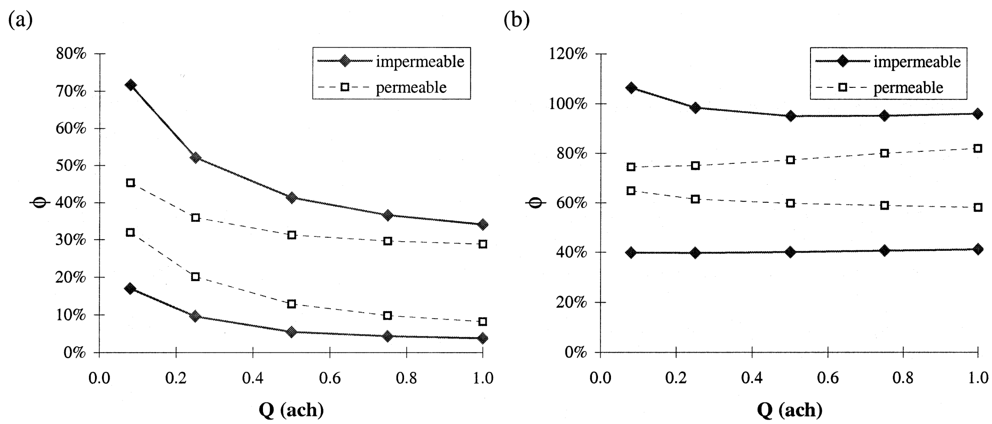

Figure 11 *Calculated maximum and minimum relative humidity of indoor air during the months of January (a) and July (b) as a function of ventilation rate. The solid lines are for a room with an impermeable paint and the dashed lines for one with vapor-permeable paint.*

independent of the ventilation rate because of the heating system.

The average relative humidity of the indoor air when the occupants enter the room (ϕ_o) in Figure 10a shows similar trends as the average relative humidity in Figure 9a. The value of ϕ_o is nearly equal in the impermeable and permeable cases, but the increase in humidity during the night ($\Delta\phi_{max}$) is significantly higher in the impermeable case as shown in Figure 10b. When the ventilation rate is 0.5 ach, the average increase in humidity during the night ($\Delta\phi_{max,ave}$) is 16% RH in the impermeable case and between 4% RH (July) and 7% RH (January) in the permeable case, which are slightly lower than the measured results in Figure 4. The fact that $\Delta\phi_{max,ave}$ is lower in July than in January is due to the nonlinear sorption isotherm of the building materials in the bedroom. For example, the slope of the sorption isotherm for gypsum board, which is a key material in this investigation, is over twice as large at 80% RH as it is at 20% RH. This shows that as the humidity increases, the effective hygroscopic capacity of common building materials increases and the effect of the structure on indoor air increases. This phenomenon is comparable to nonlinear control because the damping increases as the relative humidity increases.

Figure 10b also shows that $\Delta\phi_{max,ave}$ is always greater in the impermeable case than in the permeable case, even when the ventilation rate is significantly higher in the impermeable case (1 ach) than in the permeable case (0.1 ach). This is important because the humidity of the bedroom in the evening is nearly the same in both simulation cases and will be even more so in real rooms where occupants often open the bedroom door and windows during the day and thus increase the air exchanges with the outdoors and the rest of the house. However, the indoor humidity will be considerably higher in the impermeable case when the occupants wake up in the morning.

Figure 11 presents the maximum and minimum relative humidity in each month and shows that the difference between the maximum and minimum humidity is always smaller for the permeable case than for the impermeable case, further demonstrating that the hygroscopic mass is damping the changes in indoor humidity. This effect is most noticeable at low ventilation rates but is significant at high ventilation rates as well. For all ventilation rates the permeable case has lower maximum humidities in the summer and higher minimum humidities in the winter. During July, with a ventilation rate of 0.1 and 0.5 ach, the maximum humidity in the permeable case is, respectively, 32% RH and 18% RH lower than in the impermeable case. In January, with a ventilation rate of 0.5 ach, the minimum humidity is 7% RH greater in the permeable case than in the impermeable case.

It is important to note that Figure 11 shows a maximum humidity greater than 100% RH when the ventilation rate is 0.1 ach. This is a numerical value that would not occur in practice because condensation would occur on the interior surfaces of the room. This anomaly occurs because the simulation model includes the vapor resistance of the interior surface in the convective mass transfer coefficient. Therefore, in the impermeable case, the convective mass transfer coefficient is very low and the moisture transfer to the surface of the room is very slow and humidities above 100% are possible. This phenomenon could be more correctly accounted for in the model by separating the convective mass transfer coefficient and the surface resistance. To accomplish this, the interior surface of the wall would be treated as a separate node that is connected to the indoor air through the convective mass transfer coefficient and then this surface node would be connected to the rest of the wall through the resistance of the interior coating. This would allow surface condensation to occur even when the indoor coating has a high vapor resistance and would help keep the indoor humidity below 100% RH. However, during normal conditions when the indoor humidity is below 100% RH, this improved model would have essentially no effect on the results.

DISCUSSION

The fact that building structures can moderate indoor humidity is important for many reasons. One is that it shows that the moisture (latent heat) produced in a space is not directly transferred to the ventilation air, even though current design methods assume that the latent load is an instantaneous load for the HVAC system. Also important is the potential for permeable structures to improve indoor humidity conditions, which can result in better comfort and air quality. For example, decreasing the humidity by 20% RH at 24°C can halve the percent dissatisfied with warm respiratory comfort and significantly improve the perceived air quality (Toftum et al. 1998a; Fang et al. 1998a). This is significant because the structures studied in this paper provide a reduction in peak humidity of this magnitude. However, the moisture transfer also increases the room temperature slightly; thus, the net effect is less remarkable (Simonson et al. 2001b). Furthermore, the minimum humidity in the winter can be increased, which will most likely improve comfort and health. It is possible that the structures studied in this paper have a lower risk of condensation and mold growth on interior surfaces (especially at thermal bridges) due to lower peak values of indoor relative humidity. This could be particularly important because many bedrooms have lower indoor temperatures than the ones investigated in this paper and decreasing the temperature will increase the relative humidity. For example, Künzel (1979) measured the mean bedroom temperature in 2000 German dwellings to be 15.5°C ± 3°C. Another possible benefit of permeable structures is better air quality due to the diffusion of gases through the envelope. This can be significant for poorly ventilated rooms but has a minor effect for rooms with a ventilation rate near design (i.e., 0.5 ach) (Simonson and Salonvaara 2000; Simonson 2000).

It should be noted that this study focused on buildings in the Finnish climate. Future work could focus on the hygrothermal performance of a bedroom in different climates. The moisture production in the room was limited to people, and the moisture storage capacity was limited to the structures. However, in real bedrooms, there exist other moisture sources (e.g., plants, pets, and cleaning) and other materials with moisture capacity (e.g., furniture and fabrics). These should be considered in future work. Also, the effect of various interior coatings, different material layers, and thermal storage should be investigated. Since some building codes require a warm-side vapor retarder (e.g., polyethylene plastic), an important future work would be to optimize the location of the vapor retarder for good indoor climate and safe moisture performance.

SUMMARY AND CONCLUSIONS

The measured and simulated results presented in this paper show that a building without a plastic vapor retarder can have satisfactory moisture contents in the indoor air and building structures. Moisture storage in the building envelope significantly improves the indoor humidity level and yet has a good moisture performance in a cold climate. To realize this good performance, the envelope must be airtight (e.g., 3 ach at 50 Pa) and the water vapor diffusion resistance must be greater on the warm side of the insulation (e.g., five times) than on the cold side. The field measurements show that the initial construction moisture in a well-designed and airtight, but moisture permeable, envelope dries after the second summer. During occupation, the moisture content in the winter is not excessively high to prevent rapid drying in the spring and summer.

The measured and simulated results presented in this paper demonstrate that moisture transfer between indoor air and the building envelope has a significant influence on the indoor humidity for both poorly and well ventilated rooms. In the field experiments, the sorption of water vapor in the bedroom walls reduced the peak humidity during the night by 15% RH at an average temperature of 27°C, which corresponds to 21% RH at 22°C. This lower humidity is significant because, according to the comfort criteria of Toftum at al. (1998a), it could possibly double the number of occupants satisfied with the indoor climate. Measurements during occupation helped confirm the controlled field experiments. The diurnal fluctuations in indoor humidity were greater in the bedrooms (particularly when the doors were closed) than in an open hallway of the house. The increase in humidity during the night in the test room, which was occupied by one occupant, was, on average, 5% RH at an expected ventilation rate of 0.25 ach. These results compare favorably to those measured in the controlled experimental test, where the increase in humidity during the night for two occupants and a similar ventilation rate and temperature was approximately 10% RH to 15% RH.

To expand the short-term field tests, a numerical model is validated with the measurements and applied to investigate water vapor transfer and sorption for different weather conditions. These results show that water vapor transfer is very important during warm weather and can reduce the maximum indoor relative humidity in July by up to 30% RH when the ventilation rate is very low (0.1 ach), which would significantly improve comfort. When the ventilation rate is near design (0.5 ach), the maximum humidity in the permeable case is 18% RH lower than in the impermeable case. In January, with 0.5 ach, the minimum humidity is 7% RH greater in the permeable case than in the impermeable case. These numerical results complement the experimental results and show that the moisture capacity of the building envelope can damp the variations in indoor humidity during both summer and winter conditions. However, the effect of individual materials was not identified. In addition to reducing the maximum humidity in the summer and winter, moisture storage in building envelopes can, in fact, help avoid very low relative humidities in indoor air by releasing the stored moisture during dry outdoor conditions. The disadvantage of the permeable case is that the average indoor temperature is higher in the summer (0.6°C at 0.5 ach). Nevertheless, there is a vast potential for passive methods (hygroscopic structures) to moderate the indoor climate.

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NOMENCLATURE

A = surface area (m^2)
Cp = specific heat capacity (J/(kg·K))
D_w = liquid moisture diffusivity (m^2/s)
g = acceleration of gravity (m/s^2)
h = enthalpy (J/kg)
IAQ = indoor air quality
K = moisture permeability (s)
$\dot{m}_{j,i}$ = mass flow rate of air from zone j into zone i including infiltration, exfiltration, and ventilation (positive for flow entering zone i) (kg/s)
P_v = partial pressure of water vapor (Pa)
ppm = parts per million
Q = air flow rate (ach)
q = heat flux (W/m^2)
q_M = mass flux (kg/(m^2·s))
S = heat sources or sinks per unit volume (W/m^3)
S_M = moisture or contaminant sources or sinks per unit volume (kg/(m^3·s))
T = temperature (°C)
t = time (s)
u = moisture content (kg/kg)
V = volume of the zone (m^3)
v_a = velocity of air (m/s)
W = absolute humidity (kg/kg)

Greek Symbols

α = convective heat transfer coefficient (W/(m^2·K))
β_p^* = permeance of the interior surface including the convective mass transfer coefficient (kg/(s·m^2·Pa))
$\Delta\phi$ = change in relative humidity after the start of occupation or humidification
$\Delta\phi_{max}$ = maximum increase in relative humidity during occupation (i.e., during the night)
ΔP = pressure difference between indoor and outdoor air
δ_p = vapor permeability (kg/(s·m·Pa))
ϕ = relative humidity
Λ = latent heat of vaporization (J/kg)
λ = thermal conductivity (W/(m·K))
ρ = density of water vapor (kg/m^3)

Subscripts

a = dry air
ave = monthly average value
g = gas phase (including dry air and water vapor)
i = zone index
j = zone index
m = dry property of the porous medium
max = maximum
n = surface index
o = initial value at the onset of occupation or humidification
s = interior surface of a zone
v = water vapor
w = liquid water

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