Potential for Hygroscopic Building Materials to Improve Indoor Comfort and Air Quality in the Canadian Climate

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ABSTRACT

This paper presents a numerical investigation of the indoor conditions in a bedroom in a wooden building located in Saskatoon, Vancouver, and Toronto, Canada. Based on correlations from the literature, which quantify the effect of temperature and humidity on warm respiratory comfort and perceived indoor air quality for sedentary adults, the results indicate that hygroscopic materials have a good potential to improve comfort and air quality in Canadian residences. However, the application of hygroscopic materials will not ensure acceptable indoor conditions and during some weather conditions (typically less than 10% of the time) hygroscopic materials may slightly degrade the indoor conditions. At a ventilation rate of 0.5 ach, it is possible to improve the indoor conditions in each climate studied such that as many as 10 people out of 100 are satisfied with the thermal comfort conditions (warm respiratory comfort) at the end of occupation. Similarly, the percent dissatisfied with perceived air quality can be 20% lower in the morning when permeable and hygroscopic structures are applied. On average, the reduction in percent dissatisfied with comfort and air quality at the end of occupation is 2% and 4%, respectively, when the outdoor ventilation rate is 0.5 ach. When the ventilation rate increases to 1 ach, the differences between the hygroscopic and nonhygroscopic cases decreases.

INTRODUCTION

Many parts of the world experience large changes in temperature from season to season, but human comfort demands a fairly constant temperature in homes and workplaces throughout the year (ASHRAE 1992). Since humans tolerate a range of relative humidity, indoor humidity levels are not as tightly controlled as temperature and many buildings experience large changes in indoor humidity levels during seasonal changes in outdoor humidity. Thus, both the building occupants and envelope are subject to a wide range of indoor humidity conditions, which, together with heat and air movement, may create unfavorable conditions for the occupants and building envelope. Many studies have shown that high moisture content in the indoor air and building material increases the risk of sick building syndrome (Sundell 1996). In most of the studies, there is no quantitative link between the two, but the studies show that as the indoor relative humidity increases above a certain level, indoor air quality becomes more unacceptable (Toftum and Fanger 1999). Also, if the humidity level is too low, the risk of respiratory illness, allergic reactions, and static electric shock increases.

Research has shown that hygroscopic building materials (materials that absorb a significant amount of moisture) can moderate indoor humidity conditions (Simonson et al. 2004a, 2002, 2001a, 2001b; Plathner and Woloszyn 2002; Rode et al. 2001; Plathner et al. 1999; Ten Wolde 1994); therefore, moisture transfer in hygroscopic materials has an effect on the whole HVAC system. Moisture affects energy consumption and building durability. One very difficult task for coil designers is the task of designing a coil that will meet the latent load of the building, most especially in the summer when the outdoor air is warm and humid. The amount of moisture generated in the building and the amount brought in from outdoors through infiltration or ventilation air determines the latent load of the building, which has to be met in order to have a comfortable indoor condition. By moderating the moisture/latent

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loads, hygroscopic materials have the potential to reduce energy consumption in building HVAC systems.

Moisture storage in hygroscopic building materials is not a new phenomenon. Already in 1966 measurements of humidity variations in Canadian homes by Kent et al. (1966) indicated that hygroscopic materials affect indoor humidity levels, especially during the transition between the summer and winter seasons. Nevertheless, moisture storage in hygroscopic materials is seldom included in HVAC design and energy calculation methods. Recently there has been renewed interest in whole building heat, air, and moisture transfer and researchers from nearly 20 countries have agreed to pursue this research in IEA Annex 41 (IEA 2004). This project is an extension of IEA Annex 24, where many models were developed and experimental measurements performed on building envelopes assuming the indoor temperature and humidity as known boundary conditions. Many of these building envelope models can be extended to calculate the indoor conditions and thereby investigate the heat, air, and moisture (HAM) response of the whole building. The numerical model used in this paper is such a model that has been extended. This numerical model will be used to investigate the potential for hygroscopic wooden materials to moderate indoor humidity conditions in the Canadian climate.

Another way to investigate whole building HAM is to adapt energy simulation tools to include moisture analysis. This method requires simplification of the moisture transfer equations and has been pursued by Liesen (1994), Mendes et al. (2002), and Kerestecioglu et al. (1990). Liesen developed a mathematical model for calculating the energy required for a building by developing response factors (response factors are infinite series that relate a current variable to past values of other variables at discrete time intervals) for combined heat and moisture transfer and incorporating them into the commercial code IBLAST. This one-dimensional, transient heat and moisture transfer model included adsorption/desorption in both the energy and moisture equations. The whole building is analyzed as a composite of different materials subjected to varying boundary conditions. The aim of this work was to improve IBLAST, which calculates energy for buildings based on sensible energy requirements only (with no consideration to moisture transport). The updated IBLAST model developed by Liesen (1994) was capable of analyzing the heat and moisture transfer in an entire building within a reasonable amount of time. The limitations of this work were the assumptions of constant material and thermodynamic properties even as the moisture content changed. Also, the model was not verified with experimental data. Mendes et al. (2002) studied the effects of moisture on sensible and latent conduction loads using a heat and mass transfer model with variable material properties under varying boundary conditions. This model was incorporated into the building energy simulation program DOE-2.1E. Mendes et al. discovered that models that ignore moisture may overestimate conduction peak loads by up to 210% and underestimate the yearly integrated heat flux up to 59%, which could lead to oversizing of HVAC equipment (especially in dry climates) and underestimating the energy consumption (primarily in humid climates). Kerestecioglu et al. (1990) analyzed heat and moisture transfer in buildings using an approach called the "effective penetration depth" theory, which was meant to be a simplified method of analyzing moisture transport in buildings that would be easy to incorporate into existing building energy computer codes. This approach has to be used very cautiously and with good judgment. As noted by Kerestecioglu et al., it should only be used when there is experimental data to back it up.

There is little doubt that indoor humidity is an important parameter that affects building durability, energy consumption, health, comfort, and IAQ. These topics are often studied independently by researchers with different backgrounds (e.g., building scientists, HVAC researchers, health scientists, and IAQ researchers). The purpose of this paper is to apply models developed by IAQ researchers to quantify the effect that hygroscopic materials have on thermal comfort and IAQ in the Canadian climate. This potential will be investigated using two extreme test cases—one with essentially no hygroscopic mass in contact with the indoor air and one with a large amount of hygroscopic mass.

EFFECT OF HUMIDITY ON COMFORT AND AIR QUALITY

There are no known human sensors that record humidity, and humidity has a small effect on general thermal comfort (i.e., thermal comfort for the body as a whole). However, humidity significantly affects local thermal comfort (e.g., respiratory comfort) and perceived air quality, and these will be used in this paper.

Local Thermal Comfort

Local thermal discomfort is generally due to temperature gradients, directional radiation, or drafts in a space causing one part of the body to be warmer or colder than another. However, recent work by Toftum et al. (1998) has shown that local thermal discomfort can also be due to insufficient cooling of the mucous membranes in the upper respiratory tract. Based on the initial response of subjects facially exposed to clean air in laboratory settings, Toftum et al. (1998) developed the following correlation, which quantifies the percent dissatisfied with warm respiratory comfort (PD_{wrc}),

$$PD_{wrc} = \frac{100}{1 + \exp[-3.58 + 0.18(30 - T) + 0.14(42.5 - 0.01P_V)]} \tag{1}$$

where T is the air temperature (°C) and P_v is the water vapor pressure (Pa).

Perceived Air Quality

Local thermal comfort due to inadequate respiratory cooling and perceived air quality are closely related because inad-

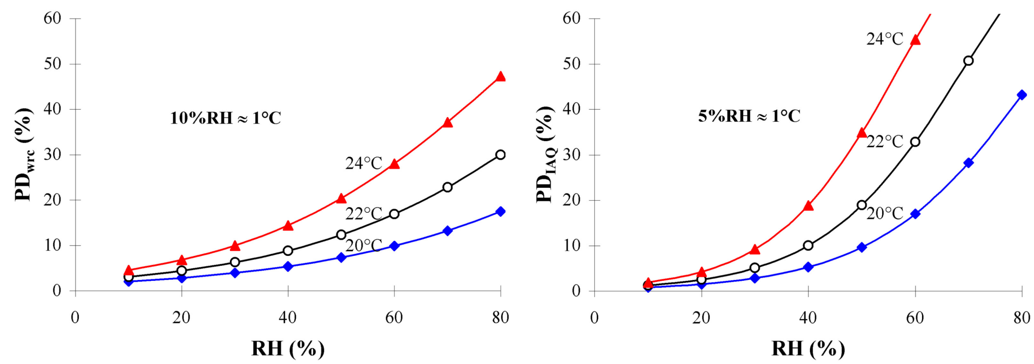

Figure 1 *Percent dissatisfied with warm respiratory comfort* (PD_{wrc}) *and perceived air quality* (PD_{IAQ}).

equate cooling makes air feel stuffy and unacceptable. The percent dissatisfied with the indoor air quality (PD_{IAQ}) can be calculated from the enthalpy of air (h in kJ/kg) using the following correlation (Fang et al. 1998a, 1998b):

$$PD_{IAQ} = \frac{\exp(-0.18 - 5.28(-0.033h + 1.662))}{1 + \exp\ (-0.18 - 5.28(-0.033h + 1.662))}100 \quad (2)$$

Equations 1 and 2 are valid for unpolluted or "clean" indoor air and will be used in this paper to estimate the percent dissatisfied with warm respiratory comfort and perceived air quality (Figure 1).

Since the relations in Equations 1 and 2 and Figure 1 are based on clean air, they underestimate *PD* compared to the normal situation in buildings. On the other hand, they are based on facial exposures, which show a greater effect of temperature and relative humidity than whole-body exposures (Fang et al. 1998b). The fact that these equations are based on the first impression of thermal comfort and air quality is not limiting because Fang et al. (1998b) have shown that the initial acceptability of air is nearly the same as the acceptability after 20 minutes of exposure (i.e., no adaptation is expected). Therefore, the equations used to estimate *PD* are not exact or exclusive but give some indication of expected human response to the indoor temperature and humidity conditions. Another limitation of Equations 1 and 2 is the fact that they do not account for different outdoor ventilation rates. Although the outdoor ventilation rate will affect the concentration of airborne contaminants in the building, this effect is not considered in this paper because it would be difficult to quantify. This is not important when comparing results at a common ventilation rate, but it may be important when comparing results at different ventilation rates. When results are compared with different ventilation rates, it must be remembered that the values of *PD* calculated with Equations 1 and 2 are based on clean air and, therefore, underestimate the value of *PD* for contaminated air and similarly underestimate the effect of ventilation on reducing *PD*.

NUMERICAL MODEL AND INPUT DATA

The model used in this paper combines the heat, air, and moisture balance of indoor air with the hygrothermal performance of building envelopes. The conservation equations are solved simultaneously for the indoor air and the structures, enabling the calculation of indoor temperature and humidity as well as comfort and IAQ. The model (often referred to as LATENITE) has been presented and validated with field and laboratory experiments in the literature (Simonson et al. 2004b, 2001a; Simonson 2000; Salonvaara and Kokko 1999; Salonvaara 1998; Geving et al. 1997; Salonvaara and Karagiozis 1994; Hens and Janssens 1993). In this paper, airflow through the building materials is neglected and perfect mixing in the indoor air is assumed.

The potential for hygroscopic materials to improve indoor conditions in the Canadian climate will be estimated by comparing an envelope that has significant hygroscopic moisture capacity with one that has essentially no hygroscopic mass in contact with the indoor air. Although all buildings have some hygroscopic mass as indicated by Kent et al. (1966), the nonhygroscopic case represents the current assumption used in HVAC design, where the moisture (latent heat) produced in a space is assumed to be an instantaneous load for the HVAC system. The test case selected is a bedroom in a wooden apartment building located in the Canadian cites of Vancouver (mild and humid), Saskatoon (cold/hot and dry), and Toronto (cool/hot and humid). The daily average values of temperature and humidity ratio for these cites are presented in Figure 2, which shows that the data cover a wide range of Canadian weather conditions. The main features of the bedroom, as well as the heating, cooling, and ventilation of the bedroom, are listed below. Other details required to set up the numerical model (e.g., grid size and detailed property data) can be found in Simonson et al. (2001b).

- The bedroom is assumed to be in an apartment building where the surrounding rooms have the same temperature

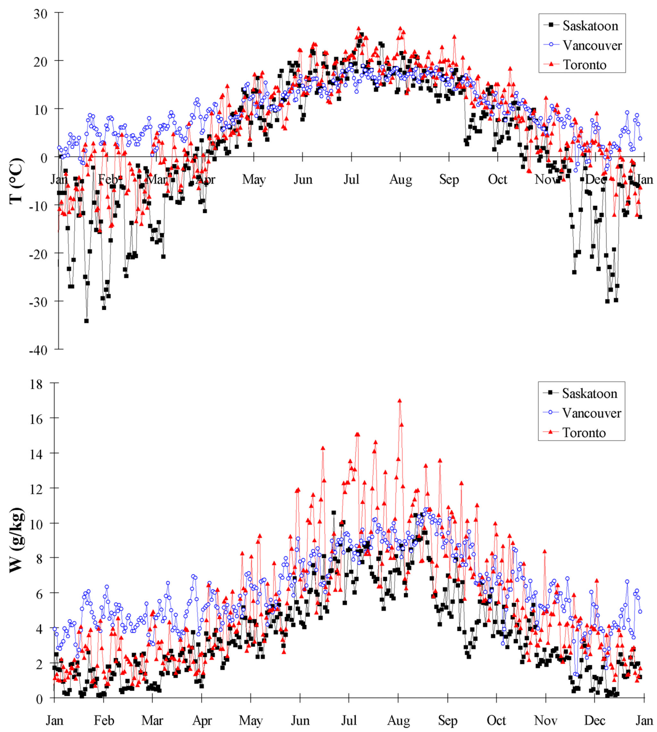

Figure 2 *Daily average outdoor temperatures and humidity ratios in Saskatoon, Vancouver, and Toronto, Canada.*

and vapor pressure as the investigated room; thus, the interior walls, floor, and ceiling are assumed to have impermeable and adiabatic boundary conditions at the mid-plane.

- The room is 4 m × 3 m × 2.7 m and the west-facing external wall is 3 m long.
- The walls and the ceiling have the same construction from inside to outside as follows: airtight interior board (11 mm, wooden panel in the hygroscopic case and porous wood fiberboard in the nonhygroscopic case), paper (0.3 mm), cellulose insulation (150 mm). On the outside of the insulation, the exterior wall has a 11 mm porous wood fiberboard sheathing, a 11 mm air gap, and 18 mm of wooden siding. The floor covering is 28 mm of wood, coated with an impermeable coating. The thermal and moisture properties of the wooden panel, porous wood fiberboard, paper, and cellulose insulation are the most important for this investigation and are presented in Figure 3 and Table 1. The paper has a permeance of 2470 ng/(s·m^2·Pa), which is similar to the permeance of kraft paper (2400 ng/[s·m^2·Pa]) in the ASHRAE Handbook (ASHRAE 2001). Typical Canadian and North American construction would have a polyethylene film between the interior board and the insulation, but kraft paper is used here to allow moisture transfer into the cellulose insulation. This increases the hygroscopic mass of the structure and permits the comparison of two extreme cases, one with a lot of active hygroscopic mass and one with very little active hygroscopic mass. The different interior material in the hygroscopic (wooden panel) and nonhygroscopic (wood fiberboard) cases is insignificant because there is no moisture accumulation in the nonhygroscopic case due to the vapor impermeable paint described below. The only difference between the two cases will be a very slight thermal effect because the nonhygroscopic envelope will have a 2% higher thermal resistance than the hygroscopic envelope.

Table 1. Density, Specific Heat Capacity, and Thermal Conductivity of Pine Wood, Porous Wood Fiberboard, Cellulose Insulation, and Paper in a Dry State

Material	Density (kg/m^3)	Specific Heat Capacity (J/[kg·K])	Thermal Conductivity (W/[m·K])
Pine wood	425	2390	0.09
Porous wood fiberboard	310	2100	0.055
Cellulose insulation	30	1400	0.041
Paper	840	1256	0.159

- All of the building materials are permeable and hygroscopic, except the internal coating, which is a vapor permeable paint (5000 ng/[s·m^2·Pa]) in the hygroscopic case and a vapor impermeable paint (5 ng/[s·m^2·Pa]) in the nonhygroscopic case. It should be noted that these values represent two extreme conditions that may not exist in practice. The vapor permeable paint with a permeance of 5000 ng/(s·m^2·Pa) is comparable to a single coat of primer (Kumaran 2002) or a very permeable emulsion paint (ASHRAE 2001), but it is five times less permeable than the natural convection boundary layer on a vertical surface (4 W/[m^2·K] and 24 000 ng/[s·m^2·Pa]). Therefore, an uncoated interior board may have a slightly higher permeance, but even a thin latex paint may have a lower permeance than assumed here. The vapor impermeable paint is comparable to 0.4 mm of vapor retarder paint, 0.1 mm of polyethylene plastic, or 0.005 mm of aluminum foil (ASHRAE 2001).
- The external wall has a 1.2 m × 1.5 m triple-pane window with a closed venetian blind, which transmits 25% of the solar radiation striking the window. For simplicity, it is assumed that the solar radiation is evenly distributed over all the internal surfaces.
- The building is located in open terrain, and the absorption coefficient for the external wall is 0.8.
- The outdoor ventilation rate is constant at 0.5 or 1 ach throughout the year. One ach in this bedroom corresponds to 9 L/s. The results for variable ventilation rates

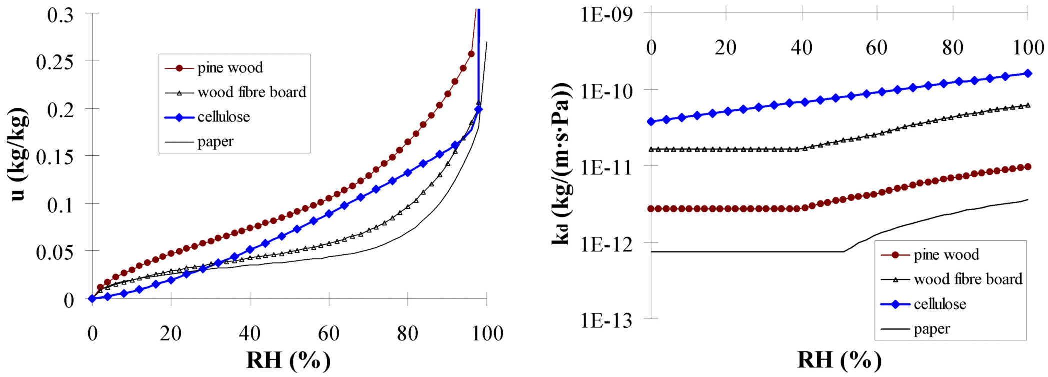

Figure 3 *Sorption isotherms and water vapor permeability as a function of air relative humidity for pinewood, porous wood fiberboard, cellulose insulation, and paper.*

Table 2. Comparison of Weekly Average Humidity Ratios Measured by Kent et al. (1966) and Those Calculated in This Paper—Measured Values Are Based on 19 Houses In Saskatoon, 13 Houses in Ottawa, and an Unknown Number of Houses in Vancouver

	Winter (December – March)		Summer (July and August)	
	Measured (g/kg)	Calculated (g/kg)	Measured (g/kg)	Calculated (g/kg)
Saskatoon	3.5 to 4.5	1.5 to 3	8.5 to 9.5	7 to 10.5
Vancouver	5.5 to 7	4 to 6.5	10 to 11.5	9 to 11.5
Ottawa/Toronto*	4.5 to 5.5	2 to 5	10 to 13	10 to 14

* Measured values from Ottawa, calculated values from Toronto.

(e.g., 0.5 ach in the winter and 1 ach in the summer) are not presented, but they can be inferred from the constant ventilation results. Other constant ventilation rates are investigated by Simonson et al. (2004c).

- The room is heated to between 20°C and 21°C using a 600 W and 700 W heater when the ventilation rate is 0.5 and 1 ach, respectively. There is no mechanical cooling in the room.
- The indoor loads are two adults for 9 h per day and lighting of 100 W for the first hour of occupation. The occupants enter the room at 10:00 p.m. and produce 60 g/h of moisture (42 W of latent heat) and 90 W of sensible heat, which is comparable to the total heat production of sleeping adults (40 W/m^2 × 1.8 m^2/person = 72 W per person) given in ASHRAE (2001).

NUMERICAL RESULTS

Comparison with Measured Data of Kent et al. (1966)

The numerical model used in this paper has been verified using field and laboratory measurements and is expected to correctly estimate the indoor conditions for the bedroom studied in this paper. Nevertheless, since these verification exercises were completed in Finland, it is useful to compare the calculated indoor temperature and humidity values with those measured in Canadian buildings. Researchers at the Division of Building Research, National Research Council Canada, performed an extensive field study of indoor conditions in Canadian dwellings from 1956 to 1961. This study included over 43 houses from different regions in Canada, and the data are plotted as weekly average indoor temperatures and humidity ratios for different climatic locations by Kent et al. (1966). From the figures in Kent et al., the range of weekly average humidity ratios during the summer and winter months in Saskatoon, Vancouver, and Ottawa are presented in Table 2. For comparison, Table 2 includes the range of W values calculated during the summer and winter for the bedroom investigated in this paper. The actual weekly average values of T and W for the entire year are presented in Figure 4. The yearly changes in indoor T and W in Figure 4 are as expected since the room has heating but no mechanical equipment for cooling or humidification and dehumidification. Since the weekly average indoor temperature is nearly the same in the hygroscopic and nonhygroscopic cases, only the nonhygroscopic results are presented. Figure 4 also demonstrates that the indoor temperature is a strong function of the ventilation rate in this bedroom that has no mechanical cooling. At low ventilation rates, the peak temperature in the bedroom is very high in the

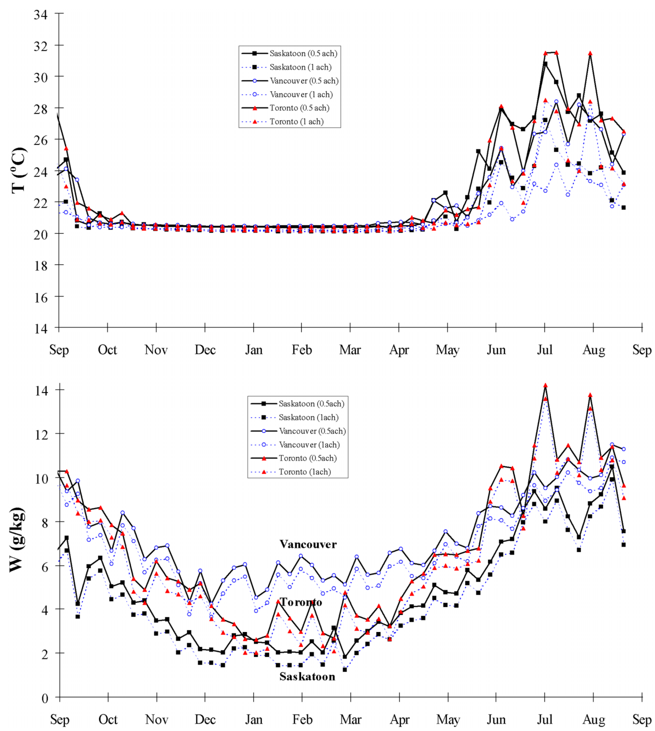

Figure 4 *Weekly average indoor temperature and humidity ratio in Saskatoon, Vancouver, and Toronto with a constant outdoor ventilation rate of 0.5 ach and 1 ach in the nonhygroscopic case.*

summer because the cooling potential of the ventilation air is very low. As the ventilation rate increases, the peak temperature and humidity ratio in the room decrease.

Table 2 shows that, in the winter, the calculated humidity ratios are lower than the measured values by about 2 g/kg. This is particularly true in Saskatoon, where both the minimum and maximum measured values of W are higher than the calculated values during these months. This difference is not surprising because the values in Kent et al. (1966) are based on the average values from 19 houses in Saskatoon, of which several (but not all) had a humidifier. During the summer months of July and August, the agreement between the measured and calculated humidity ratios is quite good. Here exact agreement is not expected because there are too many factors that are different between the measured data and the simulation data. Nevertheless, these results help to confirm the range of indoor humidities calculated in this paper. This indicates that the calculated indoor humidities for the simple bedroom selected in this paper are reasonably representative of those in Canadian houses.

The calculated results in Figure 4 show that the indoor humidity and temperature are highest in the summer and lowest in the winter, as is typical in Canadian houses and as was measured by Kent et al. (1966). The indoor conditions in Vancouver display a smaller change from winter to summer than the indoor conditions in Saskatoon and Toronto. During the winter, the indoor humidity is very low in Saskatoon and significantly higher in Vancouver (W in Vancouver is about three times that in Saskatoon). During the summer, the humidity ratio becomes quite high, especially in Toronto, where the weekly average indoor humidity ratio exceeds 14 g/kg in July.

The effect of ventilation on indoor temperature and humidity can be seen in Figure 4. The 1 ach case has a lower indoor temperature (~3°C to 4°C) in the summer and a lower indoor humidity (~0.5 g/kg) throughout the year compared to the 0.5 ach case. This is consistent with the results of Simonson et al. (2004c) that cover ventilation rates from 0.1 ach to 1 ach. The simulation results also suggest high indoor temperatures during the summer. In Toronto and Saskatoon, the weekly average temperature exceeds 30°C, which is higher than the maximum values (27°C or 80°F) measured by Kent et al. The calculated indoor temperatures are slightly exaggerated because the occupants of the room will increase the ventilation rate by opening windows to reduce the peak temperature in the summer, which is not considered in the simulation. These results show why air conditioning is becoming a popular option in many Canadian houses (even in Saskatoon), especially in airtight houses with no mechanical ventilation.

A natural extension of these simulations would be to assume a varying ventilation rate throughout the year. A more realistic assumption may be a lower ventilation rate (0.5 ach) in the winter to reduce energy consumption and a higher ventilation rate (1 ach) in the summer to simulate ventilation through open windows. The results from such a situation are not presented separately but can be deduced from the constant ventilation results. The only differences between the variable and constant ventilation results would be during the first week or so following the change in ventilation rate in the spring and fall.

Comparison Between Hygroscopic and Nonhygroscopic Case

Hourly values of indoor relative humidity at a ventilation rate of 0.5 ach and 1 ach are presented in Figures 5, 6, and 7 for Saskatoon, Vancouver, and Toronto, respectively. These results show a similar summer to winter trend as the humidity ratio data of Figure 4. During the winter, the relative humidity is very low in Saskatoon and Toronto (commonly as low as 10% RH), especially when the ventilation rate is 1 ach and there are no hygroscopic materials in the room. The relative humidity is significantly higher in Vancouver during the winter where the relative humidity seldom goes below 20% RH. During the summer, the indoor RH is higher and the peak values are in the range of 65% RH in Saskatoon, 75% RH in Vancouver, and 90% in Toronto.

Figures 5, 6, and 7 allow a direct comparison of the indoor relative humidity in a bedroom with and without hygroscopic materials. In all cities and at all ventilation rates, the nonhygroscopic case shows significantly more scatter (peak RH is greater and the minimum RH is lower) than the hygroscopic

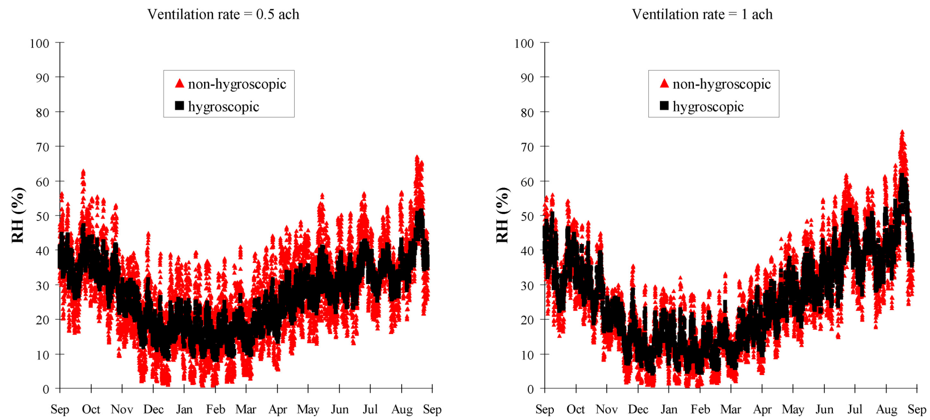

Figure 5 *Calculated hourly indoor relative humidity in Saskatoon for outdoor ventilation rates of 0.5 ach and 1 ach with and without hygroscopic materials. The narrow dark band represents the indoor RH in the hygroscopic case, and the shaded triangles represent the indoor RH in the nonhygroscopic case.*

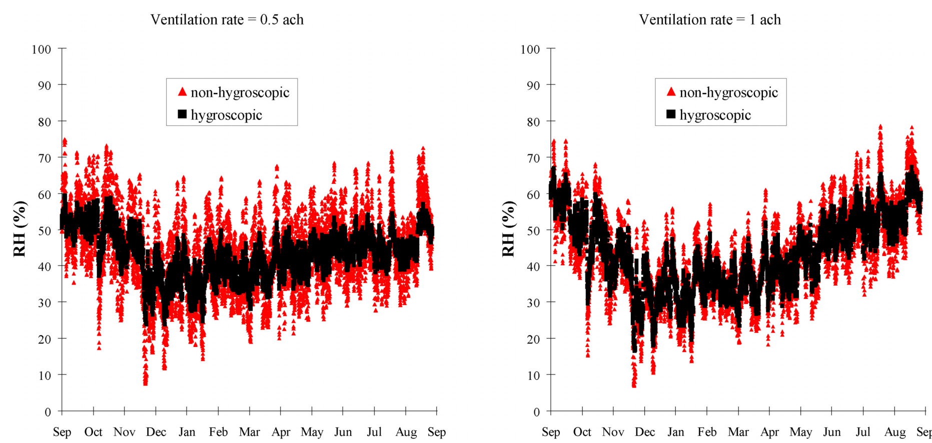

Figure 6 *Calculated hourly indoor relative humidity in Vancouver for outdoor ventilation rates of 0.5 ach and 1 ach with and without hygroscopic materials. The narrow dark band represents the indoor RH in the hygroscopic case, and the shaded triangles represent the indoor RH in the nonhygroscopic case.*

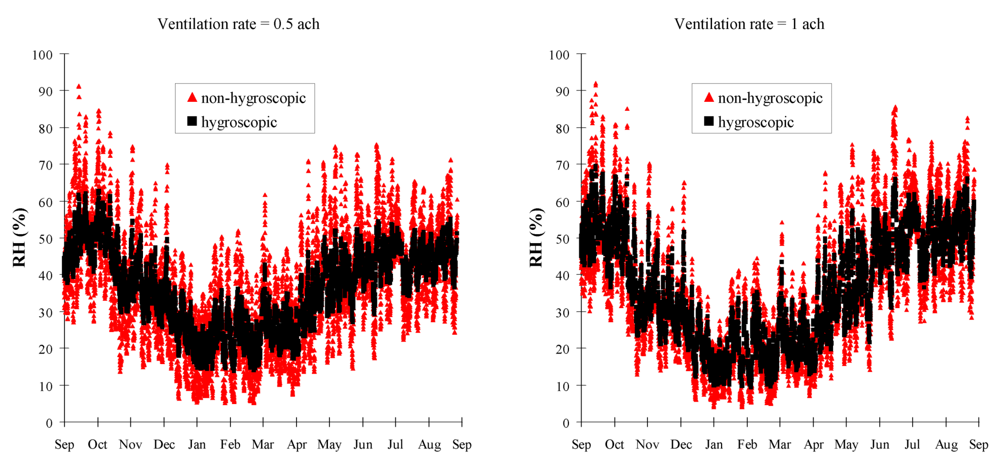

Figure 7 *Calculated hourly indoor relative humidity in Toronto for outdoor ventilation rates of 0.5 ach and 1 ach with and without hygroscopic materials. The narrow dark band represents the indoor RH in the hygroscopic case, and the shaded triangles represent the indoor RH in the nonhygroscopic case.*

case throughout the entire year. This demonstrates that an 11-mm-thick hygroscopic wooden panel, together with paper and cellulose insulation, is able to moderate significantly the indoor humidity in the bedroom. The difference between the hygroscopic and nonhygroscopic cases is greater at a ventilation rate of 0.5 ach than at a ventilation rate of 1 ach. Comparing the results at a ventilation rate of 0.5 and 1 ach shows that both hygroscopic materials and outdoor ventilation rate are able to moderate indoor humidity levels. In Saskatoon and Vancouver, the peak RH values are reduced by 10% to 20% RH when the ventilation rate is 0.5 ach and 5% to 10% RH when the ventilation rate is 1 ach. From Figure 5 it can be seen that the hygroscopic materials reduce the peak RH values more than they increase the minimum RH values. This result is likely due to the fact that the occupation period or moisture production period (9 hours) is 40% shorter than the unoccupied period (15 hours).

In Toronto the effect of the hygroscopic material is even more pronounced. Here the RH is typically reduced by 15% to 25% RH and sometimes as high as 30% RH. The amount by which the hygroscopic material damps the changes in indoor humidity is quite consistent through the year. The high relative humidity levels in the nonhygroscopic case (60% to 70% RH in the spring and fall) indicates that condensation on windows and construction joints may be a problem in the bedroom with no hygroscopic materials. Condensation at the interior surface is unlikely but may also be a concern in the bedroom with no hygroscopic material and may lead to severe moisture degradation. The high indoor relative humidity in the nonhygroscopic bedroom (70% to 80% RH in the summer) is expected to decrease thermal comfort for the occupants and reduce the air quality in the bedroom as will be discussed later.

Diurnal Performance

To further understand the performance of the bedroom and to highlight the role of hygroscopic materials, the indoor temperature (T), relative humidity (RH), percent dissatisfied with warm respiratory comfort (PD_{wrc}), and the percent dissatisfied with perceived indoor air quality (PD_{IAQ}) are presented in the following sections for short periods in each city.

Humid Period (Toronto). The outdoor and indoor conditions for this three-day period at the end of June are in Figure 8. During the first day (June 28), the outdoor temperature increases from 10°C to 20°C and fluctuates between 15°C and 25°C for the rest of the test period. The outdoor humidity ratio increases from 6 g/kg to 12 g/kg during the first two days of this humid period. The results in Figure 8 show that the hygroscopic materials and ventilation rate have a large impact on the indoor temperature, humidity, comfort, and air quality in the bedroom. With a ventilation rate of 1 ach (represented by triangular symbols in Figure 8), the indoor temperature is about 2°C lower than with a ventilation rate of 0.5 ach (represented by square symbols in Figure 8). The hygroscopic materials (represented by a thick line) have less impact on the indoor temperature than does the air change rate. As the ventilation rate decreases, the indoor temperature and humidity increase as expected because less heat and moisture are removed from the room to outdoors. As a result, the percent dissatisfied also increase as the ventilation rate decreases.

The diurnal fluctuation of the indoor conditions is evident in Figure 8. When the occupants enter the room (10:00), the indoor humidity (and consequently PD) increases and when they leave the room the next morning (7:00), the indoor humidity and PD decrease.

Increasing the outdoor ventilation rate decreases the temperature and the humidity and therefore it is not surprising that the higher ventilation rate provides more comfortable and clean indoor conditions (i.e., lowest PD). The hygroscopic structure, on the other hand, causes the indoor humidity to decrease but the temperature to increase due to the heat released during moisture accumulation in the envelope. The net effect of the increased temperature and decreased humidity on thermal comfort and IAQ can be quantified using the percent dissatisfied equations presented previously. Figure 8 shows that the percent dissatisfied with warm respiratory comfort is up to 15% and 10% lower in the hygroscopic case than in the nonhygroscopic case for ventilation rates of 0.5 ach and 1 ach, respectively. Similarly, the percent dissatisfied with indoor air quality is up to 25% and 20% lower in the hygroscopic case than in the nonhygroscopic case for ventilation rates of 0.5 ach and 1 ach, respectively. During the mornings of June 29 and June 30, the PD_{wrc} and PD_{IAQ} values in the hygroscopic (0.5 ach) case are very similar to the values in the nonhygroscopic (1 ach) case, which indicates that a room with significant hygroscopic mass may not require as much ventilation as a room with little or no hygroscopic mass. It is important to remember that PD_{IAQ} is calculated assuming that the indoor air is equally clean in both cases, which neglects the fact that the air will have a higher concentration of contaminants at the lower ventilation rate. The results in Figure 8 show very high values of PD for this room with no cooling. The hygroscopic materials are able to reduce the peak values of PD but are not able to keep them within acceptable limits. Therefore, the integration of hygroscopic materials and cooling systems will be needed to optimize the benefits of hygroscopic materials in Canada. These results confirm the need for air conditioning in the Toronto area.

Cool Period (Vancouver). Figure 9 presents the indoor and outdoor variables during a cool period in Vancouver (Nov. 6 to Nov. 9) when the outdoor conditions are quite constant (11±2°C and 6.5±0.5 g/kg). With these nearly constant outdoor conditions, the diurnal changes in the indoor conditions are very evident. During these cool test conditions, the indoor conditions that exist when the occupants enter the room are nearly the same regardless of the ventilation rate and the hygroscopicity of the envelope. As the occupants generate moisture during the night, the indoor RH increases and the comfort and IAQ decrease (i.e., PD_{wrc} and PD_{IAQ} increase). The most unfavorable conditions occur in the morning. At this time the RH in the hygroscopic case

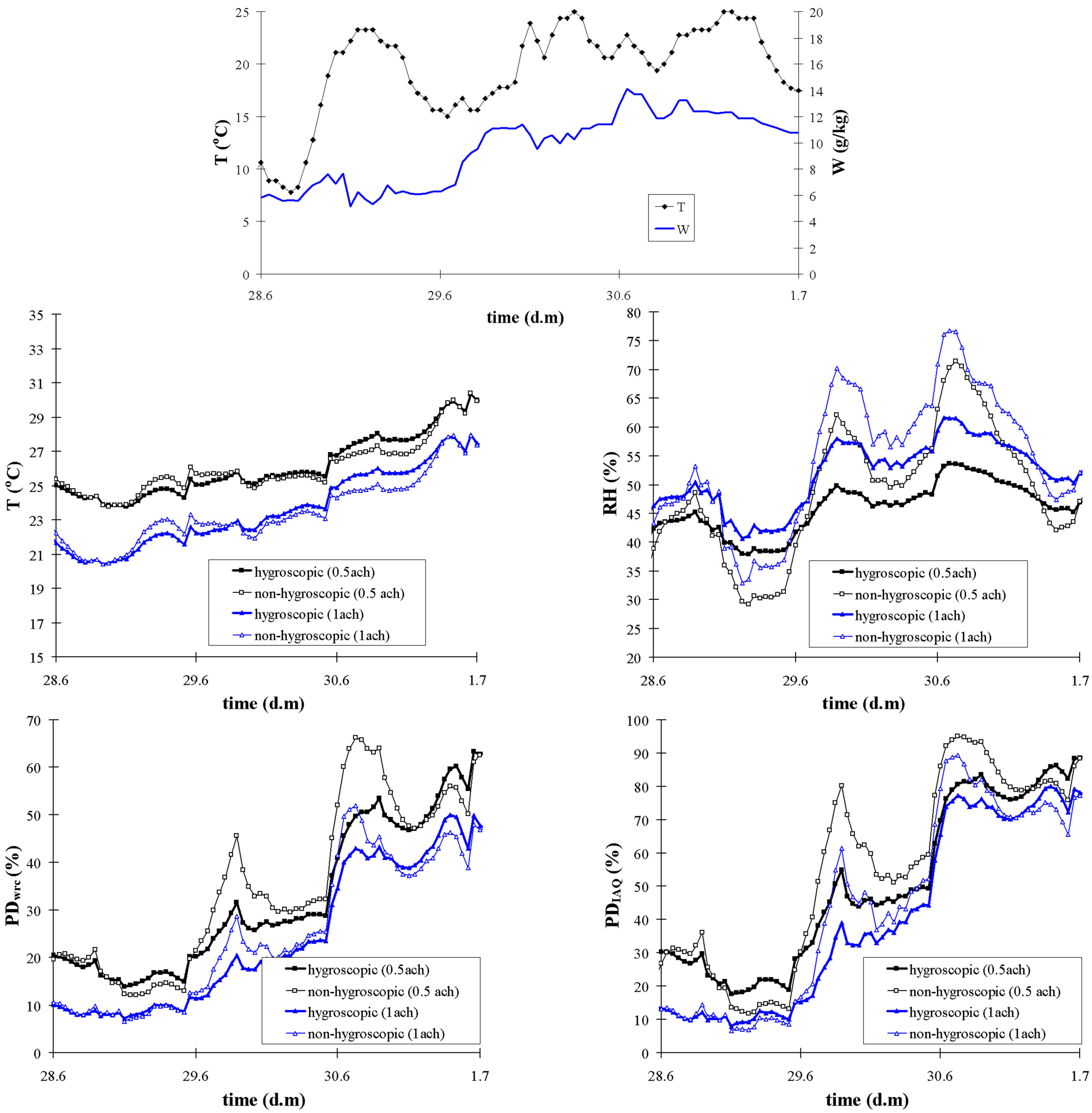

Figure 8 *Temporal variation of the indoor and outdoor temperatures, indoor and outdoor humidity, and percent dissatisfied with warm respiratory comfort and perceived indoor air quality during humid weather in Toronto.*

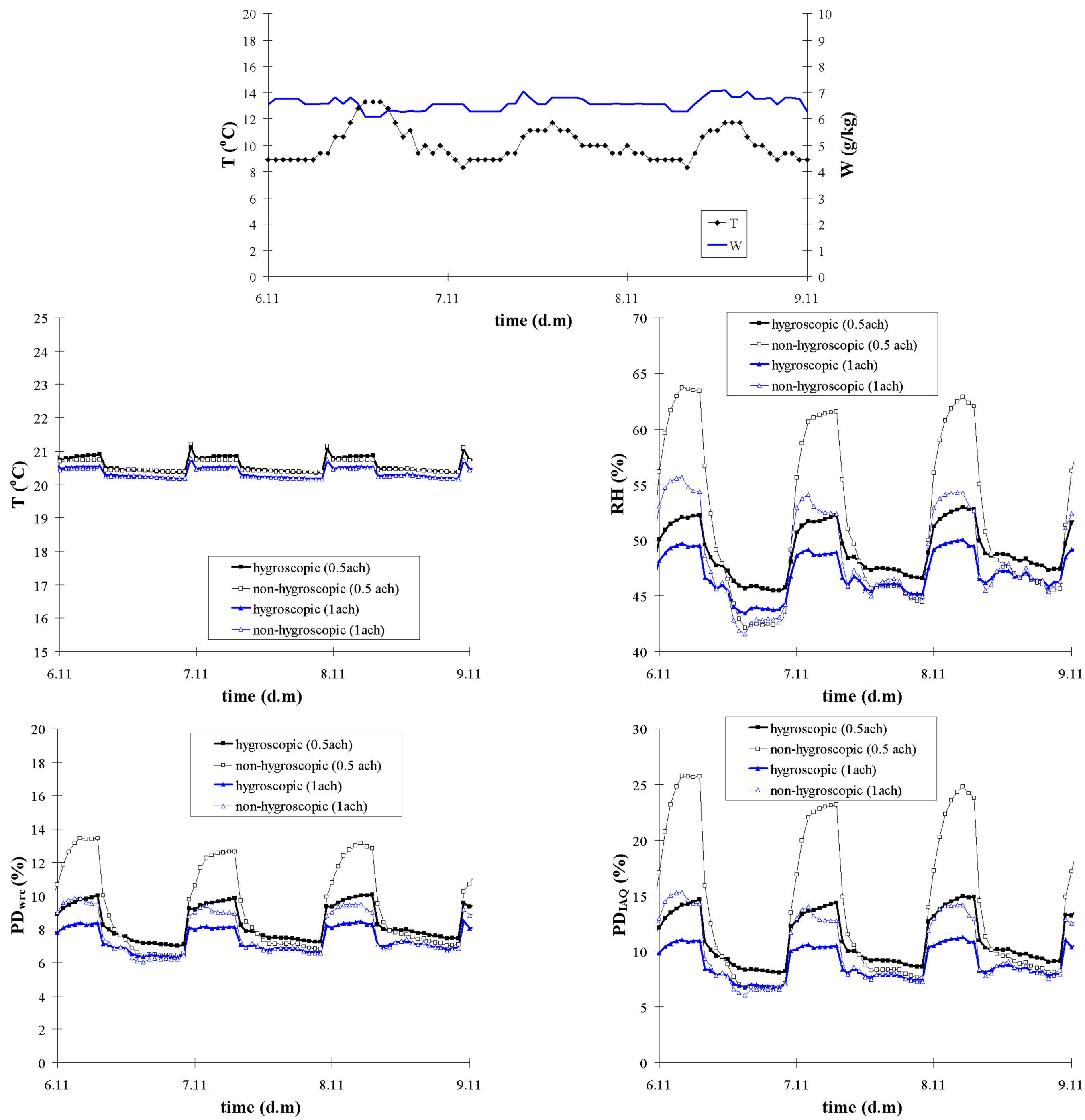

Figure 9 *Temporal variation of the indoor and outdoor temperatures, indoor and outdoor humidity, and percent dissatisfied with warm respiratory comfort and perceived indoor air quality during cool weather in Vancouver.*

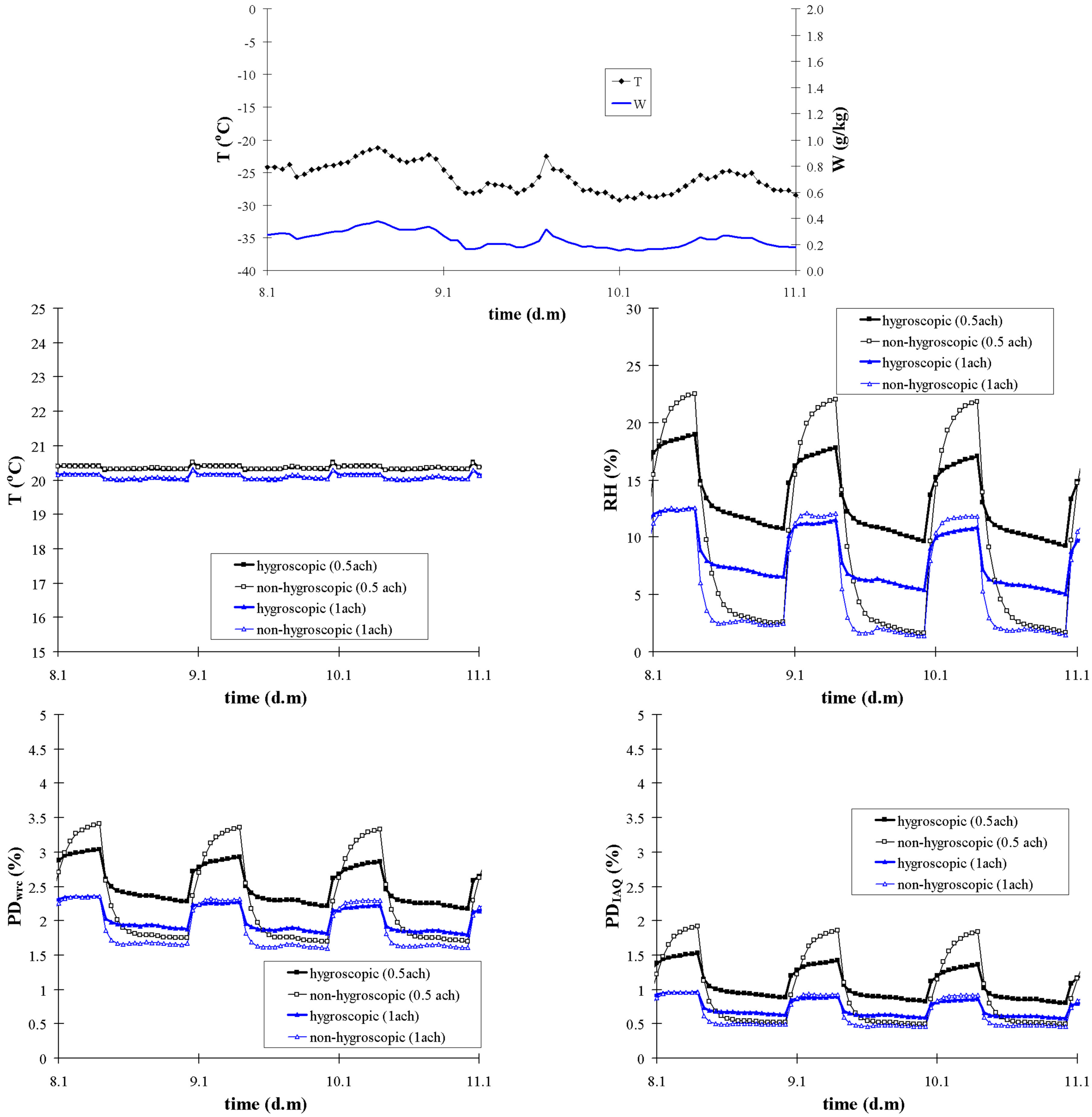

Figure 10 *Temporal variation of the indoor and outdoor temperatures, indoor and outdoor humidity, and percent dissatisfied with warm respiratory comfort and perceived indoor air quality during cold weather in Saskatoon.*

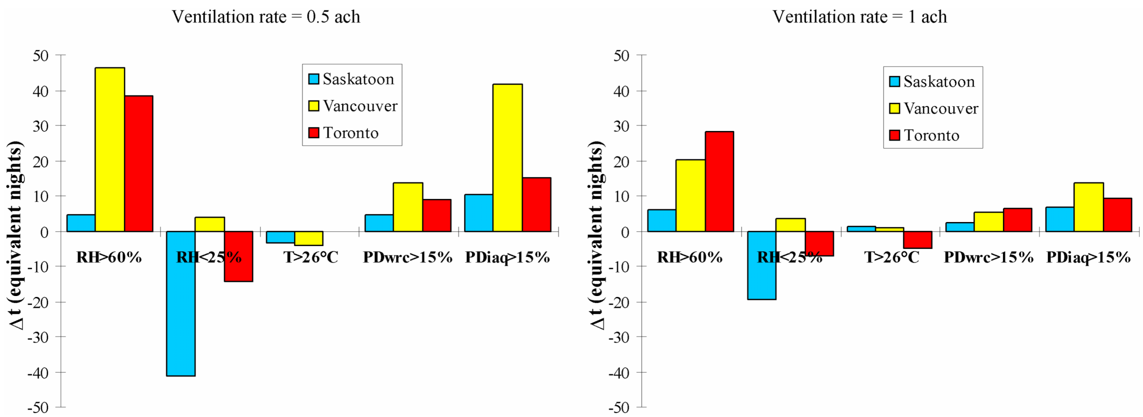

Figure 11 *Difference in the duration of poor performance during occupancy between the nonhygroscopic and hygroscopic cases as defined in Equation 3. A positive value indicates better performance in the hygroscopic case, and a negative value indicates better performance in the nonhygroscopic case. An equivalent night is equal to one night of occupation (ten hours).*

is about 10% RH and 5% RH lower than in the nonhygroscopic case when the ventilation rate is 0.5 ach and 1 ach, respectively. During most of the occupied hours, the RH is higher with a ventilation rate of 1 ach and nonhygroscopic materials than with 0.5 ach and hygroscopic materials. A similar trend is evident in the calculated values of PD_{wrc} and PD_{IAQ}. The values of percent dissatisfied are comparable in the hygroscopic (0.5 ach) case and the nonhygroscopic (1 ach) case. At a ventilation rate of 0.5 ach, moisture storage in the hygroscopic materials reduces PD_{IAQ} by about 10% at the end of occupation.

Cold Period (Saskatoon). From Jan. 8 to Jan. 11, the outdoor temperature and humidity ratio in Saskatoon are very low (–25°C and 0.2 g/kg). During this time, the indoor relative humidity and values of *PD* are very low (less than 25% RH and 4% *PD*) with significant diurnal fluctuations in RH as shown in Figure 10. The difference between the various cases is quite small, but the nonhygroscopic (0.5 ach) case may be preferable because it gives the highest RH values at the end of the occupation period.

Comfort and Indoor Air Quality during Occupation

The previous sections presented conditions in the bedroom during both occupied and unoccupied times. This section will present comfort and IAQ parameters when the bedroom is occupied.

Duration of Poor Performance. The duration of poor performance is the amount of time during occupation (i.e., from 22:00 to 7:00 each day) when the indoor variables are outside certain limits. The limits have been chosen as follows: 25% > RH > 60%, $T > 26$°C, $PD_{wrc} > 15\%$, and $PD_{IAQ} > 15\%$, which are intended to represent conditions that are too dry, humid, hot, uncomfortable, and with poor air quality, respectively. The limits for *PD* have been set at 15% because warm respiratory comfort and perceived air quality may be considered as local thermal comfort parameters, which are recommended to be kept below 15% dissatisfied (ASHRAE 1992). The time durations are calculated in equivalent nights, where one equivalent night means that the variable is outside the limit for one entire night (i.e., from 22:00 to 7:00 or 10 hours). Figure 11 presents the difference between the time durations of the hygroscopic and nonhygroscopic cases, where

$$\Delta t = time_{unfavorable}\big|_{non-hygroscopic} - time_{unfavorable}\big|_{hygroscopic} \quad (3)$$

Since a positive value in Figure 11 means that the bedroom with hygroscopic materials has fewer hours outside the specified criteria, Figure 11 shows that hygroscopic materials improve certain conditions but degrade others. Hygroscopic materials have the greatest effect on the amount of time that the indoor RH is too high or too low and have the smallest effect on the amount of time that the temperature is too high. The hygroscopic case has less time with RH>60% than the nonhygroscopic case in all climates, with the most significant improvement in Vancouver. On the other hand, the hygroscopic case has more time with RH<25% (i.e., poorer performance) than the nonhygroscopic case in Saskatoon and Toronto but slightly less time (i.e., better performance) in Vancouver. The time when *PD*>15% is lower in the hygroscopic bedroom in all climates and ranges from 5 to 40 nights. From Figure 11 it would appear that hygroscopic materials provide the most benefit in Vancouver, followed by Toronto and then Saskatoon. The differences in Figure 11 are lower at a ventilation rate of 1 ach than at a ventilation rate of 0.5 ach.

Highest PD Each Night. Another way to assess the performance of the bedroom is to consider the most unfavorable conditions each night, which typically occurs at the end of occupancy as noted previously. Since this is the estimated value of *PD* when the occupants wake, it may have very imporant implicatons on their frame of mind and

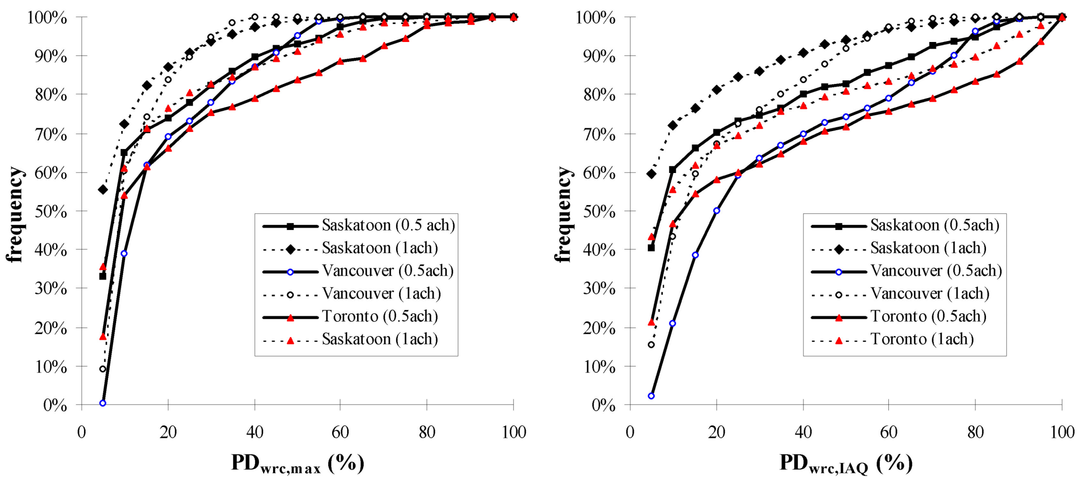

Figure 12 *Frequency distribution of the daily maximum values (during occupation) of the percent dissatisfied with warm respiratory comfort and indoor air quality for the nonhygroscopic cases.*

temperament. The most unfavorable conditions are represented by the maximum value of PD:

$$PD_{max} = max[PD(22:00):PD(7:00)] \tag{4}$$

The frequency distribution of $PD_{wrc,max}$ and $PD_{IAQ,max}$ are given in Figure 12 for the nonhygroscopic cases. Since PD_{wrc} is a variable of local thermal comfort, values below 15% should indicate an acceptable design. The results in Figure 12 show that PD_{wrc} exceeds 15% during 30% to 40% of the nights when the ventilation rate is 0.5 ach and during 20% to 30% of the nights when the ventilation rate is 1 ach. The indoor comfort and air quality conditions are typically the best in Saskatoon and the worst in Toronto. The conditions in Vancouver tend to fall between the values in Saskatoon and Toronto. It is important to remember that these values of PD are based on "clean" indoor air and therefore underestimate the value of PD in real dwellings. Nevertheless, the air will be equally polluted in the hygroscopic and nonhygroscopic cases when the ventilation rate is the same in both cases and, therefore, the difference between the cases should be representative of real buildings.

To demonstrate the difference between the hygroscopic and nonhygroscopic cases, Figure 13 contains the frequency distribution of ΔPD in Vancouver and Table 3 presents a summary table for each climate where

$$\Delta PD = PD_{max}\big|_{non-hygroscopic} - PD_{max}\big|_{hygroscopic}. \tag{5}$$

Figure 13 shows that the worst conditions are almost always improved (i.e., $\Delta PD>0$) by the hygroscopic materials in Vancouver. There are a few days when the nonhygroscopic case has a lower value of PD ($\Delta PD<0$). Similar results are evident in the other climates as summarized in Table 3. In extreme cases, the value of PD_{max} can be as much as 15% to

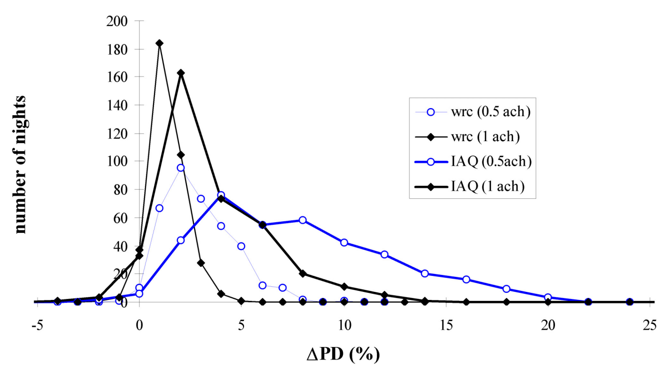

Figure 13 *Difference between daily maximum values of PD_{wrc} and PD_{IAQ} during occupation in the hygroscopic and nonhygroscopic cases in Vancouver. A positive value indicates a higher acceptability in the hygroscopic case.*

20% lower when hygroscopic materials are applied. The average difference between $PD_{wrc,max}$ in all climates is 2% at 0.5 ach and 1% at 1 ach. The average difference between $PD_{IAQ,max}$ is from 4% to 7% at 0.5 ach and 2% to 3% at 1 ach. The improvement in indoor conditions is the greatest in Vacouver and Toronto and the lowest in Saskatoon. These results show that it is possible to improve warm respiratory comfort and perceived air quality with hygroscopic structures made of wood-based materials.

SUMMARY AND CONCLUSIONS

This paper investigates the application of hygroscopic wooden paneling to moderate indoor humidity conditions in a bedroom in three Canadian cities (Saskatoon, Vancouver,

Table 3. Statistics of fhe Difference in Maximum Values of Percent Dissatisfied during Occupation in Various Climates. Maximum Differences Usually Occur at the End of Occupation (i.e., 7:00)

Location and Ventilation Rate		ΔPD_{wrc} (%)				ΔPD_{IAQ} (%)			
		ave.	max.	min.	st. dev.	ave.	max.	min.	st. dev.
Saskatoon	0.5 ach	2.0	11	-5	2.1	4.2	18.5	-6.3	4.6
	1 ach	0.7	6.7	-2.5	1.1	1.6	13.7	-10.9	2.7
Vancouver	0.5 ach	2.4	9.1	-1.9	1.7	6.6	19.4	-3.9	4.5
	1 ach	0.9	4.5	-2.1	0.9	2.5	12.3	-4.6	2.7
Toronto	0.5 ach	2.4	17.7	-10.8	3.4	5.1	32.1	-14.3	6.9
	1 ach	1.1	10.8	-7.9	2.0	2.5	24.0	-12.4	4.6

and Toronto) using a numerical model. To help confirm that the numerical results are applicable in the Canadian climate, the calculated indoor humidity ratios are compared with results from a large field study of Canadian houses (Kent et al. 1966). The measured and calculated humidities agree quite well in the summer, but the calculated humidities are lower than the measured values in the winter because the model assumes that there is no humidifier, while several of the houses in the field study had humidifiers. With the amount of hygroscopic material applied in this paper, the moisture capacity is not large enough to alter the yearly cycle of humidity but is able to reduce the daily humidity peaks (which occur at the end of occupation in the morning) and increase the daily minimum (which occurs prior to occupation in the evening). At a ventilation rate of 0.5 ach, the peak humidity is typically reduced by 10% to 25% RH. The reduction is slightly greater in Toronto than in Vancouver and Saskatoon. At a ventilation rate of 1 ach, hygroscopic materials have a smaller effect on the indoor humidity, and the reduction in the peak humidity typically varies from 5% to 10% RH.

A comparison of the hygroscopic and nonhygroscopic materials using data from three-day test periods during humid weather in Toronto (June), cool weather in Vancouver (November), and cold weather in Saskatoon (January) further demonstrate the importance of hygroscopic materials. During the humid and cool weather, the hygroscopic materials improve the indoor conditions, but during the cold weather, the effect is minimal. An important result from the humid and cool test periods is that the comfort and air quality in a room with significant hygroscopic materials and a ventilation rate of 0.5 ach is nearly the same as that in a room with no hygroscopic materials and a ventilation rate of 1 ach. This indicates that buildings with a large amount of hygroscopic material may not need as much outdoor ventilation air as buildings with no hygroscopic material to provide a comparable thermal comfort and perceived air quality. However, the ventilation required to dilute pollutants is likely independent of the amount of hygroscopic material.

To better understand the impact hygroscopic materials have on thermal comfort and IAQ, the final section in this paper focuses on the conditions that exist when the room is occupied. The results show that hygroscopic materials typically improve warm respiratory comfort and air quality conditions during occupied hours, but in some cases there is a slight degradation. For example, hygroscopic materials increase the time that the indoor air is too dry (RH<25%) but decrease the time that the air is too humid (RH>60%). Similarly, the most unfavorable conditions are nearly always improved with the application of hygroscopic materials, but there are a few days in each climate where the indoor conditions are worse. The improvement in warm respiratory comfort and IAQ conditions is typically the greatest in Vancouver, followed by Toronto and then by Saskatoon.

REFERENCES

ASHRAE. 1992. *ANSI/ASHRAE Standard 55-1992, Thermal environmental conditions for human occupancy.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2001. *2001 ASHRAE Handbook—Fundamentals.* Atlanta: Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Fang, L., G. Clausen, and P.O. Fanger. 1998a. Impact of temperature and humidity on the perception of indoor air quality. *Indoor Air* 8:80-90.

Fang, L., G. Clausen, and P.O. Fanger. 1998b. Impact of temperature and humidity on the perception of indoor air quality during immediate and longer whole-body exposures. *Indoor Air* 8:276-284.

Geving, S., A. Karagiozis, and M. Salonvaara. 1997. Measurements and two-dimensional computer simulations of the hygrothermal performance of a wood frame wall. *Journal of Thermal Insulation and Building Envelopes* 20:301-319.

Hens, H., and A. Janssens. 1993. *Inquiry on HAMCAT CODES*. International Energy Agency, Heat, Air and Moisture Transfer in Insulated Envelope Parts, Report Annex 24, Task 1, Modeling.

IEA. 2004. Annex 41: Whole building heat, air and moisture response (MOIST-ENG), http://www.kuleuven.ac.be/bwf/projects/annex41/index.htm.

Kent, A.D., G.O. Handegord, and D.R. Robson. 1966. A study of humidity variations in Canadian houses. *ASHRAE Transactions* 72(2):11.1.1-11.1.8.

Kerestecioglu, A.A., M.V. Swami, and A.A. Kamel. 1990. Theoretical and computational investigation of simultaneous heat and moisture transfer in buildings: "Effective penetration depth" theory. *ASHRAE Transactions* 96(1):447-454.

Kumaran, M.K. 2002. A thermal and moisture transport property database for common building and insulating materials. Final Report from ASHRAE Research Project 1018-RP, 229 pp.

Liesen, R.J. 1994. Development of a response factor approach for modeling the energy effects of combined heat and mass transfer with vapor adsorption in building elements. Ph.D. thesis, University of Illinois.

Mendes, N., P.C. Philippi, and R. Lamberts. 2002. A new mathematical method to solve highly coupled equations of heat and mass transfer in porous media. *Int. J. Heat Mass Transfer* 45:509-518.

Plathner, P., and M. Woloszyn. 2002. Interzonal air and moisture transport in a test house: experiment and modelling. *Building and Environment* 37(2): 189-199.

Plathner, P., J. Littler, and R. Stephen. 1999. Dynamic water vapor sorption: measurement and modeling. *Proceedings of IA99* 1:720-725.

Rode, C., K. Grau, and T. Mitamura. 2001. Hygrothermal conditions in the envelope and indoor air of buildings. *Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Salonvaara, M.H. 1998. Prediction of hygrothermal performance of building envelope parts coupled with indoor climate. *ASHRAE Transactions* 104(2):908-918.

Salonvaara, M., and A. Karagiozis. 1994. Moisture transport in building envelopes using an approximate factorization solution method. *Proceedings of the Second Annual Conference of the CFD Society of Canada, Toronto, Canada, June* (J. Gottlieb and C. Ethier, eds.), pp. 317-326.

Salonvaara, M., and E. Kokko. 1999. Sellukuiturakenteiden lämmön- ja aineensiirtotekninen toiminta (Heat and mass transfer in cellulose fibre insulation structures). Espoo, *VTT Research Notes*; 1946, 51p., ISBN 951-38-5650-X, 951-38-5651-8, http://www.inf.vtt.fi/pdf/tiedotteet/1999/T1946.pdf, (in Finnish).

Simonson, C.J., M. Salonvaara, and T. Ojanen, T. 2004a. Heat and mass transfer between indoor air and a permeable and hygroscopic building envelope, Part I—Field measurements. Accepted for publication in the *Journal of Thermal and Envelope Building Science* 28(1):63-101.

Simonson, C.J., M. Salonvaara, and T. Ojanen. 2004b. Heat and mass transfer between indoor air and a permeable and hygroscopic building envelope, Part II – Verification and numerical studies. Accepted for publication in the *Journal of Thermal and Envelope Building Science* 28(2):161-185.

Simonson, C.J., M. Salonvaara, and T. Ojanen. 2004c. Moderating indoor conditions with hygroscopic building materials and outdoor ventilation. *ASHRAE Transactions* 110(2):804-819. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Simonson, C.J, M. Salonvaara, and T. Ojanen. 2002. The effect of structures on indoor humidity—Possibility to improve comfort and perceived air quality. *Indoor Air* 12:1-9.

Simonson, C.J., M. Salonvaara, and T. Ojanen. 2001a. Moisture content of indoor air and structures in buildings with vapor permeable envelopes. *Proceedings of Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes* (CD). Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engneers, Inc.

Simonson, C.J., M. Salonvaara, and T. Ojanen. 2001b. Improving indoor climate and comfort with wooden structures, Espoo.*VTT Publications*, 431, 200 pages + App. 91 pages, 2001. http://www.vtt.fi/inf/pdf/publications/2001/P431.pdf.

Simonson, C.J. 2000. Moisture, thermal and ventilation performance of Tapanila ecological house, Espoo. *VTT Research Notes*, 2069, 143 pages + App. 5 pages, http://www.inf.vtt.fi/pdf/tiedotteet/2000/T2069.pdf.

Sundell, J. 1996. What we know and don't know about sick building syndrome. *ASHRAE Journal* 38(6):51-57.

Ten Wolde, A. 1994. Ventilation, humidity, and condensation in manufactured houses during winter. *ASHRAE Transactions* 100(1):103-115.

Toftum J., and P.O. Fanger. 1999. Air humidity requirements for human comfort. *ASHRAE Transactions* 105(2):641-647.

Toftum J., A.S. Jorgensen, and P.O. Fanger. 1998. Upper limits of air humidity for preventing warm respiratory discomfort. *Energy and Buildings* 28:15-23.