# Modeling of Uncontrolled Indoor Humidity for HAM Simulations of Residential Buildings

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**ABSTRACT**

*Moisture balance methods have been developed to estimate the indoor humidity in residential buildings that are without mechanical humidity control. Inaccuracies in the assumption of the indoor humidity can result in misleading results from heat-air-moisture models because the models are highly sensitive to the indoor humidity as it is one of the boundary conditions for the simulations.*

*This paper examines the current approaches to modeling the indoor humidity for use in heat-air-moisture computer simulations. Included in the discussion is the range of parameters published for calculations employing moisture balance methods, and how these methods and the selection of these parameters must further evolve.*

*This paper makes the case for establishing parameters that are different for non-heating and heating seasons. Calculations of indoor humidity are presented for a representative mild marine climate and it is demonstrated that the controlling parameters must be carefully selected to produce realistic indoor humidity levels.*

## INTRODUCTION

Computer simulations are sometimes used in consulting engineering to aid in making design decisions and as a tool in forensic investigations to evaluate the hygrothermal performance of building envelope assemblies. Hourly simulations can be used to evaluate the long-term wetting and drying behavior of an assembly modeled with realistic environmental boundary conditions. Inconsistencies in the selection of the indoor conditions for heat-air-moisture (HAM) modeling will lead to misleading results since the indoor temperature and humidity form the indoor boundary conditions for the simulations.

Climatic data are used for the outdoor boundary conditions. Statistically analyzed data are used to determine the response of a building envelope assembly to any combination of climatic years, for example, average, cold, wet, and dry. This work has been done for some Canadian and US cities for Task 4 of the Moisture Management for Exterior Wall Systems (MEWS) Project (Cornick et al. 2002) and provides a clear direction for appropriate external environmental conditions for computer simulations. It is practical to obtain and utilize raw weather data in any heat-air-moisture (HAM) model. Once the reference climatic years are identified for a particular climate, only combinations of years and the input of any missing data points have to be determined.

Most residential buildings in North America have uncontrolled indoor humidity and the indoor humidity is a function of the outdoor conditions and the occupancy. Methods have been presented in the literature to calculate the indoor humidity using a balance between the moisture gained by indoor moisture generation and removed by ventilation (Hutcheon 1960, IEA 1991, Jones 1995, Djebbar et al. 2001, TenWolde and Walker 2001).

ASHRAE Standard Project Committee 160P, Design Criteria for Moisture Control in Buildings, is working to standardize the calculation of indoor humidity (TenWolde and Walker 2001). The approach accounts for short-term (24-hr) moisture storage by using 24-hr running averages for input values. The intent of Standard 160P is to provide design

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values, which are more severe than average conditions. The authors have calculated indoor humidity using both the approach recommended in ASHRAE Standard 160P (160P approach) and via a model that accounts for absorption/desorption of moisture from hygroscopic materials (BRE Admittance Model) for a representative mild Maritime climate (Vancouver). The calculated indoor humidity using both approaches was compared to measured data for a multi-unit residential building with several years of monitored data. An estimate of 0.15 ACH for the building's ventilation rate was used in the calculations based on knowledge of the building envelope construction, measured $CO_2$ levels, measured exhaust fan capacity, and exhaust fan operation (Roppel et al. 2007). Furthermore, the authors consider the moisture generation high for the building since clothes are regularly dried in the suites combined with higher than normal occupant density. A comparison of the calculated indoor vapour pressure for both models to the measured data during one heating season is presented in Figure 1. The outcome of this work is the authors found it difficult rationalizing the input parameters required to match measured data using the 160P approach. In contrast, the BRE Admittance Model appeared to match the measured indoor vapour pressures with parameters more consistent with observations and measurements. Moreover, the BRE Admittance Model appeared to calculate a dampening of the indoor vapour pressure closer to the measured data than compared to the 160P approach using 24-hour running averages.

Practical experience using both approaches has highlighted the following issues that are discussed further in this paper.

- Indoor humidity predicted using models that include moisture storage can be significantly different than humidity predicted using models that do not include moisture storage and the input parameters of ventilation and moisture generation rates, which both approaches require, cannot be directly compared.
- The input parameters recommended for the 160P approach do not produce results that compare well with measured indoor conditions for a mild Maritime climate (Vancouver), especially for low ventilation rates.
- Different parameters may be required for the heating and non-heating seasons to evaluate both the amount of moisture stored in an assembly and the capacity for the assembly to dry out, these parameters will not be captured by a simple moisture balance equation.

This paper presents the difficulties of modelling uncontrolled indoor humidity without accounting for seasonal differences and occupant behavior, and provides direction toward further evolution of a consistent framework that works in practice.

## INDOOR MOISTURE BALANCE CALCULATIONS

There are several models with varying complexity that can be used to calculate indoor humidity (Jones 1995). The models employ different approaches to account for moisture absorption and desorption of indoor hygroscopic materials as follows:

1. Time-averaged values to approximate short-term moisture storage (160P approach)
2. Admittance factors (BRE Admittance model)

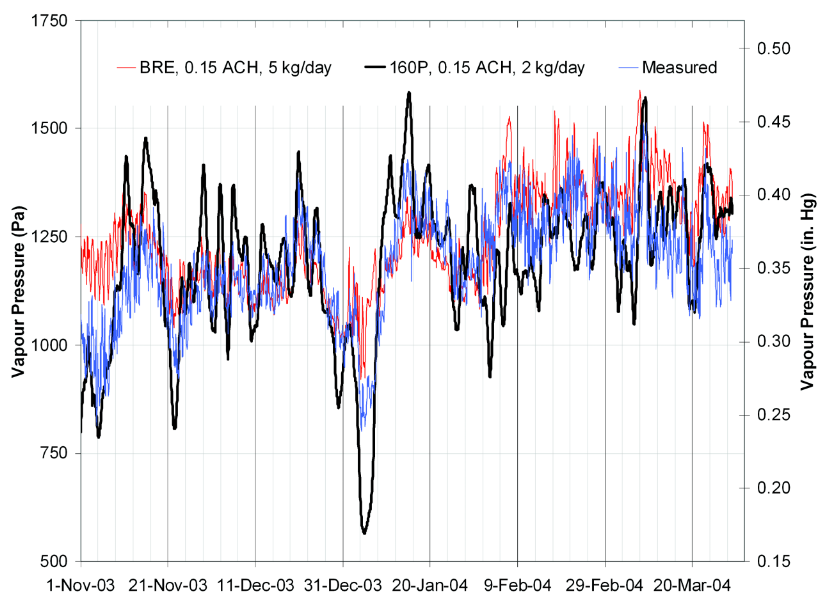


***Figure 1*** *Comparison of the 160P and BRE approaches to measured data of a multiunit residential building during the heating season for a mild marine climate (Vancouver).*

3. Solving the humidity growth or decay using differential equations.

We will focus on Approaches 1 and 2 in this paper as, for the practitioner, the parameters for humidity calculations are not known with sufficient accuracy to warrant employing Approach 3. Approaches 1 and 2 are reproduced in this paper for clarity only and one should refer to the referenced papers for a more in-depth study.

### ASHRAE Standard 160P Approach

The 160P approach does not implicitly include moisture storage in the moisture balance equation, but uses time average values (24-hour running average) to determine the indoor vapour pressure as follows (TenWolde and Walker 2001):

$$P_i = P_{o,24\mathrm{h}} + \frac{cQ_{source}}{Q_{ventilation}} \quad (1)$$

where

$P_i$ = indoor air vapour pressure, Pa (in. Hg)

$P_{o,24\mathrm{h}}$ = outdoor air vapour pressure, Pa (in. Hg)

$c$ = $1.36 \times 10^5$ m/s (10.7 in. Hg. ft$^3$/lb)

$Q_{source}$ = moisture generation rate, kg/s (lb/h)

$Q_{ventilation}$ = ventilation rate, m/s (cfm)

### BRE Admittance Model

The BRE Admittance model, presented using consistent nomenclature, is as follows (Jones 1995):

$$\frac{dW_i}{dt} = \frac{Q_{source}}{\rho v} - I(W_i - W_o) - (\alpha W_i - \beta W_{sat}) \quad (2)$$

where

$W_i$ = indoor air moisture content, kg/kg (lb/lb)

$W_o$ = outdoor air moisture content, kg/kg (lb/lb)

$W_{sat}$ = saturation moisture content of indoor air, kg/kg (lb/lb)

$Q_{source}$ = moisture generation rate, kg/h (lb/h)

$I$ = air exchange rate (ach)

$\rho$ = density of air, 1.22 kg/m$^3$ (0.075lb/ft$^3$)

$v$ = volume of space, m$^3$ (ft$^3$)

$\alpha$ & $\beta$ = moisture admittance factors (h$^{-1}$)

For steady-state conditions this formulae reduces to the following (Djebbar et al. 2001):

$$P_i = \frac{I}{I+\alpha}P_o + \frac{Q_{source}P_{total}}{0.622\rho v(I+\alpha)} + \frac{\beta P_{sat}}{I+\alpha} \quad (3)$$

where

$P_i$ = indoor air vapour pressure, Pa (in. Hg)

$P_o$ = outdoor air vapour pressure, Pa (in. Hg)

$P_{sat}$ = saturation vapour pressure of indoor air, Pa (in. Hg)

$P_{total}$ = total atmosphere pressure, Pa (in. Hg)

Note that this steady-state equation equals the 160P approach equation when $\alpha$ and $\beta$ are set to zero.

## DESIGN LIMITS FOR INDOOR HUMIDITY

The benefit of applying a moisture balance to calculate the indoor humidity from outdoor measured data is that realistic boundary conditions can be applied to a model that follow the same pattern of real indoor humidities. The difficulty is that definitive input parameters and combinations are not yet known, which may lead to applying conservative assumptions to all the input parameters, which may result in unrealistic boundary conditions. To help overcome this tendency we will first look at what is known and not known (with any certainty).

### Occupant Comfort and Operating Conditions

The operating conditions of a building are dependent on the occupants' thermal comfort, if the occupants are given control of the ventilation and temperature.

The ASHRAE comfort limit is 60% RH for all seasons, at winter operating temperatures between 20ºC (68ºF) to 23ºC (74ºF) and summer operating temperatures between 23ºC (73ºF) to 26ºC (79ºF), which represents human occupancy comfort for 80% of sedentary or slightly active persons in a thermally controlled environment (ASHRAE Standard 55).

Most residential buildings have operable windows to provide natural ventilation and the occupants will likely open their windows anytime when conditions are not within their personal comfort zone. ASHRAE Standard 55 suggests that this may occur anytime the outside conditions are in the comfort zone or when no energy penalty will occur from doing so.

### Ventilation

The ventilation rate can vary considerably depending on the building construction and ventilation strategy. ASHRAE Standard 62.2 (2004) recommends a minimum ventilation rate of 14 L/s (30 CFM) and 21 L/s (45 CFM) for the heating season for one bedroom and two bedroom apartments respectively, for a floor area less than 140 m (1500 ft). The corresponding air exchange rate is approximately 0.3 ACH for an apartment of 70 m (750 ft) area and 2.4 m (8 ft) ceiling height with the minimum ventilation rate of 15 L/s (30 CFM). Building codes typically allow for natural ventilation during the non-heating season in residential dwellings by operable windows (at a specified unobstructed area) or by mechanical ventilation at minimum exhaust rate. Natural ventilation is dependent on many factors including temperature difference, pressure difference, and the location and area of openings in the building envelope.

Many studies have measured the natural ventilation rate for whole buildings, which provides a range of values for different kinds of construction for both Canada and the US (Chapter 27 of 2005 ASHRAE Handbook of Fundamentals). However, the rate of air leakage between dwelling units in multi-unit residential buildings is not as well known as that of single dwelling units because of the difficulty and expense of making these measurements (Finch 2007, Sherman et al. 2004).

A mean natural air exchange rate has been measured for new Canadian conventional houses. The air exchange rate, which has been broken down by province, is in the range of 0.15 to 0.22 ach (Hamlin et al. 1997).

## Moisture Generation

Data on residential moisture generation rates vary widely and are difficult to interpret or analyze since the data originates from different authors and is measured under different conditions, climates, and building constructions (TenWolde and Walker 2001).

IEA Annex XIV indicates that the average moisture generation rate for one or two adults is approximately 8.2 kg/day (18.4 lb/day) based on field measurements (IEA 1991, Christian 1993). Whereas TenWolde and Walker (2001) indicate that the average moisture generation rate for one or two adults is approximately 6.8 kg/day (15.0 lb/day) based on field measurements of seven houses.

Lawton (1998) measured the air change rates for 55 houses out of a sample of 400 homes in Wallaceburg, ON using a tracer gas decay method and calculated the moisture generation rate. For the Wallaceburg project, the following was reported:

- Of 35 homes that were ranked in the top 50 for measured biological contamination (400 sample size), a mean air exchange rate of 0.95 ACH and a calculated mean moisture generation rate of 0.85 kg/h (1.87 lb/h) were determined for a single one hour measurement during the day. The sample house characteristics had a mean age of 32 years, 464 m (16 400 $ft^3$) heated volume and 4.46 occupants.
- Of 20 homes that were ranked in the bottom 50 for measured biological contamination (400 sample size), a mean air exchange rate of 0.51 ACH and a calculated mean moisture generation rate of 0.51 kg/h (1.12 lb/h) were determined for a single one hour measurement during the day. The sample house characteristics had a mean age of 32 years, 517 m (18 300 $ft^3$) heated volume and 4.26 occupants.

Published moisture generation rates based on whole building measurements do not typically distinguish between peak and average values, therefore one assumes that absorption/desorption of moisture from hygroscopic materials are included in the values. Furthermore, published values for moisture generation rates are typically for detached homes with a family of four (CMHC 1982, Handegord 1983, Hansen 1984).

ASHRAE 160P assumes an average moisture generation rate of 8 kg/day (0.7 lb/h) for one bedroom, 12 kg/day (1.1 lb/h) for two bedrooms, 14 kg/day (1.3 lb/h) for three bedrooms, and 1 kg/day (0.1 lb/h) for each additional bedroom (TenWolde and Walker 2001).

It is expected for typical North American multi-unit residential buildings that there will be air and moisture transport between suites, there will be less moisture sources such as basements, crawlspaces, and gas appliances than would be present in detached houses, and the overall building moisture sources will be dependent on the typical occupant lifestyle.

Given that most whole building measurements for moisture production are for single detached homes that do not separate absorption/desorption of moisture by hygroscopic materials, then it can be expected that appropriate moisture generation rates for a moisture balance that includes absorption/ desorption must be derived from published occupant moisture generation rates.

## Moisture Storage of Indoor Hygroscopic Materials

Research on the moisture storage of indoor hygroscopic materials shows that the fluctuations of indoor humidity are greatly reduced by the building envelope and indoor furnishings. Estimates of up to 1/3 of the water vapour generated in a room can be absorbed by its surfaces (Kusuda 1983). Accordingly the exchange of moisture from the building envelope and indoor furnishings with the indoor air becomes increasingly significant as the ventilation rate becomes low, i.e. 0.5 ACH or less (Jones 1993).

Jones (1995) states that the BRE Admittance Model assumes the whole mass of the materials is involved in the moisture exchanges, so there is an inherently large moisture storage capacity compared to the amount of moisture that is exchanged with the indoor air. Jones assumes that the whole building materials come into equilibrium in weeks to months and only the surface layer several millimeters deep responds to daily cycles. Consequently the BRE Admittance Model assumes that the moisture content of the indoor materials reach an equilibrium with the indoor air over a time period where the indoor conditions remain fairly constant (ventilation and moisture generation rates). A significant change in the equilibrium moisture content of the surface of the building materials and furnishings may occur for different seasons and therefore may require different admittance factors. However, the increased ventilation due to occupants opening their windows during the summer and shoulder seasons for a mild marine climate such as Vancouver is likely to have more significance and will be discussed in more detail in this paper. Jones (1995) predicts that six pairs of admittance factors may be sufficient to model vapour conditions for categories of high, medium and low moisture admittance under summer and winter conditions and proposes typical values for admittance factors for wood-lined rooms of = 0.6 and = 0.4 (Jones 1993). Others have also completed experiments similar to Jones to assess the moisture buffering of indoor hygroscopic materials by comparing rooms lined with aluminum foil, plaster and wood (Kuenzel et al. 2003).

The admittance terms in the BRE Admittance Model should be considered empirical to sufficiently capture dampening effects when applied to real buildings and it is important to look at both the dampening terms together when selecting the admittance parameters. The first term $\alpha \cdot W_i$ (see Equation 2) calculates the rate at which indoor humidity is absorbed into the building materials and furnishings and is balanced by the second term $\beta \cdot W_{sat}$ that is essentially the rate at which moisture desorbs from the surface of the building materials and furnishings. If the term $\alpha \cdot W_i$ is greater than $\beta \cdot W_{sat}$, then the BRE Admittance Model calculates absorption of moisture into the building materials and if the term $\alpha \cdot W_i$ is less than $\beta \cdot W_{sat}$, then the model calculates desorption of moisture from the materials to the indoor air.

The term $\beta \cdot W_{sat}$ is an approximation derived from a more theoretical form of the BRE Admittance Model and is based on the moisture content at the surface of materials where the surface temperature is assumed to equal the temperature of the indoor air (Jones 1993). For this approximation the parameter $\beta$ is equivalent to $\alpha \cdot RH_s$, where $RH_s$ is the relative humidity at the surface of the building materials and furnishings. Jones (1993) found that the RH at the surface of the building materials during the course of experiments ranged from 50 to 70%. Jones showed through experiments that the vapour pressure changed significantly with temperature but the surface relative humidity changed by less than 10% over a period of one day. An approximation for the dependency of the vapour pressure on temperature is incorporated into the $\beta \cdot W_{sat}$ term.

The practical implication of the BRE Admittance Model is that the selection of $\alpha$ or $\beta$ alone has only a small impact on the calculated indoor vapour pressure and the relative difference between the $\alpha$ and $\beta$ (or $RH_s$) has a large impact. Since the admittance terms are dependent on the indoor vapour pressure, which is dependent on the outdoor vapour pressure, the calculated net hourly moisture mass flux from absorption/desorption is relatively independent of the selection of the admittance parameters. The effect is that a change of $\beta$ relative to $\alpha$ will shift the calculated hourly indoor vapour pressure curve similar to a change in the assumed moisture generation rate. The same effect occurs for a change in the assumed indoor air temperature. Essentially changes in the parameter $\beta$ relative to $\alpha$ or the assumed air temperature, changes the assumed equilibrium air moisture content that balances whether absorption or desorption will occur.

### Combining the Input Parameters into a Moisture Balance Equation

Of the parameters required to calculate indoor humidity, the ventilation rate has the most available and reliable information to provide guidance on the selection of input parameters.

Estimated moisture generation rates based on field measurements probably have moisture both from the occupants and their activities and from moisture stored in building materials and furnishings. Therefore, if one assumes that the moisture generation rate of the occupants remains constant for all seasons and the influence of hygroscopic materials is not accounted for separately in indoor humidity calculations, then the moisture generation rate has to be adjusted to account for changes in the absorption/desorption rate.

Aoki-Kramer et al. (2004) raised some of the difficulties of using a single design moisture production rate and suggested that standards should require hygrothermal analysis using different ranges of indoor moisture production, i.e., low, medium, or high, based on the building occupancy and type of HVAC system used. Though this approach has merit and could be incorporated using a moisture balance, it will be difficult to incorporate different moisture generation rates into a consistent framework to account for changes in the rate of absorption/desorption of hygroscopic materials.

With these considerations in mind, a standardized approach to indoor humidity calculations might be as follows:

1. **Select a ventilation rate for the building:** Is there mechanical ventilation that meets the minimum ventilation recommended by ASHRAE Standard 62? Is only a principal exhaust fan provided that relies on the occupants for operation times? Should the natural ventilation rate be selected based on the perceived or measured level of air tightness of the building or an average ventilation rate?
2. **Select a typical occupant moisture generation rate**: A moisture generation rate should be chosen that reflects the type of building (single family or multi-unit), the volume of heated space, and the expected number of occupants. The chosen moisture generation rate should be appropriate for the calculation method.
3. **Assign admittance factors from best available information**: Admittance factors for different constructions, seasons, and finishes are not yet known. As a minimum, use the admittance factors as a method to smooth out fluctuations in indoor humidity and provide a closer correlation to measured data for a particular climate for all seasons.
4. **Compare calculations to known values and limits:** Compare the calculated humidity levels to the ASHRAE comfort zone, measured data, and what is known about a particular climate.
5. **Revise assumptions if calculations do not match reality:** If the calculated indoor humidity does not match reality, then the combination of parameters may require adjustment.

## EXAMPLE CALCULATIONS

This section uses example calculations with Canadian exterior climatic data from Environment Canada to demonstrate how the considerations presented in the previous sections impact uncontrolled indoor humidity calculations.

As demonstrated in the following example, the differences between the ASHRAE 160P approach and the BRE

**Table 1. Assumed Indoor Humidity Parameters for Multi-Unit Residential Buildings**

| | 160 P | BRE 1 | BRE 2 | BRE 3 |
|---|---|---|---|---|
| Floor Area | 70 $m^2$ (750 $ft^2$) | 70 $m^2$ (750 $ft^2$) | 70 $m^2$ (750 $ft^2$) | 70 $m^2$ (750 $ft^2$) |
| Room Volume | 170 $m^3$ (6025 $ft^3$) | 170 $m^3$ (6025 $ft^3$) | 170 $m^3$ (6025 $ft^3$) | 170 $m^3$ (6025 $ft^3$) |
| Minimum Ventilation (ASHRAE Standard 62.2 for two people) | 17 L/s (34 cfm) | 17 L/s (34 cfm) | 17 L/s (34 cfm) | 17 L/s (34 cfm) |
| ach | 0.35 ach | 0.35 ach | 0.35 ach | 0.35 ach |
| Moisture Production Rate (ASHRAE Standard 160P) | 8.0 L/day (0.7 lb/h) | 8.0 L/day (0.7 lb/h) | 8.0 L/day (0.7 lb/h) | 4.0 L/day (0.4 lb/h) |
| Admittance Factors | N/A | $\alpha = 0.6$ $\beta = 0.4$ | $\alpha = 0.6$ $\beta = 0.35$ | $\alpha = 0.6$ $\beta = 0.4$ |

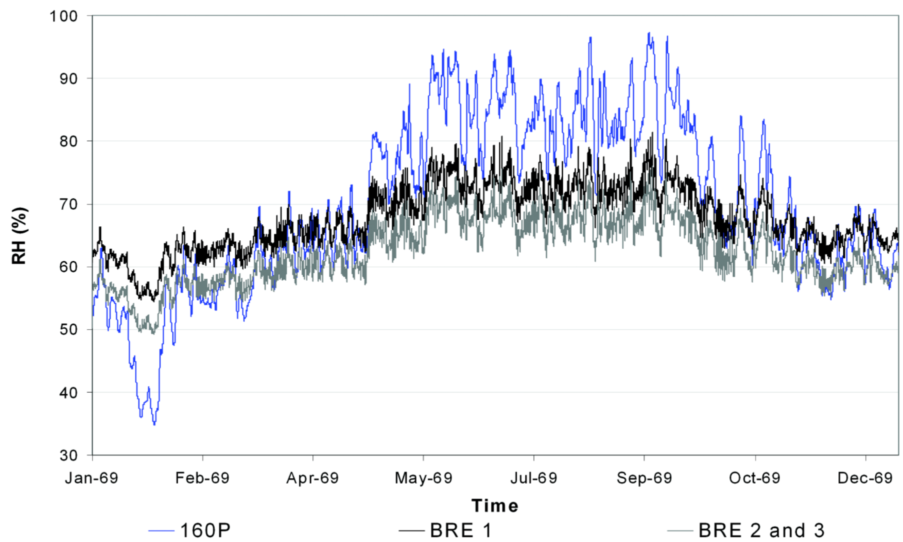


***Figure 2*** *Comparison of relative humidity calculated using ASHRAE 160P and BRE approaches with moisture generation rates as recommended by ASHRAE 160P and with Vancouver (1969) climatic data.*

approach for the same ventilation and moisture generation rates for a mild marine climate are:

- The BRE approach may predict higher or lower humidity in the heating season dependent on the assumed admittance factors and indoor temperature
- The BRE approach generally predicts lower humidity in the non-heating season
- The BRE approach predicts more dampening in the humidity levels (weekly and monthly) than the 160P approach does with 24-hour running average outdoor vapour pressures.

## Example 1: Impact of the Admittance Factors

To demonstrate the impact of the admittance factors on the calculation of the indoor humidity, let us look at Vancouver climatic data for a typical year (1969) and the input parameters summarized in Table 1.

Figure 2 compares the calculated relative humidity using these parameters for the ASHRAE 160P approach and the BRE Admittance Model for different input parameters, and Table 2 summarizes the monthly averages of these calculations.

One objective of this example is to show humidity levels calculated using the parameters recommended by ASHRAE Standard 160P. However, a ventilation rate of 0.2 ach with the ASHRAE 160P approach yields an average RH of 81% during the heating season and 98% during the non-heating season (assumed indoor temperature for these calculations is as per ASHRAE 160P indoor design temperatures). These humidity levels are clearly not realistic values for Vancouver. Therefore, we adjusted the ventilation rate to reflect the minimum ventilation recommended by ASHRAE Standard 62.2. Note reducing the moisture generation rate

**Table 2. Monthly RH Averages Calculated Using the ASHRAE 160P and BRE Admittance Model Approaches (Shaded Areas Indicate the Heating Season)**

| | 160P | BRE 1 | BRE 2 and BRE 3 |
|---|---|---|---|
| January | 47 | 59 | 54 |
| February | 51 | 62 | 57 |
| March | 60 | 64 | 59 |
| April | 65 | 66 | 61 |
| May | 75 | 70 | 65 |
| June | 87 | 74 | 69 |
| July | 84 | 73 | 68 |
| August | 84 | 73 | 68 |
| September | 85 | 74 | 68 |
| October | 72 | 68 | 63 |
| November | 64 | 66 | 60 |
| December | 63 | 65 | 60 |
| Heating Season | 58 | 64 | 58 |
| Nonheating Season | 81 | 72 | 67 |

by the same amount would produce the same humidity levels for the 160P approach.

This example demonstrates that the BRE Admittance Model will not necessarily calculate higher humidity in the heating season than the 160P approach, but is dependent on the estimated level of absorption/desorption of moisture from hygroscopic materials relative to the moisture generation and ventilation rate. Figure 2 shows how a change in the assumed moisture generation rate will shift the curve of calculated vapour pressures in the same manner as a change in the relative difference between the admittance parameters.

Chown et al. (2005) showed, using measured data for Vancouver, that the indoor RH for a coastal climate is typically higher than 35% in the heating season. Aoki-Kramer et at. (2004) reported a typical range of measured indoor humidities between 35% and 60% RH with indoor humidity above 60% only a small fraction of the time. One can also expect that the indoor RH for Vancouver should be in the range of 35% to 60% RH during the heating season under normal operating conditions.

The heating season average RH calculated by the 160P approach is generally within the range that one expects for Vancouver (with a ventilation rate of 0.35 ACH). The BRE Admittance Model appears to over predict the humidity during the heating season using the parameters listed for BRE 1 in Table 1 but is within the expected range by adjusting either the moisture generation rate or admittance factors as shown for BRE 2 and BRE 3. If using the BRE Admittance Model for a standard framework, the standard input parameters for moisture generation rate and admittance factors could be based on ranges of indoor-outdoor vapour pressure differences and ventilation rates.

### Example 2: Impact of Temperature

One key difference between the 160P approach and the BRE Admittance model is the impact of the indoor air temperature:

- The BRE Admittance Model approximates a varying vapour pressure and a constant indoor relative humidity with varying indoor air temperature (via the $\beta \cdot W_{sat}$)
- The 160P approach approximates a constant vapour pressure and varying indoor relative humidity with varying indoor air temperature

This difference between models may partially explain why the BRE Admittance Model appears to better match the measured vapour pressures presented in Figure 1 since the measured indoor air temperatures where used.

The authors have observed a general trend in the indoor-outdoor vapour pressure difference in measured data from Vancouver over several years of monitoring. The indoor vapour pressure will nearly always be greater than the outdoor vapour pressure for uncontrolled indoor humidity during the heating season. The difference decreases over the non-heating season until at some point the indoor vapour pressure will be close to the outdoor vapour pressure. This is illustrated in Figures 3 and 4 for measured field data of a multi-unit residential building in Vancouver (Finch et al. 2006).

One may speculate that a higher level of ventilation due to occupants opening windows will reduce the difference between the indoor and outdoor vapour pressures during the non-heating season, however this trend is more difficult to explain during the heating season without acknowledging the influence of absorption/desorption. Figure 5 shows the corre-

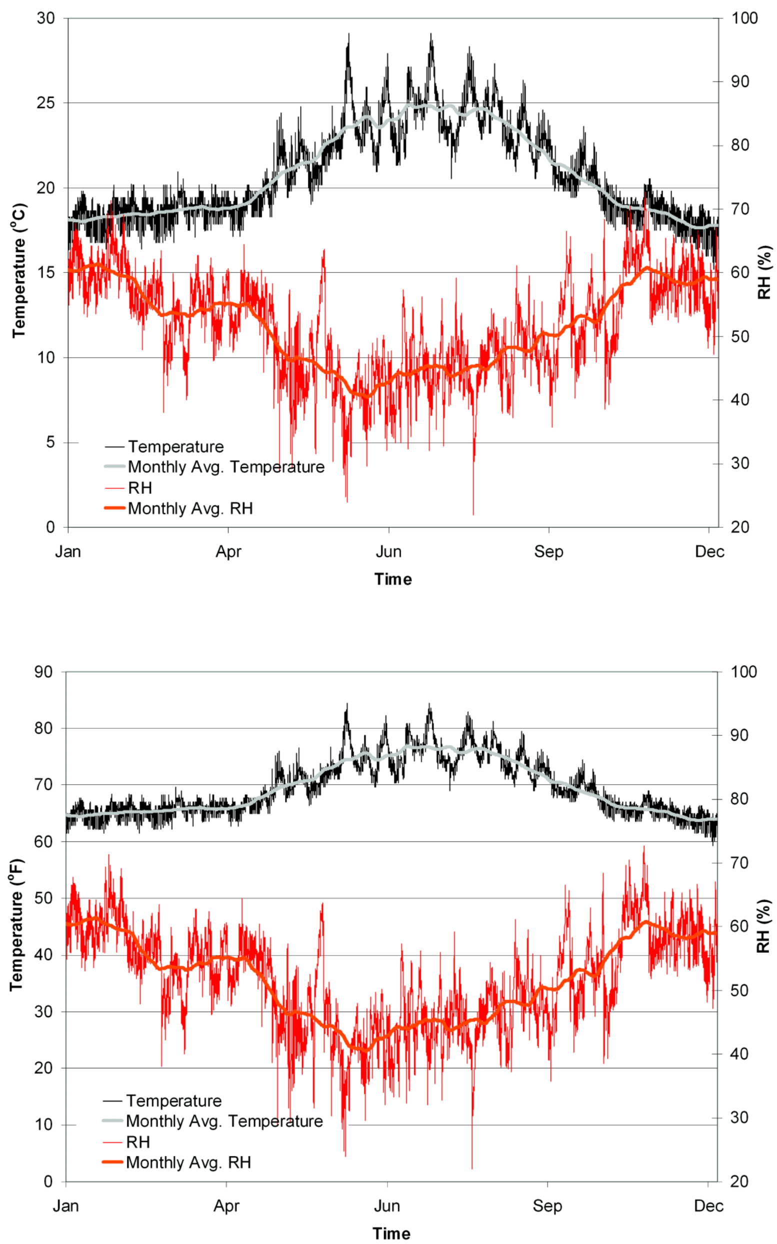


***Figure 3*** *Measured indoor conditions for a Vancouver multifamily building.*

lation of the outdoor vapour pressure (plotted in reverse order) to the indoor-outdoor vapour pressure difference. Note the exterior temperature or outdoor vapour pressure can be interchanged to demonstrate this pattern. The BRE Admittance Model calculates the same pattern in the indoor-outdoor vapourvapour pressure difference as shown in Figure 6 for constant ventilation and moisture generation rates, in contrast to the 160P approach that calculates a constant difference between the inside and outside vapour pressure.

Figure 7 compares measured and calculated indoor vapour pressures using different indoor temperatures for the corresponding indoor-outdoor vapour pressure differences presented in Figure 6. Using the measured indoor air temperatures appears to match best with the measured indoor-outdoor vapour pressure difference during the heating season, however does not match well during the non-heating season. This likely due to increased ventilation during the non-heating season (note the 160P approach over predicts the non-heating season vapour pressure by a larger margin). Assuming a constant equilibrium moisture content at the surface of building materials and furnishings matches relatively well in both

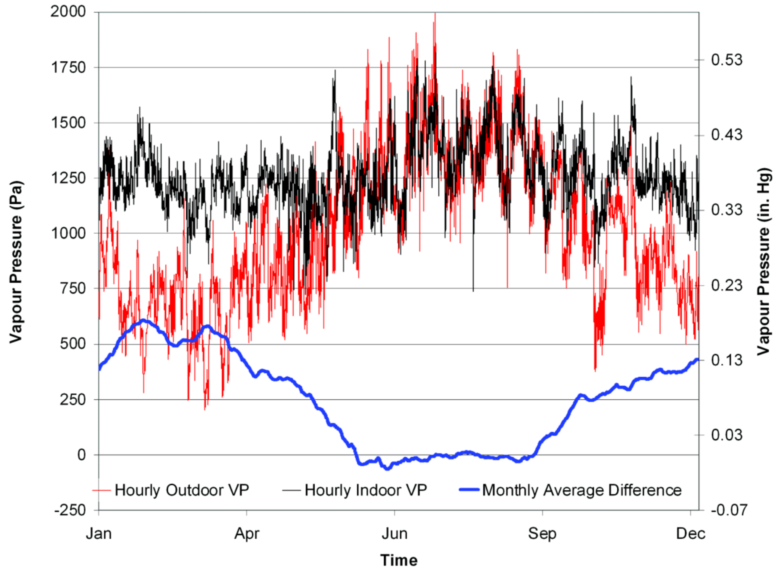


***Figure 4*** *Comparison of measured indoor vapour pressure and outdoor vapour pressure.*

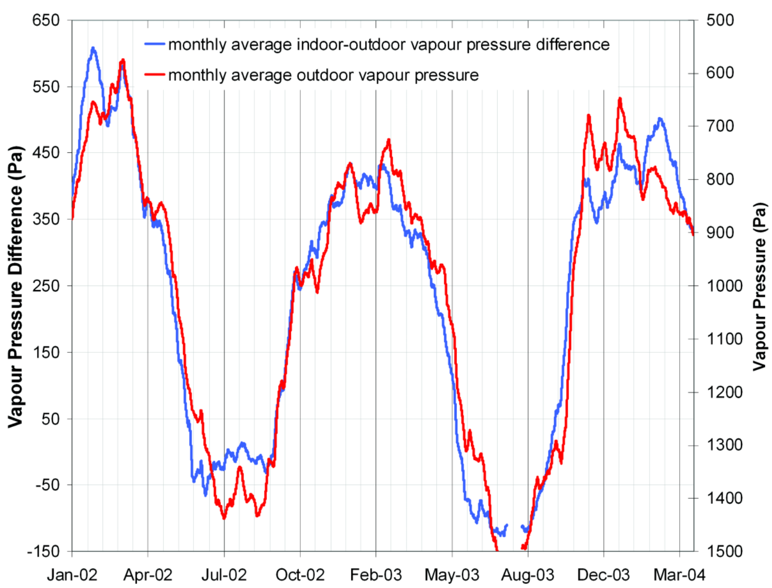


***Figure 5*** *Comparison of measured indoor-outdoor vapour pressure difference to outdoor vapour pressure.*

the heating and non-heating season, but this likely is a coincidence and not entirely due to absorption since the occupants indicated that they regularly keep their windows open in the non-heating season. An explanation is the increase in ventilation in the non-heating season likely equals approximately the difference in calculated absorption of moisture between the constant value (at 19$^{o}$C selected for the winter) and the measured indoor temperatures. The non-heating ventilation is discussed more in the next example.

## Example 3: Non-Heating Season Ventilation

For the example monitored building, the high indoor humidity contributed to condensation and moisture accumulation in the wall assembly during the winter. However, the moisture that accumulated during the winter dried out during the summer. It is desirable to account for the indoor humidity that results from increased ventilation from operable windows to fully evaluate the capacity of a wall to dry out in the summer. Figure 8 compares measured and calculated indoor vapour

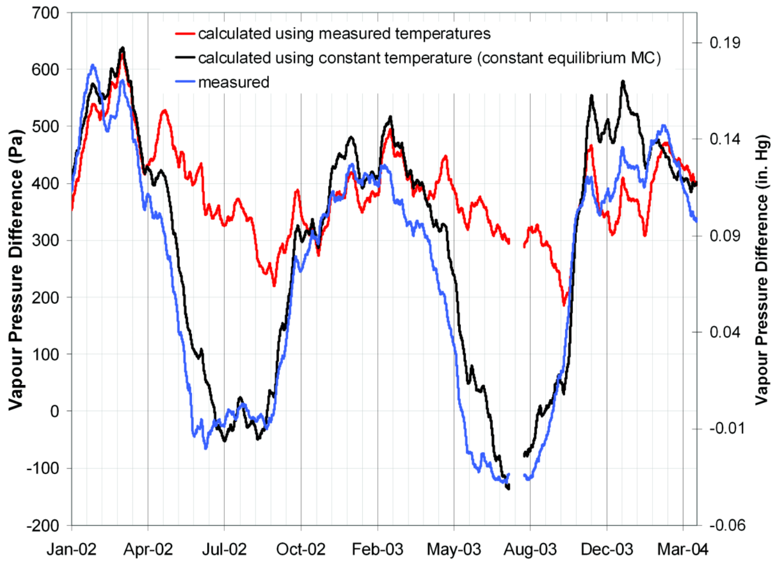


***Figure 6*** *Comparison of measured and calculated indoor-outdoor vapour pressure difference for different indoor*

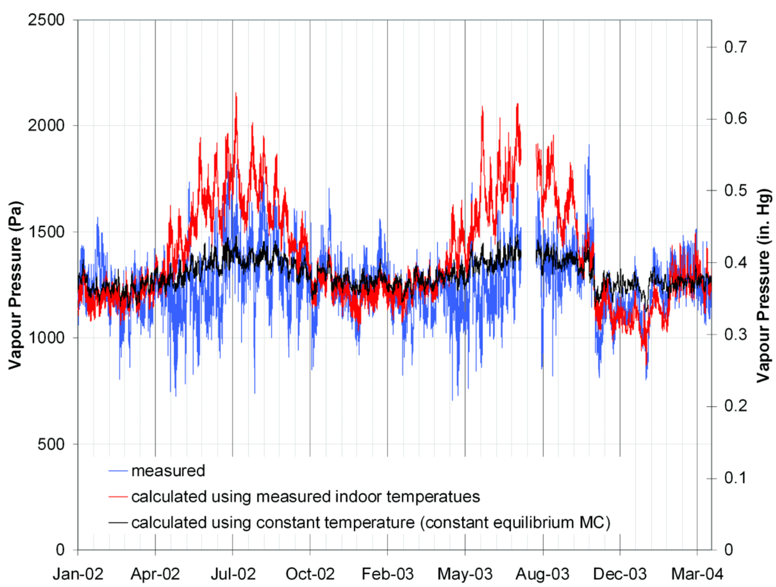


***Figure 7*** *Comparison of measured and calculated indoor vapour pressure for different indoor temperatures.*

pressures using different parameters for different seasons as summarized in Table 3. Figure 9 is the corresponding indoor-outdoor vapour pressure differences for these calculations for both the BRE Admittance Model and 160P approach. Note the parameters are only a guess to match the pattern of the measured data using a constant moisture production rate and a higher ventilation rate for the non-heating season.

This example shows that the BRE Admittance Model with optimized parameters gives a good fit to this particular set of measured data. However, there are too many additional parameters and uncertainties involved to determine whether the physical explanation is moisture buffering by hygroscopic materials alone.

Future frameworks might have ranges of vapour pressures differences between the indoor and outdoor air based on statistical data of monitored buildings for different climates. The ranges may also be divided into low, medium, high moisture generation levels and distinguish between the heating and non-heating seasons.

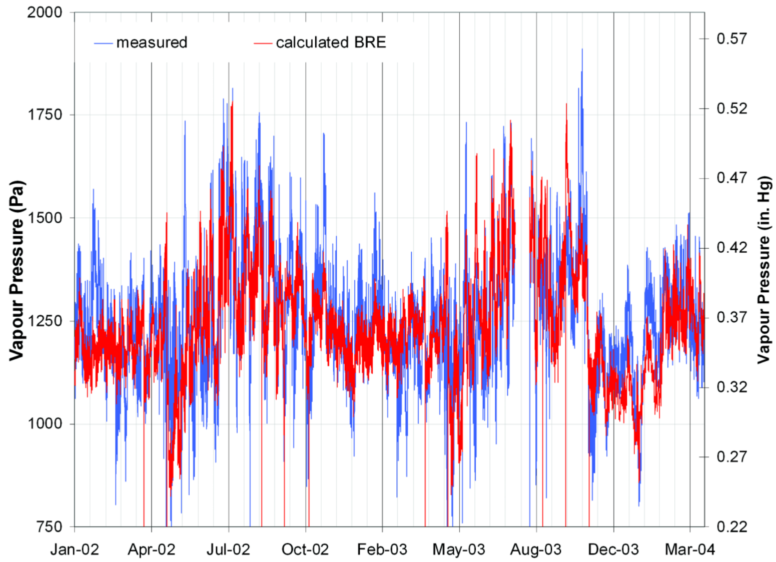


***Figure 8*** *Comparison of measured and calculated indoor vapour pressure for changes parameters for different seasons.*

**Table 3. Assumed Parameters for Different Seasons**

| | Nov. 1 to Mar. 31 | Apr. 1 to Apr. 31 Oct. 1 to Oct. 31 | May 1 to Sept. 31 |
|---|---|---|---|
| ACH | 0.15 ach | 0.15 ach | 0.75 ach |
| Moisture Production Rate | 5 L/day (0.45 lb/h) | 5 L/day (0.45 lb/h) | 5 L/day (0.45 lb/h) |
| Admittance Factors | $\alpha = 0.6$ $\beta = 0.3$ | $\alpha = 0.65$ $\beta = 0.3$ | $\alpha = 0.7$ $\beta = 0.25$ |

## Example 4: Moisture Generation for Multifamily Apartment Buildings

The following example explores the selection of an appropriate moisture generation rate for the BRE Admittance Model.

Estimates of moisture generation rates based on field measurements probably include moisture from both the occupants and their activities and from moisture stored in building materials and furnishings. In addition, most estimates of moisture generation rates are based on field measurements for detached homes that may include potentially significant moisture sources, such as conditioned basements, that are not significant in apartment buildings. These reasons may be why the calculated indoor humidity using a design moisture generation rate of 8 kg/day (0.7 lb/h), which is based on field measurements (TenWolde and Walker 2001), appears to be too high for indoor humidity calculations using the BRE Admittance Model.

One method to provide guidance in the selection of assumed moisture generation rates is to add up the expected individual moisture sources using published data (CHMC 1982, Handegord et al. 1983, Hansen et al. 1984, Chown 2003). Table 4 summarizes assumed moisture loads for a multi-family apartment.

There may be other peak loads such as washing and drying of laundry in suites that will add a significant amount of moisture to the building. However, one can argue that peak loads for drying of laundry in suites should not be considered as normal operating conditions and some of the moisture from peak loads will be transported to adjacent suites.

Figure 10 demonstrates the calculated indoor RH levels using the BRE Admittance Model and the moisture generation rates identified in Table 4. Vancouver climatic data for a typical year (1969) and the assumed parameters summarized in Table 5 were used for this calculation.

As can be seen in Figure 10, the assumptions presented in Table 5 still yield high values for Vancouver with the average monthly indoor RH between 50 to 60% for the heating season. To capture the full drying potential of an assembly in Vancouver, the non-heating season ventilation rate and/or admittance factors should be adjusted as previously discussed.

It should be noted that the assumed indoor temperature for this calculation was as per ASHRAE 160P design temperatures with an assumed heat gain (indoor temperature is equal

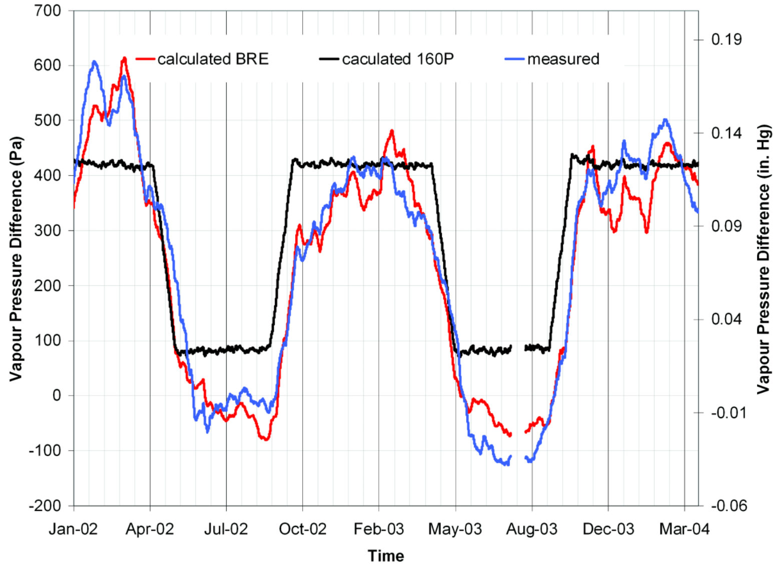


***Figure 9*** *Comparison of measured and calculated indoor vapour pressure.*

**Table 4. Moisture Loads for Multifamily Apartment**

| Source | 1 Bedroom Apartment | 2 Bedroom Apartment |
|---|---|---|
| People | 1.25 L/day × 2 people = 2.5 L/day (0.23 lb/h) | 1.25 L/day × 3 people = 3.75 L/day (0.34 lb/h) |
| Bath/Shower | 0.6 L/day (0.055 lb/h) | 0.8 L/day (0.073 lb/h) |
| Cooking (3 meals) | 0.9 L/day (0.083 lb/h) | 0.9 L/day (0.083 lb/h) |
| Dish Washing | 0.5 L/day (0.046 lb/h) | 0.5 L/day (0.046 lb/h) |
| Plants | 0.2 L/day (0.019 lb/h) | 0.2 L/day (0.019 lb/h) |
| Washing (floors) | 0.3 L/day (0.028 lb/h) | 0.3 L/day (0.028 lb/h) |
| Total | 5.0 L/day (0.46 lb/h) | 6.4 L/day (0.59 lb/h) |

to 2.8°C (5°F) above the 24-hour running average outdoor temperature when above 18.3°C (65°F)). In reality, a building's heat gain is highly dependant on exposure and construction and can vary quite widely as seen in the previous examples. Furthermore without air conditioning the indoor temperature during the non-heating season is difficult to predict and measured RH might be much different since RH is a function of temperature. For this reason the selection of indoor moisture loads for modeling should be selected based on vapour pressures to avoid confusion.

Future frameworks for indoor humidity calculations might have different admittance factors for the non-heating season and increase the ventilation rate any time that the outdoor temperature is above an assumed balance point temperature. In our opinion, more field and lab measurements are needed before such parameters are implemented in a standardized framework.

## CONCLUSIONS

This paper explored two current methods of calculating uncontrolled indoor humidity in residential occupancies and discussed the selection of parameters for the heating and non-heating seasons. Different parameters are required to evaluate both the potential magnitude of stored moisture in an assembly and the capacity for the assembly to dry out.

The impact of ventilation, moisture generation, and moisture storage on uncontrolled indoor humidity calculations was compared for the ASHRAE Standard 160P approach, where short-term moisture storage is approximated by using 24-hr running averages for input values, and the BRE Admittance model, where the absorption/desorption of moisture from hygroscopic materials have separate terms.

A perceived advantage of the BRE Admittance Model is the ability to calculate a level of dampening of the indoor vapour pressure that appears to compare well with measured data with ventilation and moisture generation rates consistent with observations and measurements. The BRE Admittance

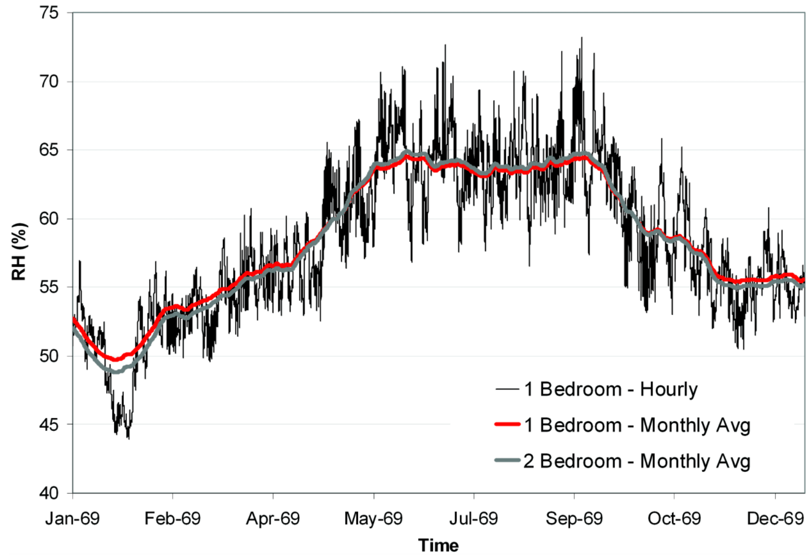


***Figure 10*** *Monthly average indoor RH calculated with BRE Admittance Model and parameters in Table 5.*

**Table 5. Assumed Indoor Humidity Parameters for Multiunit Residential Buildings**

| Parameter | 1 Bedroom Apartment | 2 Bedroom Apartment |
|---|---|---|
| Floor Area | 70 $m^2$ (750 $ft^2$) | 80 $m^2$ (860 $ft^2$) |
| Room Volume | 170 $m^3$ (6025 $ft^3$) | 195 $m^3$ (6900 $ft^3$) |
| Minimum Ventilation | 14 L/s (30 cfm) | 21 L/s (45 cfm) |
| ach | 0.35 ach | 0.4 ach |
| Moisture Production | 5.0 L/day (0.36 lb/h) | 6.4 L/day (0.59 lb/h) |
| Admittance Factors | $\alpha = 0.6$ & $\beta = 0.35$ | $\alpha = 0.6$ & $\beta = 0.35$ |

Model was shown to have the ability to match a trend in the difference between the indoor-outdoor vapour pressures observed in a few monitored suites and buildings in Vancouver, in contrast to the current ASHRAE Standard 160P approach where a constant indoor vapour pressure elevation is applied to the 24-hour running average outdoor vapour pressure. The observed varying difference between the indoor-outdoor vapour pressure difference in the monitored buildings can be contributed to varying ventilation, moisture generation, and absorption/desorption of moisture from hygroscopic materials. The author's expect that the buffering from absorption/desorption has a significant impact on the calculated indoor vapour pressure during the heating season for low ventilation rates, but less of an impact for a mild climate during the non-heating season where the windows are likely to be regularly open.

The level of ventilation can be controlled by the designers and are better known than moisture generation rates for North America buildings. Therefore, ventilation rates that correlate with field measurements are desirable to complete analysis (design or forensic) such as the impact of ventilation on indoor humidity. This will require the adjustment of assumed moisture generation rates for different types of buildings and occupancy to calculate indoor humidity levels similar to monitored data for a given level of ventilation.

Occupants may open their windows to provide additional ventilation when cooling is required for buildings without air conditioning or when the indoor humidity is above their comfort zone, if the mixture of the indoor and outdoor air will improve the indoor conditions. Consideration for separate ventilation rates should be made for indoor humidity calculations of the heating and non-heating seasons for building without air conditioning and uncontrolled humidity.

To avoid confusion, the difference between the indoor and outdoor vapour pressure should be used for the selection of the indoor moisture levels. The indoor RH during the non-heating season without air conditioning is difficult to predict, since heat gain and exposure have a large impact on the indoor temperatures. Small inaccuracies in the assumed indoor temperature may have a large impact on the calculated indoor RH during the non-heating season, but will likely have only a small impact on computer simulations of building envelope assemblies since the moisture content of the indoor air remains constant and the difference in the temperatures of individual materials in an assembly will be minimal.

## REFERENCES


Aoki-Kramer, M. and A.N. Karagiozis. 2004. A new look at residential interior environmental loads. Proceedings of the IX International Conference on the Performance of Whole Buildings.

ASHRAE. 2005. ASHRAE Handbook - Fundamentals.

ASHRAE. 2004. Standard 55 Thermal Environmental Conditions for Human Occupancy.

ASHRAE. 2004. Standard 62.2 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.

Chown, G.A. and P. Mukhopadhyaya. 2005. NBC 9.25.1.2.: The On-Going Development of Building Code Requirements to Address Low Air and Vapour Permeance Materials. Proceedings of the 10th Canadian Conference on Building Science and Technology.

Chown, G.A. 2003. Committee Paper on Application of NBC Part 9 Building Envelope Diffusion Requirements Depending on Indoor Relative Humidity. National Research Council Canada.

CMHC. 1982. Condensation in the Home: Where, Why, and What to Do About It. Canada Mortgage and Housing Corporation.

Cornick, S., A. Dalgliesh, N. Said, R. Djebbar, F. Tariku and M.K. Kumara. 2002. Report from Task 4 of MEWS Project – Task 4 – Environmental Conditions Final Report. IRC-RR-1130. National Research Council Canada.

Djebbar, R., D. van Reenen and M.K. Kumaran. 2001. Indoor and Outdoor Weather Analysis Tool for Hygrothermal Modelling. National Research Council Canada.

Finch, G., J. Straube and B. Hubbs. 2006. Building Envelope Performance Monitoring and Modeling of West Coast Rainscreen Enclosures. Proceedings of the 3rd Annual International Building Physics Conference.

Finch, G. 2007. Chapter 7: Air Leakage Testing of Multiunit Residential Buildings in Vancouver, B.C. MASc Thesis. University of Waterloo.

Hamlin, T. and J. Gusdorf. 1997. Airtightness and Energy Efficiency of New Conventional and R-2000 Housing in Canada”. CANMET Energy Technology Centre. Department of Natural Resources Canada.

Handegord, G.O. 1983. Moisture Sources in Houses. Building Science Insight. National Research Council Canada.

Hansen, A.T. 1984. Moisture Problems in Houses. Canadian Building Digest No. 231. National Research Council Canada. (see also CBD No.1 Humidity in Canadian Buildings)

Hutcheon, N.B. 1960 (revised 1968). Humidity in Canadian Buildings. Canadian Building Digest No.1. National Research Council Canada.

Jones, R. 1993. Modelling Water Vapour Conditions in Buildings. Building Services Engineering Research and Technology, Vol 14, No 3, pp.99–106.

Jones, R. 1995. Indoor Humidity Calculation Procedures. Building Services Engineering Research and Technology, Vol 16, No 3, pp 119–126.

Kuenzel, H.M., D. Zirkelbach and K. Sedlbauer. 2003. Predicting Indoor Temperature and Humidity Conditions including Hygrothermal Interactions with the Building Envelope. Proceedings of the 1st International Conference on Sustainable Energy and Green Architecture.

Kusuda, T. 1983. Indoor Humidity Calculation. ASHRAE Transactions, Vol 89 (2), pp. 728-738.

IEA. 1991. Annex XIV Condensation and Energy, Source Book.

Lawton, M.D., R.E. Dales and J. White. 1998. The Influence of House Characteristics in a Canadian Community on Microbiological Contamination. Indoor Air.

Roppel, P., M. Lawton and B. Hubbs. 2007. Balancing the Control of Heat, Air, Moisture, and Competing Interests. Proceedings of the 11th Canadian Building Science and Technology Conference.

Sherman, M.H. and R. Chan. 2004. Building Airtightness: Research and Practice. Lawrence Berkeley National Laboratory Report No. LBNL-53356.

TenWolde, A., and I. S. Walker. 2001. Interior Moisture Design Loads for Residences. Proceedings of the VII International Conference on the Performance of Whole Buildings.