Journal of ASTM International, Vol. 6, No. 9
Paper ID JAI102052
Available online at www.astm.org

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Setting Realistic Design Indoor Conditions for Residential Buildings by Vapor Pressure Difference

ABSTRACT: Indoor relative humidity (RH) is commonly used to characterize the indoor environment for heat-air-moisture (HAM) simulations, chamber studies, analysis of monitoring data, or test hut studies of buildings without recognition that indoor RH and condensation potential depend on concurrent outdoor temperature and RH. This can lead to the use of unrealistic boundary conditions for HAM simulations and test programs, which may result in misleading conclusions. In buildings operating without mechanical dehumidification, the indoor air moisture level (vapor pressure) is directly related to the outdoor vapor pressure, moisture sources in the space, and the level of ventilation. Mathematics suggests that one can expect buildings with similar operation, occupancy, and construction, but affected by different weather conditions, to have a similar difference between indoor and outdoor vapor pressures. This paper provides a foundation for selecting appropriate and realistic boundary conditions for the design of residential buildings that are based on vapor pressure difference with the aim to eliminate any significant bias for a particular climate. The paper will present the following: (1) Discussion of current standards that provide some guidance to selecting appropriate indoor moisture levels based on vapor pressure difference; (2) Moisture balance equations will be used to show the impact of ventilation and moisture generation rates on the vapor pressure difference; (3) Monitoring data for six multi-unit residential buildings in two Canadian climates (Toronto and Vancouver) showing the relationship between the outdoor temperatures and vapor pressure difference; (4) Analysis of seasonal indoor moisture conditions and their impact on HAM modeling based on assumed indoor RH and conditions derived by a constant vapor pressure difference; and (5) Exploration of the concept that vapor pressure difference and indoor RH are limited by moisture removal on windows.

KEYWORDS: residential buildings, building envelope, indoor environment, tools, field monitoring and measurements

Introduction

An essential consideration when evaluating the hygrothermal performance of building envelope assemblies is how to characterize the indoor environment. Conclusions based on heat-air-moisture (HAM) simulations, chamber studies, analysis of monitoring data, and test hut studies are largely dependent on the, simulated or actual, indoor environment.

An appropriate representation of the indoor environment of a building for a particular use and expected operation should reflect conditions that have realistic probabilities to be expected in service. Relative humidity (RH) is sometimes mistakenly used to compare different indoor environments without recognition that indoor RH and condensation potential depend on concurrent outdoor temperature and RH. This can lead to the use of unrealistic boundary conditions for HAM simulations and test programs, which may result in misleading conclusions.

In buildings operating without mechanical dehumidification, such as most residential buildings when air-conditioning is not operating, the indoor air moisture level (vapor pressure) is directly related to the outdoor vapor pressure, moisture sources in the space, and the moisture removed by ventilation.

Mathematical models to calculate indoor vapor pressure are well documented in the literature [1–9]. They can vary in complexity depending on secondary effects, such as absorption of hygroscopic materials, but all embody a moisture balance between the outdoor and indoor air. The fundamental form of all the moisture balance models is that indoor vapor pressure is equal to the outdoor vapor pressure plus indoor

Manuscript received July 31, 2008; accepted for publication June 30, 2009; published online August 2009.
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moisture generation minus moisture removed by ventilation. The mathematics suggests that buildings with similar moisture sources and ventilation should have a similar difference between the indoor and outdoor vapor pressures (ΔVP) regardless of outdoor temperature. Often the indoor vapor pressure is converted into a resultant indoor RH using design temperatures. See Appendix A for additional information on the mathematics of the moisture balance between the indoor and outdoor air.

In practice, the indoor vapor pressure may vary by climatic factors other than temperature and outdoor vapor pressures. The range in outdoor vapor pressure could affect the amount of moisture gained or removed by hygroscopic building materials, and differences in wind pressures could change ventilation rates. For example, the outdoor air for a cold climate typically has low vapor pressures and less ability to hold moisture than the typical range of outdoor vapor pressures in a mixed marine climate during Winter. Consequently the range in Winter indoor RH is quite different, which could theoretically affect the average vapor pressure difference for individual climates by varying magnitudes. Attempts to capture secondary effects, such as moisture buffering, are incorporated in some models; however, these effects are much less significant and predictable than temperature driven effects [3,8,9].

Indoor air moisture conditions in cold weather can also be limited by another factor: The condensation resistance of windows. Typically, windows are the thermally weakest components of the building envelope and present the coldest interior surface temperature. Window performance moderates the dew point of the indoor air in an absolute sense by removing moisture from the indoor air via condensation and in a practical sense because it is not rational to assume that the dew point of the indoor air is significantly above what can be supported, without excessive condensation, by windows that are generally available in buildings. This suggests that one upper design limit for ΔVP can be determined from the condensation resistance of good thermally efficient windows.

The objective of this paper is to build a stronger foundation for selecting appropriate and realistic boundary conditions for the design of residential buildings that are based on vapor pressure difference. The aim is to eliminate any significant bias for a particular climate and focus on residential buildings in mixed marine to cold climates that normally require several months of heating.

Realistic Design Indoor Air Moisture Levels

Published values of the difference between the indoor and outdoor vapor pressures for monitored buildings are not widely available. There are recent studies in Europe focused on compiling ΔVP statistical data [10–12], but in a macro sense the data is still sparse and more work is required to develop limits that are based on monitored data over complete years that can be applied, with confidence, to a wide range of:

- Occupancy (moisture generation, window use, and occupant comfort);
- Construction (hygric buffering capacity, and air tightness);
- Operation (ventilation, humidification/dehumidification, and heating); and
- Climates.

The European Indoor Climate Class Model sets limits for interior moisture levels using ΔVP statistical data from early European studies, with limits defined by a single parameter called the occupant type (ISO Standard 13788-01) [13]. The occupant type represents the combined effect of occupant moisture generation, ventilation, and adsorption/desorption of hygroscopic materials.

Indoor moisture design limits are more often than not based on established RH limits either due to unfamiliarity with available ΔVP limits or confidence in the limits for specific applications. RH limits are typically not established on a definite basis from measured values for individual climates but are loosely based on recommendations for health, occupant comfort, and historical measured values for a range of climates [14–16]. The difficulty is that indoor humidity and the temperature of surfaces in the building envelope depend on concurrent outdoor temperature. Without acknowledging this, computer simulations and testing can be carried out under unrealistic and inconsistent conditions.

Figure 1 illustrates how an assumed design condition of indoor air at 35 % RH and 21°C translates to vapor pressure difference between indoor and outdoor air for ten climates across Canada. This condition represents a historical design condition for the majority of Canada based on occupant comfort and measured values. However, an indoor RH of 35 % represents a design (high) indoor moisture load during the heating season for a cold climate (for example, Ottawa) but is a very low moisture load for a mixed marine climate (for example, Vancouver).

Two outdoor conditions are presented in Fig. 1: The 2.5 % January design temperature and the

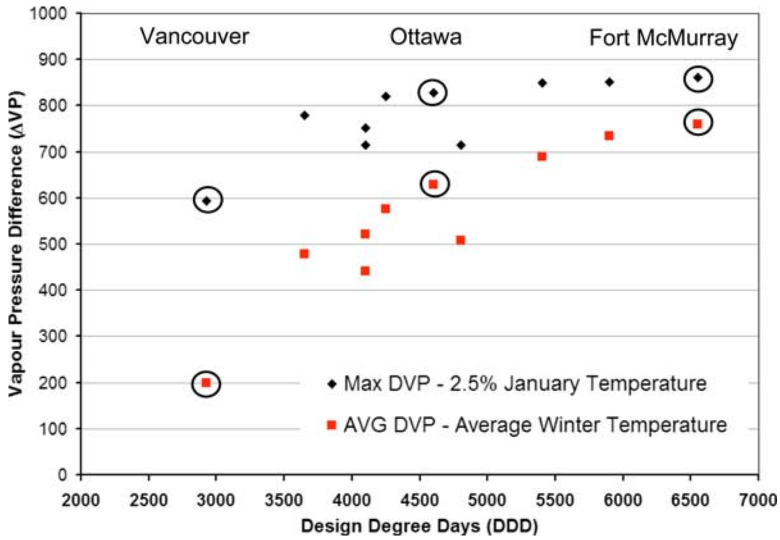

FIG. 1—*Vapor pressure difference (ΔVP) versus design degree days for Winter outdoor temperatures for Canadian climates.*

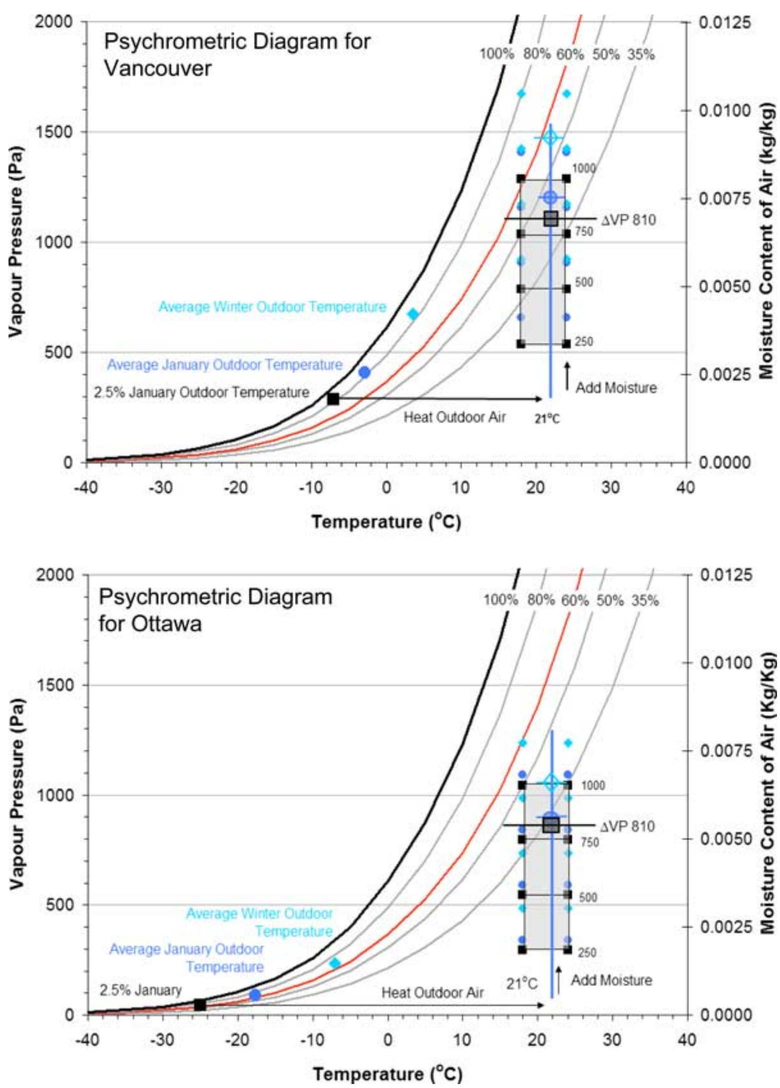

FIG. 2—*Psychrometric diagrams showing heating and moisture addition process of outdoor air to indoor air and the resulting range of indoor RH for a mixed marine and cold climate.*

TABLE 1—*Resultant RH (%) at 21°C for a ΔVP equal to 810 Pa.*

	Mixed Marine Climate, Vancouver	Cold Humid Climate, Ottawa	Very Cold Climate, Fort McMurray
2.5 % design January outdoor temperature	44	34	33
Average January outdoor temperature	49	36	34
Average Winter outdoor temperature	60	42	37

calculated average outdoor air temperature for the Winter months (January, February, March, November, and December). Average values were calculated from two successive climatic years, which have the highest heating degrees days (HDD18°C) selected from 20 years of Environment Canada climatic data (1985–2005). A calculated average outdoor RH from the same time period was used for calculation of the outdoor vapor pressure.

For Ottawa (cold humid,[4] HDD18°C=4600), at the 2.5 % January design temperature (−25°C) the ΔVP is about 830 Pa. At the mean outdoor air temperature for the heating season (−7.1°C), the ΔVP is about 630 Pa. If the same indoor conditions are applied to Vancouver (mixed marine, HDD18°C=2925), then the corresponding vapor pressure difference for the 2.5 % January design temperature (−7°C) and the average January temperature (3.6°C) are 600 and 200 Pa, respectively. A ΔVP of 600–850 Pa represents a moderate to high moisture load compared to 200 Pa, which represents a very low moisture load for a residential building.

It is worth noting that for very cold continental climates (HDD18°C > 5000 in Fig. 1), the outdoor vapor pressure in Winter is so low that the presumption of an RH based design condition makes less of a difference than for milder coastal climates.

This comparison reveals the difficultly of establishing consistent design conditions for indoor moisture based only on RH. A single limit can unrealistically represent varying moisture loads over the course of a heating season, and the variance can be significant depending on the climate.

Questions that arise from this comparison are: What is the right design limit for individual climates? and How do we set design or evaluation criteria without being biased to any particular climate? A start to answering these questions is to plot the process of heating and adding moisture to outdoor air on a psychrometric diagram and figuring out the resultant indoor moisture levels. Psychrometric diagrams for Vancouver and Ottawa are shown in Fig. 2.

Figure 2 illustrates the resultant indoor vapor pressure (and RH) for outdoor air at the 2.5 % January temperature, average January temperature, and average Winter temperature, which is then heated to the indoor operating temperature (18−24°C). Moisture is added by occupants and their activities (ΔVP of 250–1000) to reach the resultant indoor RH. Figure 2 shows how a constant ΔVP results in little difference between the resultant indoor RH for a cold climate, such as Ottawa, for 2.5 % design, average January, and average Winter outdoor temperature. Comparatively for a mixed marine climate, such as Vancouver, there is a much greater range in the resultant indoor RH for a smaller range in outdoor temperature. Table 1 summarizes the resultant RH for a ΔVP equal to 810 Pa for an example mixed marine, cold humid, and very cold climate. At this ΔVP level the resultant indoor RH is close to a historical RH limit for cold and very cold climates for both the 2.5 % design and average January outdoor temperature and at the upper

TABLE 2—*ΔVP limits embodied in the European Indoor Climate Class Model.*

Class	Occupancy	ΔVP (Pa)
1–very low	Storage area	0
2–low	Office, shops	270
3–medium	Dwellings with low occupancy	540
4–high	Dwellings with high occupancy, sport halls, kitchens, canteens, and buildings heated with un-flued gas heaters	810
5–very high	Special buildings, e.g., laundry, brewery, and swimming pool	1080

[4]Climate classification as identified in 2006 IECC [17], ANSI/ASHRAE 169-06 [18], and ANSI/ASHRAE/IESNA 90.1-07 [19].

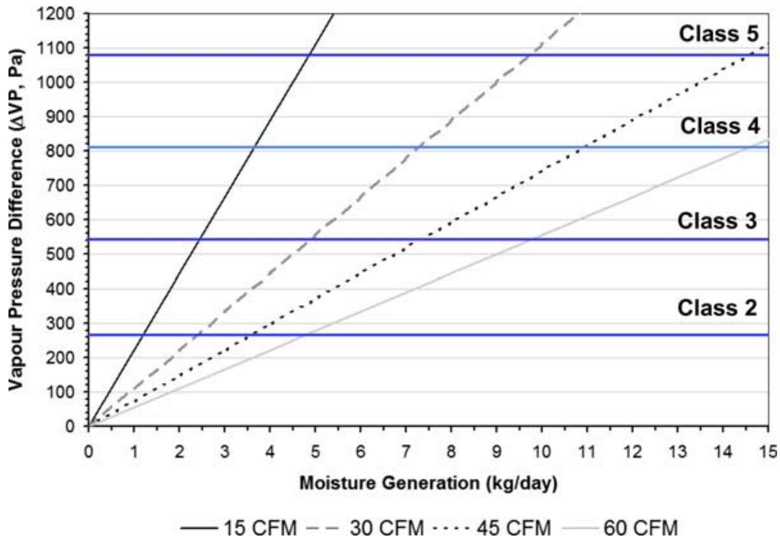

FIG. 3—*Relationship between ventilation and moisture generation with regard to vapor pressure difference.*

limit of 60 % RH in Vancouver for average Winter outdoor temperatures. Clearly a single ΔVP cannot represent both the historical upper limit of 35 % RH for a cold climate and the upper limit of 60 % RH for mild (mixed marine) climate without bias to a particular climate because this will require using January temperatures for the cold climate and only average Winter temperatures for the mild climate.

If 35 % RH is the upper limit for a cold climate during average Winter conditions, then the ΔVP is approximately 630 Pa. At a ΔVP equal to 630 Pa, the resultant indoor RH is 52.5 % RH for a mixed marine climate and 30 % RH for a very cold climate at the average Winter temperature. The preceding discussion should make it apparent why RH limits cannot be used in isolation and should be used in conjunction with ΔVP values, but the discussion has not yet provided definitive answers to what ΔVP values can be realistically expected in buildings and what ΔVP limits should be used for design. Table 2 summarizes the ΔVP limits embodied in the European Indoor Climate Class Model during Winter time (ISO Standard 13788-01) [13], which can provide a point of reference for determining ΔVP limits for climates outside of Europe.

Note that the European Indoor Class Model is based on the mean monthly outdoor air temperature, but Class 4 with ΔVP equal to 810 Pa compares well with the cold climate assumptions of established RH limits of 35 % at 21°C for the 2.5 % design and average January outdoor temperatures. Conversely, Class 3 with ΔVP equal to 540 Pa compares more favorably to the same cold climate assumption for indoor conditions for average Winter outdoor temperatures. Though it is not stated directly in ISO Standard 13788-01 [13], most residential buildings are considered to be Class 3 [12].

The direct relationship between the vapor pressure difference, ventilation rate (mechanical plus infiltration), and moisture generation in a building was previously mentioned in the Introduction. Figure 3 shows the relationship between ΔVP, moisture generation, and ventilation using a simple moisture balance equation of the indoor and outdoor air (see Appendix A for additional information). The horizontal lines represent criteria for the European Indoor Climate Class Model of 540, 810, and 1080 Pa difference in the indoor and outdoor vapor pressures that have already been discussed.

ASHRAE Standard 62.2-04 [16] recommends a minimum ventilation rate of 14 L/s (30 CFM) and 21 L/s (45 CFM) for the heating season for one and two bedroom dwellings, respectively, for a floor area less than 140 m^2 (1500 ft^2). Table 3 shows the amount of daily moisture generation that would produce the

TABLE 3—*Daily moisture generation (L/day) that results in defined vapor pressure differences assuming ASHRAE recommended ventilation rates.*

Number of Bedrooms	Ventilation Rates	ΔVP=540 Pa	ΔVP=810 Pa	ΔVP=1080 Pa
1	14 L/s (30 CFM)	4.8	7.3	9.7
2	21 L/s (45 CFM)	7.3	10.9	14.6

TABLE 4—*Moisture generation rates calculated from published data.*

Source	One Bedroom Apartment	Two 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 (three 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)**	**6.5 L/day (0.59 lb/h)**

ΔVP limits identified in the European Indoor Climate Class Model assuming the minimum ventilation rates recommended by ASHRAE Standard 62.2-04.

A rate of 7.5 L/day has been shown to represent a high moisture production rate for a four person dwelling unit by summing peak moisture generation rates [20]. Note that ASHRAE Standard 62.2-04 recommends ventilation rates of 15 CFM/person and assumes two people for one bedroom and three people for two bedroom dwellings. Table 4 summarizes moisture generation rates calculated using individual moisture sources using published data and using the same assumptions as ASHRAE Standard 62.2-04 for occupancy [8,11,12,21,22]. The moisture generation rates in Table 4 can be considered high moisture generation daily values for weekly mean conditions in a residential building.

There may be other peak loads such as washing and drying of laundry in buildings that will add a significant amount of moisture to the building during short periods of time. We consider these activities not frequent enough to add to the weekly and monthly mean moisture generation rates, and excluding these loads allows comparison to ΔVP limits embodied in the European Indoor Climate Class Model, which are based on monthly outdoor values. There are published moisture generation rates based on whole building measurements and BSR/ASHRAE Standard 160P-06 that are higher than the total moisture generation values in Table 3; however, whole building measurements values typically do not distinguish between peak and average values [6,11,12,23].

Comparison of published moisture generation rates appears to agree well with the limits in the European Indoor Climate Class Model of 540 Pa for dwellings with low occupancy and moderate moisture generation and 810 Pa for buildings with high humidity for standard minimum North American ventilation rates.

Indoor Moisture Limits Compared to Window Performance

Buildings operating at a high ΔVP require not only special design considerations for the building envelope (e.g., air tightness, vapor resistance, moisture tolerant materials, etc.) but also good window condensation

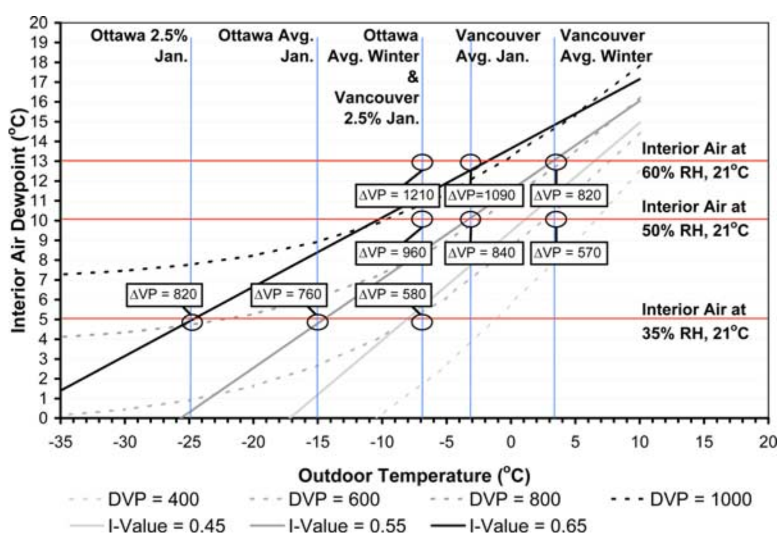

FIG. 4—*Comparison of window I-value and vapor pressure difference (interior air at 21°C).*

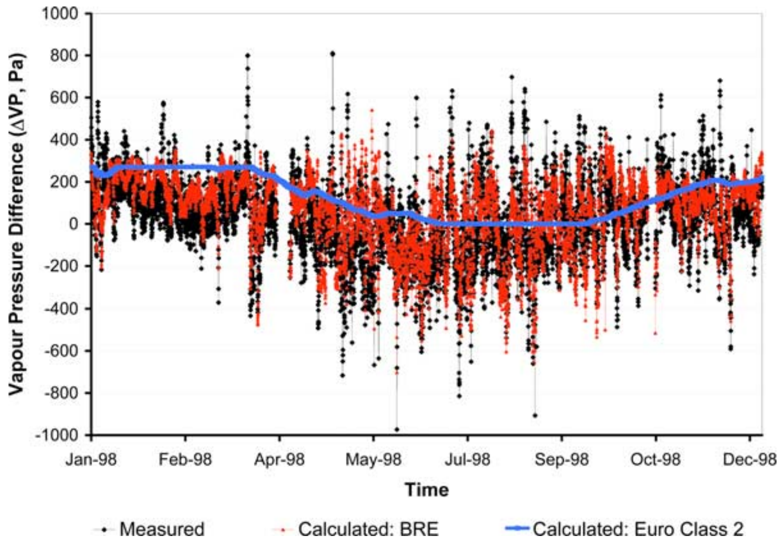

FIG. 5—*Comparison of monitoring data to BRE model and European Indoor Climate Class Model (Class 2) for a cold humid climate (Toronto, HDD18°C = 3650).*

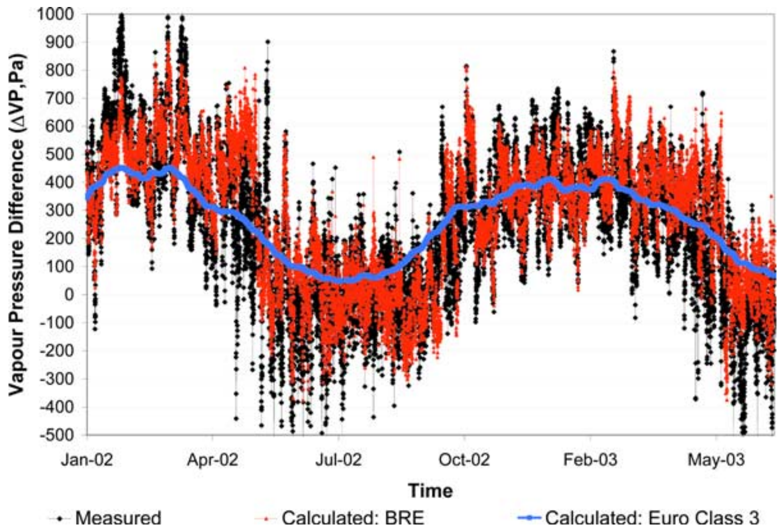

FIG. 6—*Comparison of monitoring data to BRE Model and European Indoor Climate Class Model (Class 3) for a mixed marine climate (Vancouver, Building 3, HDD18°C = 2925).*

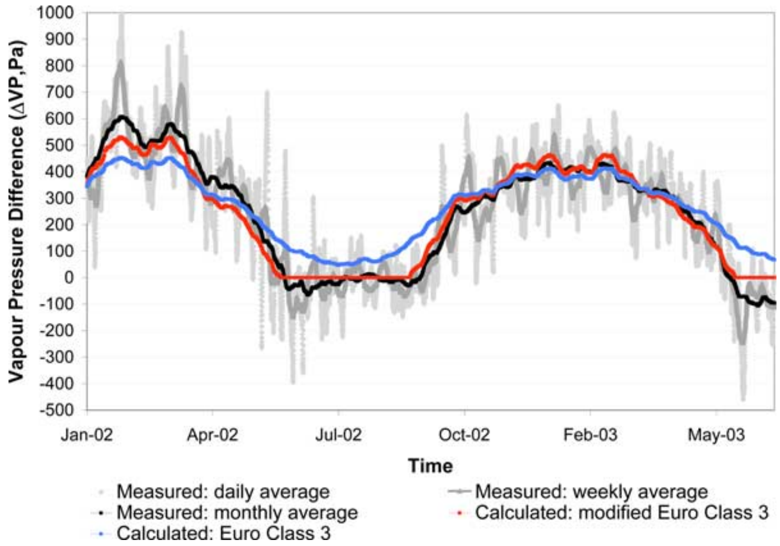

FIG. 7—*Comparison of monitoring data to European Indoor Climate Class Model (Class 3) with different deflection points for a mixed marine climate (Vancouver, Building 3, HDD18°C = 2925).*

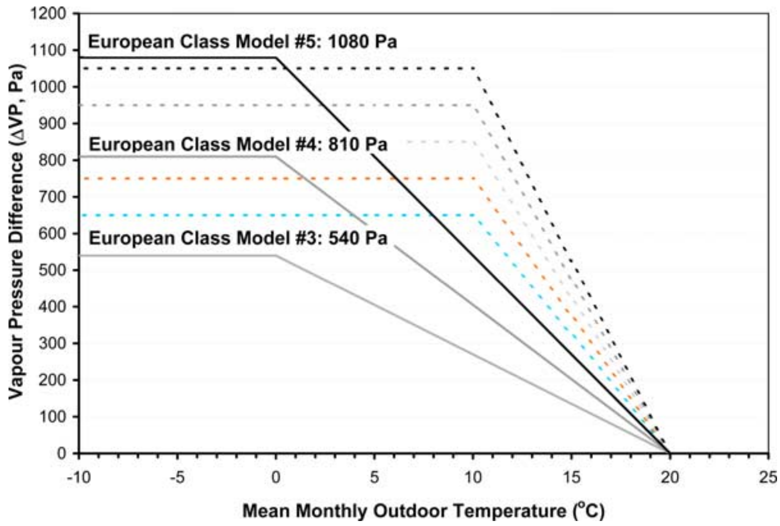

FIG. 8—*European Indoor Climate Class Model with adjusted heating season.*

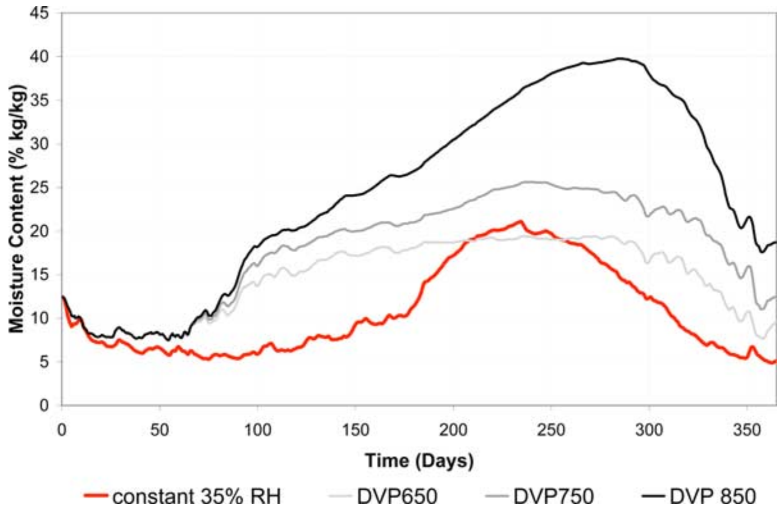

FIG. 9—*Moisture content of bottom wood plate of example wall assembly for Ottawa.*

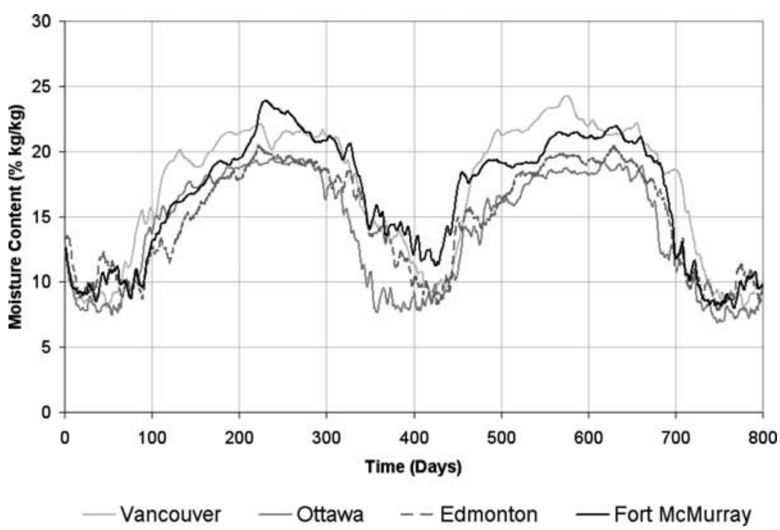

FIG. 10—*Moisture content of bottom wood plate of example wall assembly for a ΔVP equal to 650 Pa for a range of Canadian climates.*

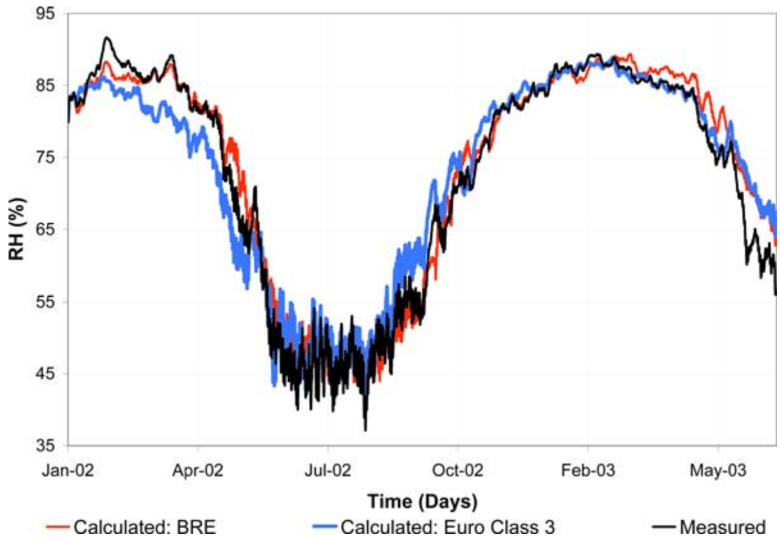

FIG. 11—*RH (%) at the interior surface of the exterior sheathing of a monitored building for calculated and measured indoor moisture conditions.*

resistance (surface temperatures) in cold climates. The likely surface temperature of windows has to be considered when determining appropriate design conditions for the indoor environment.

To prevent excessive condensation on windows, it is necessary to balance moisture source control, ventilation, and condensation resistance performance of the windows. Note that vapor pressure difference is defined by the first two parameters.

A designer should be able to count on the minimum ventilation rates referenced in standards and building codes (for example, ASHRAE Standard 62.2-04) to be sufficient enough to control indoor moisture levels without condensation occurring on good windows that are readily available and commonly used in practice. Continuing with this logic, an indication of realistic maximum difference between the indoor and outdoor vapor pressures is the maximum value that good windows that are commonly available and used in practice can sustain without excessive condensation occurring during Winter design conditions.

Moisture removed from the air by condensation will also, in theory, moderate the indoor vapor pressure by dehumidifying the indoor air. However, condensation that forms on windows during peak conditions is available to evaporate back to the indoor space during non-condensing conditions. The net effect is that the windows will moderate the indoor moisture levels, or conditions will be such to overwhelm the ability of the windows to moderate the indoor dew point, in which case it is safe to assume that excessive condensation is a problem. If excessive window condensation is a problem, then usually the solution is to remove more moisture from the indoor air (i.e., strategies to increase ventilation effectiveness or dehumidification).

Figure 4 shows the maximum vapor pressure difference that can be maintained without condensation occurring on the windows for typical indoor RH limits. A range of window *I*-values[5] and relevant outdoor temperatures for Ottawa and Vancouver is presented as examples. The vertical lines indicate the 2.5 % January design temperature, average January, and average Winter outdoor temperatures for Ottawa and Vancouver. The horizontal lines show the dew point temperature for the interior air at 35, 50, and 60 % RH at 21°C. An outdoor RH of 85 % was used in the calculation of the ΔVP, which is a bias to the mild marine climate but makes little difference for a cold climate as can be seen in Fig. 2.

At ΔVP=800 Pa, the dew point temperature of the interior air is below the surface temperature of a window with an *I*-value=0.65 (typical for good double glazing available in Ottawa) for outdoor temperatures down to approximately −25°C, the 2.5 % January design temperature for Ottawa. For a ΔVP =1000 Pa in Ottawa, a window with an *I*-value of 0.65 will result in continuous condensation below an outdoor temperature of −10°C. Comparatively, a window with an *I*-value of 0.55 will not result in condensation at a ΔVP=800 Pa in Vancouver during the 2.5 % January design temperature. However, it is very common in Vancouver to have aluminum windows with an *I*-value closer to 0.45 for multi-unit

[5]A definition of temperature index is found in Appendix A.

residential buildings, where a maximum of $\Delta VP=600$ Pa appears to be a more appropriate design condition.

The concept of limiting the design conditions to what the windows can support without excessive condensation by ensuring that sufficient ventilation is provided and realistic indoor conditions using vapor pressure difference is further discussed in the following section using monitoring data as examples.

Comparison to Monitoring Data

Monitoring data from one building in Toronto (two suites) and five buildings in Vancouver (including three buildings with multiple suites) was analyzed with regard to the difference between the indoor and outdoor vapor pressures. All these buildings are multi-unit residential buildings, which are expected to have slightly different indoor conditions than a detached house due to differences in occupant density, moisture generation, ventilation, and air leakage characteristics. Note that a significant moisture source in detached buildings can be the soil adjacent conditioned basements [24,25], which are not a moisture source for the monitored suites.

A description of the monitored buildings, a summary of the monitoring data, and analysis can be found in Appendix B, and Figs. 13–34

Analysis of the monitored data for these buildings shows a distinct pattern with regard to the vapor pressure difference that is expected to exist for any type of residential building without humidity control in cold and mixed marine climates. The monitoring data shows that the vapor pressure difference is greatest in the heating season coinciding with the coldest outdoor temperature and varies directly with the monthly mean outdoor temperature as seen in the monitoring data [Appendix B, Figs. 13, 16, 19, 23, 27, and 31]. Generally, the average indoor to outdoor vapor pressure difference will be positive during the heating season, depending on the indoor moisture generation and ventilation rates, and decrease to near zero during Summer.

The data was analyzed to explore the relationship between the indoor and outdoor air with relation to temperature, RH, vapor pressure, and how the vapor pressure difference relates to the design limits discussed in the previous section.

The average ΔVP during the heating season was below 500 Pa for all the monitored buildings, except the running monthly mean vapor pressure difference was measured up to 750 Pa for one of the monitored buildings during 1 month. A ΔVP of 750 Pa is close to the ΔVP for Class 4 buildings (high humidity) for the European Indoor Climate Class Model. This value also compares favorably to the ΔVP calculated from a recognized high limit in indoor RH for cold climates (35 % RH at 21°C) during average Winter conditions as seen in Fig. 1.

The monthly mean indoor RH in all the Vancouver buildings was below 50 % during the heating season, except for Building 3. Excessive condensation on the windows (*I*-value of approximately 0.45) and high moisture generation (high number of occupants and drying clothes in suites) were observed in the monitored suites in Building 3, and ventilation was generally not provided as per code as demonstrated by CO_2 and exhaust fan capacity measurements [26,27].

The peak ΔVP for short time periods was greater than 1000 Pa for three of the buildings in Vancouver, but 90 % of the measured ΔVP is below 850 Pa for all the buildings. If Building 3 is removed from the sample, then 90 % of the measured ΔVP is below 750 Pa for the rest of the buildings. The highest monthly average and peak ΔVP were measured in Buildings 1, 3, and 5a during periods where the indoor temperature was greater than 20°C and the indoor RH was greater than 60 %.

Despite apparent high moisture production and poor ventilation in Building 3, the average monthly ΔVP during the heating season was higher in Building 1 for some periods. One may speculate that part of the difference is due to the amount of moisture removed by the windows. Building 1 has vinyl windows with high indoor operating temperatures, making condensation forming on the windows less likely than compared to Building 3, with aluminum framed windows with low operating temperatures.

The impact of lower operating temperatures on actual ΔVP can be calculated by comparing expected surface temperatures of windows to the dew point temperature of the interior air as presented in Fig. 4. For example, a window with an *I*-value of 0.45 will intersect the 650 Pa curve at an outdoor temperature of −6°C for indoor air at 21°C. For indoor air at 18°C this same intersection occurs at 550 Pa. This reveals how condensation on windows may occur more frequently and consequently remove more moisture from the indoor air, at lower indoor temperatures than compared to the typical design temperature of 21°C for elevated vapor pressure difference. In theory, the vapor pressure difference may be limited by the windows more for lower operating indoor temperatures than for the typical design temperature of 21°C.

Impact of Vapor Pressure Difference on Heat-Air-Moisture Simulations

A constant vapor pressure difference during the heating season is appropriate as an input for design and research using HAM simulations and testing since there are many factors affecting the operation conditions of a building. However, modeling indoor moisture levels using a constant vapor pressure does not account for the varying vapor pressure with outdoor temperature that we have seen in the monitoring data. A model such as the British Research Establishment (BRE) model [3,4] is able to follow the same pattern of varying vapor pressure difference with the outdoor temperature and vapor pressure as seen in the monitoring data [8]. However adjusted parameters are required for each climate to select appropriate equilibrium indoor vapor pressures for both the heating and non-heating seasons.[6] This implies that calibration to accepted vapor pressure difference limits is required to utilize the BRE model in a standard framework or requires significant judgment.

A comparison of monitoring data to both the BRE model and the European Indoor Climate Class Model (Class 2) is presented in Fig. 5 for a monitored building in Toronto (cold humid climate, HDD18°C=3650). Note that the European Indoor Climate Class Model specifies a constant ΔVP of 270 Pa for a climate Class 2 at mean outdoor temperatures below 0°C and a linear relationship to the mean monthly outdoor temperature between 0 and 20°C. Figure 5 shows how the BRE model is able to trend the daily and weekly measured ΔVP using separate parameters for the heating and non-heating seasons. This is in contrast to the European Indoor Climate Class Model that only has the potential to trend monthly ΔVP data. Figure 6 is a similar comparison of the BRE and European Climate Class Model to a monitored building in Vancouver (Building 3).

Comparison of the calculated ΔVP by the European Indoor Climate Class Model between the mixed marine and cold humid climates reveals how during the heating season the calculated ΔVP can have different trends depending on the climate and coldest monthly mean outdoor temperature. The deflection points stated in the European Indoor Climate Class model are 0 and 20°C. A constant ΔVP at the maximum ΔVP climate class limit is estimated for a cold climate for most of the heating season by the European Indoor Climate Class Model. In contrast, the climate class maximum ΔVP limit may never be reached for a marine climate during a mild Winter or for only a brief period during a cold Winter; by definition a marine climate has a mean outdoor temperature greater than −3°C during the coldest month (ANSI/ASHRAE 169-06) and typically has temperatures above 0°C during Winter. Similarly a marine climate will not likely reach the lower ΔVP limit of zero because of the expected cool Summers with mean monthly temperatures below 20°C (ANSI/ASHRAE 169-06 [18] defines a marine climate as having a monthly mean less than 22°C for the warmest month).

Recent comparisons between the deflection points stated in the European Indoor Climate Class Model and field measurements in Finland [11] reveal that other deflection points can better match different types of climates, building operation, and occupancy. For example, deflection points at 5 and 15°C are reported to better match the studied buildings in Finland. From a practical perspective, the deflection points embodied in the European Indoor Climate Class Model appear highly subjective to the selected ΔVP limits and climate of the underlying statistical data. Figure 7 demonstrates this point by showing how the Indoor Climate Class 3 (ΔVP=540 Pa, deflection points at 0 and 20°C) can trend closely to monthly mean measured data for a mixed marine climate (Vancouver, Building 3) during the Winter of 2003 of the measured data but does not trend as well in the Summer or in the Winter of 2002. A ΔVP=540 with deflection points at 5 and 15°C better matches the trend in the measured monthly mean ΔVP for the monitoring period, as well as other combinations of ΔVP limits and deflection points. For example, a ΔVP=700 with deflection points at 0 and 15°C produces almost identical results. The practical implication is that there are many combinations of ΔVP limits and deflection points that will yield similar curves if the monthly mean outdoor temperature does not drop below the lower temperature deflection point.

The sensitivity of vapor pressure difference to HAM modeling was explored using a time variant two-dimensional model (DELPHIN). A wood stud wall assembly with rigid polystyrene insulating sheathing and fiberglass batt cavity insulation was selected for the analysis. Air leakage was modeled by laminar

[6]See Appendix A for additional discussion.

flow through the batt insulation and gaps at the top and bottom plates. The modeled air leakage rate is characterized by 0.1 $L/(s \cdot m^2)$ at 75 Pa and exterior conditions utilized Environment Canada climatic data. A complete summary of the simulations and additional parameters can be found in the Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings Tenth International Conference [28]. Additional information can also be found in Appendix A.

The ΔVP limits and deflection points embodied in the European Indoor Climate Class Model appears to suggest that the ΔVP is constant at the maximum limit during the heating season because the windows are closed and people are regularly indoors creating moisture. For this analysis, the indoor conditions were modeled using a model similar to the European Indoor Climate Class Model, except we chose to extend the heating season to 10°C and we completed simulations at increments of 100 Pa. These modifications were made because the ΔVP limits and deflection points in the European Indoor Climate Class Model are based on measured data of Western European buildings. Limits and deflection points could be different in other countries and climates due to differences in climate, building operation, and occupancy. For example, average window use and ventilation in the measured countries can represent significantly different operation than typically realized in other countries and climates. A comparison between the European Indoor Climate Class Model and our adjusted model is shown in Fig. 8.

The performance of the modeled wall assembly is highly sensitive to ΔVP at increments of 100 Pa. Using Ottawa as an example (cold humid, HDD18°C 4600), a ΔVP between 650 and 850 Pa corresponds to indoor humidity in the range of 25–45 % RH during the heating season. In this range, increments of 100 Pa in ΔVP result in as little as a 4 % change in indoor RH but have a significant impact on the moisture content of the wood in the stud cavity adjacent to the exterior sheathing. Figure 9 shows the modeled moisture content of the bottom wood plate for Ottawa using the example wall assembly. This example wall assembly and model is highly sensitive to the indoor conditions because air leakage transports moisture directly to the interior surface of the exterior sheathing where it can condense on any surface below the dew point temperature.

Simulations were completed for ten climates across Canada using the difference between the indoor and outdoor vapor pressures to characterize the indoor moisture levels. These simulations showed that for a given ΔVP limit and wall assembly, that similar hygrothermal performance is produced. There were some slight differences in absolute moisture content depending on climate that appear to be related to the outdoor temperature conditions (temperature compared to vapor pressure gradient across the assembly). However, the difference in the moisture content is less sensitive between different climates for a set ΔVP than for a set climate to a range of ΔVP. Figure 10 shows the moisture content of the bottom wood plate of the example wall assembly for a ΔVP equal to 650 Pa for four distinct Canadian climates (Vancouver: HDD18°C=2925; Ottawa: HDD18°C=4600; Edmonton: HDD18°C 5400; Fort McMurray: HDD18°C 6550).

The wall assembly for Building 3 of the Vancouver monitored buildings was simulated using a one-dimesional hygrothermal model (WUFI) for the calculated indoor conditions illustrated in Fig. 6. The calculated RH at the interior surface of the exterior sheathing is illustrated in Fig. 11.

Comparison of Figs. 6 and 11 shows that a modified European Indoor Climate Class Model is capable of yielding similar results as simulations as real measured indoor conditions and similar results as the BRE model with optimized parameters. This comparison reveals that though the European Indoor Climate Class Model does not trend the weekly and daily ΔVP as well as the BRE model, the European Indoor Climate Class Model will produce similar simulation results as the BRE model if both yield similar monthly averages during the heating season. This exercise indicates that realistic design conditions for transient HAM simulations could be selected from the monthly average ΔVP (i.e., average January conditions).

Discussion

Characterizing the indoor environment using the difference between the indoor and outdoor vapor pressure needs to be better integrated into the practice of evaluating the hygrothermal performance of the building envelope. North American standards need to provide more reference to expected vapor pressure difference for specific ventilation rates that are calibrated to the actual building operation. That is, care should be exercised when combining calculated moisture production rates based on field measurements with ventilation rates measured in isolation since field measurement of moisture production is dependent on ventilation. Reference ΔVP values should not only embody established RH limits but also expected window performance, minimum ventilation requirements, and realistic moisture production. The goal is to produce reference values for residential buildings in North America that are relevant to common building practice and operation and is not biased to any particular climate. The European Indoor Climate Class (ISO Standard 13788-01) can be used for guidance to reach this goal, but more work is needed to validate a similar model for climates outside of Western Europe since this type of model relies on statistical analysis of measured data.

Conclusions

This paper compared monitoring data to expected window performance, ventilation, moisture production, and RH limits, with the objective to provide a foundation for selecting appropriate and realistic boundary conditions for the design and evaluation of residential buildings. Clearly more rigor and comparison to more monitored buildings will help establish firm values that concurrently relate all relevant parameters to probability of occurrence.

In the interim, ΔVP limits for North American residential buildings appear to be somewhere between Classes 3 and 4 of the European Indoor Climate Class Model. A constant ΔVP value of approximately 540 Pa (Class 3) appears almost high enough for design conditions for average conditions during the heating season and appears appropriate for transient hygrothermal simulations. We conclude this because a model of the indoor climate using European Indoor Climate Class Model during the heating season was shown, by HAM modeling, to produce similar results as using measured indoor conditions that have similar monthly averages but more fluctuation in the daily and weekly averages (ΔVP of up to 810 Pa). Note that the example building used for this analysis had conditions that can be considered above design conditions: Excessive window condensation, regular drying of clothes in the suite, mold on interior surfaces, non code compliant ventilation, and RH above 60 % RH during the heating season. However, the vapor pressure difference may have been limited by the windows since the theoretical maximum ΔVP for the window *I*-value (0.45) appears to coincide closely with the measured conditions. Therefore, for design conditions (i.e., at 2.5 % January outdoor temperature) a higher ΔVP appears appropriate.

A ΔVP of approximately 810 Pa (Class 4) is required to reach the minimum recommended RH lower limit of 35 % RH for cold climates (such as Ottawa) during the heating season during design conditions. Most residential buildings in cold climates likely require humidification during Winter design conditions to reach this humidity level. This ΔVP limit is also close to the theoretical maximum ΔVP for a window with an *I*-value of 0.65 (typical for good double glazing available in Ottawa) at the 2.5 % January outdoor temperature.

Reference limits based on the difference between the indoor and outdoor vapor pressure difference do not have to be used in isolation as the European Indoor Climate Class Model. Reference ΔVP limits can be integrated into standards, utilized with more complicated models, or used in testing to determine moisture production rates for design ventilation rates that represent realistic indoor moisture levels in absolute terms (vapor pressure).

Acknowledgments

The writers like to thank Hua Ge from BCIT for providing the Vancouver monitoring data to support the analysis work reported in this paper. The monitoring data was donated to BCIT after completion of a research project entitled “Performance Monitoring of Rainscreen Wall Assemblies in Vancouver, British Columbia” [26].

Appendix A: Additional Information

Mathematics of the Moisture Balance between the Indoor and Outdoor Air for Residential Buildings without Dehumidification

$$\dot{m}_{\text{indoor}} = \dot{m}_{\text{outdoor}} + \dot{m}_{\text{sources}} \tag{A1}$$

where:
$\dot{m}_{\text{indoor}}$ = moisture mass flux of indoor air (kg/s),
$\dot{m}_{\text{outdoor}}$ = moisture mass flux of the outdoor air (kg/s), and

$\dot{m}_{source}$=indoor moisture production (kg/s).

Separate moisture flux into the moisture content of air and ventilation

$$w_{indoor}Q_{ventilation} = w_{outdoor}Q_{ventilation} + \dot{m}_{sources} \quad (A2)$$

where:

w_{indoor}=indoor moisture content of air (kg/m^3),

$w_{outdoor}$=outdoor moisture content of air (kg/m^3), and

$Q_{ventilation}$=ventilation rate (m^3/s).

Use ideal gas law to convert units, $P_wV=wR_wT$,

$$\frac{(P_o - P_i) \times Q_{ventilation}}{R_wT} = \dot{m}_{sources} \quad (A3)$$

where:

w=mass of water vapor (g),

T=absolute temperature (K),

V=volume (m^3), and

R_w=0.4615 J/g·K.

Rearrange terms

$$\Delta VP = R_wT\frac{\dot{m}_{sources}}{Q_{ventilation}} \quad (A4)$$

Temperature Index

$$I = \frac{T_{surface} - T_{outside}}{T_{inside} - T_{outside}} \times 100 \quad (A5)$$

where:

I=temperature index (−),

$T_{surface}$=coldest temperature of the inside surface of a window,

$T_{outside}$=outdoor temperature, and

T_{inside}=indoor temperature.

BRE Model and Adjusted Parameters

The BRE Admittance Model, presented using consistent nomenclature, is as follows [3,4,8]:

$$\frac{dW_i}{dt} = \frac{Q_{source}}{\rho v} - I(W_i - W_o) - (\alpha W_i - \beta W_{sat}) \quad (A6)$$

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),

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

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

α,β=moisture admittance factors (h^{-1}).

For steady-state conditions this formulae reduces to the following [5]:

$$P_i = \frac{I}{I+\alpha}P_o + \frac{Q_{source}P_{total}}{0.622\rho v(I+\alpha)} + \frac{\beta P_{sat}}{I+\alpha} \quad (A7)$$

where:

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

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

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

TABLE 5—*Summary of parameters utilized in the BRE Model for Figs. 5 and 6.*

	Toronto (Fig. 5)	Vancouver–Building 3 (Fig. 6)
Temperature set point	15°C	11°C
Heating season	$RH_{avg}=22$ %	$RH_{avg}=57$ %
	$\alpha=0.6$	$\alpha=0.6$
	$\beta=0.6\times RH_{avg}=0.132$	$\beta=0.6\times RH_{avg}=0.342$
Non-heating season	$RH_{avg}=39$ %	$RH_{avg}=38$ %
	$\alpha=0.6$	$\alpha=0.6$
	$\beta=0.6\times RH_{avg}=0.234$	$\beta=0.6\times RH_{avg}=0.228$

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

Note that this steady-state equation equals the 160P approach equation when α and β are set to zero.

Moisture Storage of Indoor Hygroscopic Materials—Research on the moisture storage of indoor hygroscopic materials shows that the fluctuations in indoor humidity are greatly reduced by the building envelope and indoor furnishings. Estimates of up to 1/3 of the water vapor generated in a room can be absorbed by its surfaces [1]. 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 [3].

Jones [4] states that the BRE Admittance Model assumes that 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 millimetres deep responds to daily cycles. Consequently the BRE Admittance Model assumes that the moisture content of the indoor materials reaches 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 Summer and shoulder seasons for a mild marine climate such as Vancouver is likely to have more significance. Jones [4] predicts that six pairs of admit-

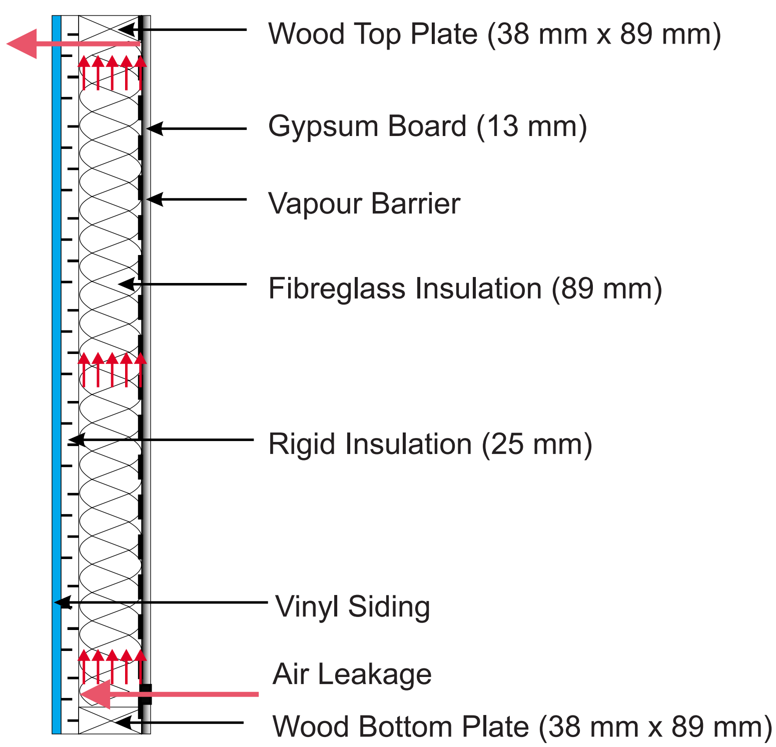

FIG. 12—*Model of wall assembly with* 38×89 *mm*^{2} *(*2×4*) studs.*

tance factors may be sufficient to model vapor 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 $\alpha=0.6$ and $\beta=0.4$ [3].

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 Eq A6) 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 [3]. For this approximation the parameter β is equivalent to $\alpha \cdot RH_s$, where RH_s is the RH at the surface of the building materials and furnishings. Jones [3] 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 vapor pressure changed significantly with temperature but the surface RH changed by less than 10 % over a period of 1 day. An approximation for the dependency of the vapor 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 α or β alone has only a small impact on the calculated indoor vapor pressure and the relative difference between the α and β (or RH_s) has a large impact. Since the admittance terms are dependent on the indoor vapor pressure, which is dependent on the outdoor vapor 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 in β relative to α will shift the calculated hourly indoor vapor 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 β relative to α or the assumed air temperature changes the assumed equilibrium air moisture content that balances whether absorption or desorption will occur.

Adjusted Parameters—The heating and non-heating α and β were selected separately to produce the calculated ΔVP using the BRE Model in Figs. 5 and 6. We adjusted the parameters between the heating or non-heating parameters based on the daily outdoor temperature. The heating parameters are used in the BRE model when temperature is below the set point and the non-heating parameters are used when the daily temperature is above the set point. The set point was selected on a single value that visually best fit the data. We kept α constant at 0.6 and selected β based on the mean measured indoor humidity for the appropriate season using the summarized data [Appendix B]. Table 5 summarizes our selected parameters.

This approach will slightly overestimate the ΔVP for a period during the shoulder seasons. We speculate that a robust empirical version of the BRE Model could be developed for use in a standard framework by creating a function for β dependent on the outdoor temperature and ΔVP limit. In our opinion this will require analysis of many monitored buildings, over several years, to determine the best shape of the function and best deflection points (daily, weekly, or monthly mean temperatures). A study that records window use, as well as the indoor and outdoor conditions, will be helpful in this pursuit.

Model Wall Assembly for Figs. 9 and 10

The wall assembly used in the simulations is based on wall assemblies that had been used previously for analysis of condensation from air leakage [28–30]. It is a cross-section of a wood stud wall with extruded polystyrene insulating sheathing, fiberglass insulation in the stud cavity, and a 60 $ng/(Pa \cdot s \cdot m^2)$ [1 perm] vapor barrier and painted gypsum wallboard on the interior surface. Wood stud top and bottom plates are included in the 2-D wall assembly as illustrated in Fig. 12.

Appendix B: Monitoring Data and Analysis

TABLE 6(a)—*Description of monitored Buildings 1, 2, and 3a.*

	Building		
	1	2	3a
Suite location	Suite 206 (south)	Suite 401 (southeast)	Suite 311 (east)
Location	Vancouver	Vancouver	Vancouver
Type	Four storey multi-unit residential	Four storey multi-unit residential	Six storey multi-unit residential
Year	Built 2000	Built 1987, rehabilitated walls and roof in 2000	Built 1990, rehabilitated walls in 2001
Glazing	2000 vinyl double glazed windows	2001 aluminum double glazed thermally broken windows	2001 aluminum double glazed thermally broken windows
Wall type	2×6 wood frame with batt, rainscreen stucco	2×6 wood frame with batt, rainscreen stucco	Concrete frame with steel stud infill and batt, exterior semi-rigid mineral fibre, stucco
Air barrier	6 mil poly	new SBPO housewrap+existing poly	SBS sheathing membrane
Interior vapor control	6 mil poly	4 mil poly	Latex paint
Number of bedrooms	2	1	2
Floor area (m^2)	80	64	63
Occupants	3 occupants	1 occupant	3 occupants
Exhaust and air leakage characteristics		NLA50=9.9 $in.^2/100\ ft^2$ @ 50 Pa exterior walls+roof, 81 % through envelope	44 CFM exhaust fan capacity on timer (approximately 6 h/day), NLA50=3.6 $in^2/100\ ft^2$ @ 50 Pa, 33 % through envelope

TABLE 6(b)—*Description of monitored Buildings 3a and 4.*

	Building		
	3b	4a	4b
Suite location	Suite 611 (east)	Suite 303 (south)	Suite 309 (north)
Location	Vancouver	Vancouver	Vancouver
Type	Six storey multi-unit residential	Four storey multi-unit residential	Four storey multi-unit residential
Year	Built 1990, rehabilitated walls in 2001	Built 2001	Built 2001
Glazing	2001 aluminum double glazed thermally broken windows	2001 aluminum double glazed thermally broken windows	2001 aluminum double glazed thermally broken windows
Wall type	concrete frame with steel stud infill and batt, exterior semi-rigid mineral fibre, stucco	2×4 wood frame with batt, cement board and stucco	2×4 wood frame with batt, cement board and stucco
Air barrier	SBS sheathing membrane	6 mil poly	6 mil poly
Interior vapor control	Latex paint	6 mil poly	6 mil poly
Number of bedrooms	2	Bachelor suite	Bachelor suite
Floor area (m^2)	63	24	24
Occupants	2 occupants home regularly	1 occupant	1 occupant
Exhaust and air leakage characteristics	50 CFM exhaust fan, occupant control, not used (noise), NLA50=6.0 $in^2/100\ ft^2$ @ 50 Pa, 36 % through envelope		NLA50=31.3 $in^2/100\ ft^2$ @ 50 Pa, 35 % through envelope

TABLE 6(c)—*Description of monitored Buildings 5 and 6.*

	Building		
	5a	5b	6a, 6b
Suite location	Suite 504 (south)	Suite 3005 (south)	Suite 205, Suite 304
Location	Vancouver	Vancouver	Toronto
Type	30 storey multi-unit residential	30 storey multi-unit residential	15 storey multi-unit residential
Year	Built 2002	Built 2002	Rehabilitated 1997
Glazing	2002 aluminum double glazed windows	2002 aluminum double glazed, window-wall	
Wall type	Concrete frame with steel stud infill, stucco wall with 50 mm exterior EXPS insulation	Window wall glazing	EIFS installed over masonry
Air barrier	SBS sheathing membrane	N/A	EIFS membrane
Interior vapor control	Latex paint	N/A	
Number of bedrooms	2	2	
Floor area (m^2)	50	50	
Occupants	Two occupants	Two occupants	
Exhaust and air leakage characteristics			

TABLE 7(a)—*Summary of monitoring data, indoor temperature (°C).*

		Building/Suite Identifier									
		1	2	3a	3b	4a	4a	5a	5b	6a	6b
Averages	January	23.7	18.1	16.2	17.2	23.5	22.7	23.8	20.4	23.4	22.1
	February	24.0	18.9	16.6	18.8	24.0	24.4	24.1	20.2	22.4	
	March	23.9	19.6	17.2	18.9	24.6	24.2	24.0	21.8	22.9	
	April	24.1	21.7	14.5	14.9		23.8	24.8	22.3	24.6	
	May	24.8	23.4	14.3	13.5	24.8	23.7	24.6	23.5	24.9	
	June	25.6	25.3	16.7	14.4	25.9	26.1	25.2	24.5	25.7	25.0
	July	26.5	27.2	17.2	15.4	27.9	27.3	25.2	24.5	27.5	26.2
	August	26.5	26.1	15.9	16.2	27.7	26.3	24.8	24.2	27.7	25.9
	September	25.7	26.0	16.0	15.2	26.4	25.0	9.4	9.0	25.5	23.4
	October	24.4	21.3	14.8	13.8	24.7	24.4	23.2	20.5	25.5	23.4
	November	24.2	18.4	21.0	21.1	22.7	23.8	11.8	9.9	23.7	24.2
	December	23.6	18.2	18.1	18.9	22.5	23.3	11.8	10.4	23.5	23.3
	Jan. 1–Mar. 31	23.9	18.9	16.7	18.3	24.0	23.8	24.0	20.8	22.9	
	April 1–Oct. 31	25.4	24.4	15.6	14.8		25.2	22.5	21.2	25.9	
	Nov. 1–Dec. 31	23.9	18.3	19.6	20.0	22.6	23.5	11.8	10.1	23.6	23.8
90th percentiles	January	25.6	20.4	17.5	18.9	25.2	25.2	25.2	22.1	24.1	23.7
	February	25.8	21.5	17.5	20.2	25.3	26.1	25.4	22.1	23.9	
	March	25.7	22.5	18.9	20.2	26.8	26.6	25.8	24.0	24.9	
	April	26.3	24.9	20.6	20.6		25.7	26.5	25.2	25.8	
	May	26.7	26.3	22.9	22.1	26.4	26.0	26.0	26.0	26.3	
	June	28.0	29.4	26.9	24.1	29.1	28.3	26.7	27.6	29.3	27.7
	July	29.5	31.9	28.3	25.6	31.1	29.1	26.6	27.3	28.8	28.1
	August	29.4	29.4	27.5	26.0	30.7	27.9	27.1	27.9	28.4	27.0
	September	28.7	29.3	26.0	26.0	28.8	26.7	24.2	24.4	26.6	25.4
	October	27.0	24.4	26.7	25.0	28.0	26.7	24.4	24.4	26.6	27.7
	November	25.9	21.1	25.6	24.7	24.8	26.2	24.0	20.6	25.5	25.2
	December	24.9	21.3	21.0	20.9	24.4	25.9	24.4	21.9	24.8	25.2
10th percentiles	January	22.1	16.0	14.5	15.2	22.1	16.0	22.2	18.7	21.8	20.6
	February	22.5	17.0	15.2	17.5	22.5	22.5	22.6	18.6	20.4	
	March	22.1	17.3	15.6	17.5	22.6	22.1	21.6	18.9	20.7	
	April	22.1	18.7				22.1	23.1	19.0	22.9	
	May	23.2	20.6			23.2	21.0	23.2	20.0	23.4	
	June	23.6	21.3			23.4	23.6	23.9	21.1	21.7	22.0
	July	23.9	23.2			24.5	25.4	23.9	21.7	26.4	24.4
	August	24.0	22.8			24.7	24.8	23.2	21.1	23.6	22.1
	September	23.5	22.8			24.3	23.3			22.0	20.9
	October	22.5	18.4			21.3	22.1			22.8	21.4
	November	22.9	15.8	17.1	18.3	20.6	21.0			22.9	17.5
	December	22.5	15.9	15.6	17.0	20.6	20.6			22.4	20.9

TABLE 7(b)—*Summary of monitoring data, indoor RH (%).*

		Building/Suite Identifier									
		1	2	3a	3b	4a	4a	5a	5b	6a	6b
Averages	January	42.7	45.1	62.3	62.4	30.3	33.1	36.5	31.6	21.4	20.1
	February	38.8	42.1	57.7	57.0	26.4	29.8	35.6	34.4	19.6	
	March	39.1	42.4	56.8	53.7	27.0	29.7	34.4	33.0	23.2	
	April	37.0	39.3	41.1	39.7		32.9	34.8	34.7	22.0	
	May	37.6	38.0	37.2	36.7	35.1	35.3	43.1	40.7	37.6	
	June	38.5	38.2	33.3	35.4	36.3	37.1	44.9	43.4	43.5	47.0
	July	40.8	40.1	27.8	30.1	37.9	40.8	48.7	47.4	43.3	46.2
	August	42.7	44.8	26.2	28.5	39.2	44.3	49.8	48.5	45.9	51.6
	September	44.5	41.8	31.4	29.1	41.3	43.5	19.9	18.9	43.1	48.3
	October	41.5	49.4	32.4	30.7	41.1	43.0	30.5	29.9	43.1	48.3
	November	41.0	39.8	52.2	52.7	31.7	32.7	17.3	15.6	24.8	23.2
	December	41.5	42.6	57.1	58.5	31.3	31.8	19.0	15.3	22.0	23.1
	Jan. 1–Mar. 31	40.2	43.2	58.9	57.7	27.9	30.9	35.5	33.0	21.4	
	April 1–Oct. 31	40.4	41.7	32.8	32.9		39.6	38.8	37.6	39.8	
	Nov. 1–Dec. 31	41.3	41.2	54.6	55.6	31.5	32.2	18.1	15.5	23.4	23.2
90th percentiles	January	48.3	52.1	70.3	68.3	37.6	41.6	43.3	40.8	29.7	31.8
	February	45.4	47.1	67.0	62.2	29.5	33.9	42.9	42.7	25.2	
	March	45.8	48.7	70.0	58.9	33.3	35.5	41.5	41.5	35.8	
	April	45.2	47.9	63.4	58.2		39.6	43.9	47.8	29.3	
	May	45.8	48.0	58.5	57.7	42.5	41.2	51.0	53.3	46.7	
	June	45.8	47.3	50.1	56.4	42.4	42.2	53.3	55.1	53.1	59.9
	July	48.3	47.5	46.7	51.0	45.1	45.6	55.7	57.2	53.4	60.5
	August	52.6	56.4	47.4	47.9	45.7	49.1	57.4	57.1	57.8	66.0
	September	52.3	48.6	53.4	50.8	48.4	47.8	54.7	52.5	56.6	61.6
	October	48.1	60.6	56.9	56.1	48.6	47.5	48.7	44.6	51.5	58.2
	November	49.4	47.2	63.3	64.4	40.8	38.7	39.9	37.5	29.6	30.7
	December	46.9	47.8	66.0	65.0	35.8	37.1	42.4	34.8	29.3	29.0
10th percentiles	January	37.5	34.5	53.1	55.6	21.7	22.0	28.4	19.3	15.1	11.6
	February	31.9	35.6	47.4	51.5	22.5	24.4	28.7	26.4	14.8	
	March	32.2	36.1	43.8	47.9	21.5	23.0	27.6	24.8	13.7	
	April	27.5	30.2				27.0	27.2	24.7	15.2	
	May	30.2	30.5			28.9	29.9	34.7	30.0	26.5	
	June	30.4	30.3			30.2	32.3	37.0	32.0	26.5	26.6
	July	33.5	32.9			31.5	35.5	42.2	39.0	33.2	33.5
	August	33.6	34.8			32.8	39.5	42.2	40.4	35.8	38.7
	September	36.3	34.2			33.6	38.7			33.9	32.7
	October	33.8	39.4			30.9	36.6			21.3	16.1
	November	32.8	32.7	41.3	42.8	22.2	25.6			15.9	16.2
	December	36.3	36.6	48.5	51.2	25.8	27.1			17.3	13.4

TABLE 7(c)—*Summary of monitoring data, indoor vapor pressure (Pa).*

		Building/Suite Identifier									
		1	2	3a	3b	4a	4a	5a	5b	6a	6b
Averages	January	1251.8	944.6	1151.4	1222.7	881.8	911.9	1085.0	762.9	611.8	545.1
	February	1155.1	921.3	1090.2	1240.6	786.3	914.2	1078.3	813.4	535.7	
	March	1154.6	966.9	1121.4	1171.3	831.2	902.6	1036.7	852.6	665.1	
	April	1104.4	1013.3	1139.7	1144.6		970.0	1093.3	924.0	679.9	
	May	1172.3	1087.5	1197.4	1092.6	1102.1	1048.1	1335.5	1160.7	1197.0	
	June	1252.9	1218.2	1054.0	907.0	1214.8	1253.7	1443.1	1322.6	1484.8	1535.1
	July	1404.0	1443.4	963.3	857.6	1428.5	1484.6	1559.8	1446.7	1599.3	1575.5
	August	1469.0	1496.0	892.7	871.3	1454.0	1515.3	1563.3	1461.9	1706.8	1734.4
	September	1461.9	1394.0	931.4	864.1	1420.9	1381.2	1457.6	1300.6	1421.3	1405.1
	October	1271.0	1264.9	878.1	812.9	1291.1	1317.0	899.9	745.7	1421.3	1405.1
	November	1229.9	840.7	1295.0	1306.8	868.2	970.7	972.9	695.9	728.9	702.6
	December	1211.8	895.5	1197.5	1282.2	852.1	914.9	1103.7	745.4	646.8	663.9
	Jan. 1–Mar. 31	1187.2	944.3	1121.0	1211.6	833.1	909.5	1066.6	809.6	604.2	
	April 1–Oct. 31	1305.1	1273.9	1008.1	935.7		1281.4	1336.1	1194.6	1358.6	
	Nov. 1–Dec. 31	1220.8	868.1	1246.2	1294.5	860.1	942.8	1038.3	720.7	687.8	683.3
90th percentiles	January	1398.3	1117.1	1329.2	1373.6	1130.5	1156.5	1349.4	990.8	887.6	907.6
	February	1319.8	1052.1	1229.9	1368.5	895.0	1062.4	1348.0	998.1	711.6	
	March	1328.7	1118.6	1438.3	1313.0	984.1	1106.6	1328.1	1025.1	1130.8	
	April	1308.6	1215.8	1299.9	1282.1		1178.1	1417.7	1163.9	884.1	
	May	1399.2	1272.8	1505.4	1301.3	1381.8	1304.9	1596.8	1356.2	1525.3	
	June	1439.0	1424.1	1569.7	1320.0	1411.9	1455.1	1742.6	1632.1	1981.6	2055.1
	July	1611.4	1681.5	1638.5	1533.3	1692.3	1738.4	1753.6	1649.5	2015.3	2136.8
	August	1687.9	1702.2	1621.9	1495.2	1677.4	1728.8	1823.3	1721.4	2193.0	2218.5
	September	1685.8	1591.8	1553.9	1528.4	1677.1	1563.9	1680.5	1448.7	1888.9	1878.0
	October	1489.1	1573.3	1520.2	1441.3	1656.2	1528.8	1633.0	1448.2	1741.3	1802.7
	November	1462.8	993.8	1538.0	1463.7	1098.3	1235.5	1243.2	927.7	913.4	865.1
	December	1355.4	1046.6	1534.6	1519.9	975.3	1144.1	1350.2	897.9	879.5	764.9
10th percentiles	January	1116.0	684.9	938.3	1060.2	616.3	627.9	767.4	457.3	411.9	284.0
	February	975.1	811.2	927.5	1097.6	672.2	745.7	809.5	653.9	382.8	
	March	996.6	831.6	832.3	999.5	683.9	637.4	788.9	676.6	361.8	
	April	871.4	841.8	950.1	997.3		795.1	834.7	708.0	473.6	
	May	967.5	891.5	911.3	909.0	905.9	778.8	1060.5	960.0	788.6	
	June	1077.9	1025.2			997.6	1054.1	1172.8	1043.0	729.1	702.0
	July	1188.0	1191.5			1151.3	1227.1	1370.4	1230.8	1171.8	1097.5
	August	1253.3	1313.8			1254.2	1319.7	1303.2	1210.2	1272.6	1197.7
	September	1229.0	1239.2			1174.6	1189.5	1246.1	1082.9	1032.6	876.9
	October	1074.7	862.1			958.2	1115.2	556.7	405.0	612.6	553.1
	November	1029.1	654.7	995.7	1147.8	624.2	716.2	684.2	444.7	483.1	403.6
	December	1078.5	748.9	905.0	1060.0	725.1	716.4	852.7	584.3	486.2	344.9

TABLE 7(d)—*Summary of monitoring data, vapor pressure difference* (ΔVP, *Pa*).

		Building/Suite Identifier									
		1	2	3a	3b	4a	4a	5a	5b	6a	6b
Averages	January	456.5	128.1	331.2	402.6	98.4	151.7	298.2	−24.0	166.1	83.1
	February	408.2	147.6	316.4	466.8	−13.7	164.9	303.2	38.3	86.1	
	March	368.6	108.1	338.8	388.7	−26.2	124.1	180.9	−3.2	74.7	
	April	199.9	81.4	195.1	198.9		82.3	152.6	−16.7	51.1	
	May	107.9	−43.0	119.2	40.4	−90.7	−33.5	205.4	30.6	−81.0	
	June	−25.3	−111.1	86.3	−60.6	−78.0	−50.1	108.1	−12.4	−102.1	−67.8
	July	−78.1	−111.5	30.3	−116.0	−74.0	−21.6	4.4	−108.7	−66.3	−90.1
	August	−49.0	−58.1	39.4	−86.4	−44.1	17.8	4.9	−96.5	−56.0	−28.3
	September	14.9	−8.8	26.3	4.1	62.6	22.9	102.1	−90.6	28.7	16.0
	October	108.0	36.0	140.2	135.6	79.6	84.7	175.7	12.2	28.7	16.0
	November	362.0	65.4	300.5	308.4	24.1	178.2	264.2	−12.7	88.5	62.2
	December	463.3	76.6	280.2	336.7	74.7	151.5	359.0	0.7	54.7	71.2
	Jan. 1–Mar. 31	411.1	127.9	328.8	419.4	19.5	146.9	260.7	3.7	109.0	
	April 1–Oct. 31	39.8	−30.7	91.0	16.6		14.6	107.6	−40.3	−28.1	
	Nov. 1–Dec. 31	412.6	71.0	290.4	322.5	49.4	164.8	311.6	−6.0	71.6	66.7
90th percentiles	January	720.4	319.8	519.1	617.0	296.5	373.8	683.5	111.4	315.5	206.4
	February	611.0	285.4	513.2	626.6	121.3	396.1	666.6	316.1	235.2	
	March	588.8	272.4	582.5	571.7	119.9	320.9	500.2	183.9	237.1	
	April	470.2	295.1	408.0	452.6		288.8	518.3	252.1	233.4	
	May	329.9	116.6	395.0	317.6	118.7	221.2	615.2	387.5	149.2	
	June	203.8	41.6	285.0	104.1	143.6	168.3	492.9	348.1	89.3	97.7
	July	112.7	56.2	193.7	58.7	228.3	236.1	322.6	176.9	217.8	76.0
	August	143.6	72.4	202.8	91.5	145.9	230.8	276.1	144.7	221.5	130.0
	September	204.8	0.0	182.1	164.4	320.7	204.8	343.1	100.9	259.2	170.5
	October	357.5	179.2	462.1	473.0	334.8	303.1	394.9	102.4	245.4	157.6
	November	587.9	240.0	859.4	759.0	204.1	395.9	581.5	78.0	256.6	151.5
	December	658.8	251.9	725.6	702.9	223.4	404.4	654.0	83.4	352.9	179.6
10th percentiles	January	235.4	−51.3	151.7	210.0	−49.8	−74.6	−42.9	−193.0	13.2	−47.2
	February	206.9	11.5	118.4	303.7	−123.5	−15.7	−11.5	−140.0	−32.4	
	March	169.6	−47.5	121.9	213.6	−157.0	−67.0	−103.0	−173.3	−94.4	
	April	−100.5	−113.1	0.0	0.0		−146.5	−147.8	−245.8	−103.0	
	May	−127.0	−186.4	−12.1	−168.5	−262.9	−265.0	−130.2	−222.4	−309.4	
	June	−290.5	−315.7	−60.7	−296.8	−332.2	−305.1	−219.4	−307.2	−291.0	−251.7
	July	−285.2	−277.6	−91.7	−451.1	−330.7	−275.5	−283.5	−384.7	−287.8	−250.3
	August	−249.5	−196.5	−64.7	−401.1	−239.6	−196.1	−287.2	−384.4	−262.4	−173.5
	September	−184.2	−65.4	−107.3	−152.9	−171.7	−158.9	−94.7	−326.9	−182.7	−157.3
	October	−123.9	−34.5	−6.6	−7.1	−153.5	−125.6	−78.7	−122.7	−155.4	−146.4
	November	149.5	0.0	0.0	0.0	−131.8	−30.9	−2.7	−102.4	−78.6	−85.7
	December	276.4	0.0	0.0	0.0	−80.6	−42.6	67.8	−72.8	−33.0	−58.7

TABLE 7(e)—*Summary of monitoring data, indoor dew point temperature (°C).*

		Building/Suite Identifier									
Dew Point (°C)		1	2	3a	3b	4a	4a	5a	5b	6a	6b
Averages	January	10.3	5.9	8.9	9.9	4.8	5.3	7.8	2.4	−0.6	−2.7
	February	9.0	5.7	8.2	10.1	3.4	5.6	7.9	3.8	−2.3	
	March	9.0	6.4	8.4	9.3	4.2	5.2	7.3	4.5	0.1	
	April	8.3	7.1	8.8	8.9		6.4	8.0	5.6	1.0	
	May	9.2	8.1	9.2	7.9	10.3	7.4	11.1	9.1	9.2	
	June	10.2	9.8	12.0	9.7	9.7	10.2	12.3	11.0	12.1	12.5
	July	12.0	12.4	12.8	10.6	12.3	12.8	13.6	12.4	13.8	13.4
	August	12.6	12.9	12.7	10.9	11.8	13.1	13.6	12.5	14.8	14.8
	September	12.6	11.9	11.9	11.4	12.1	11.7	12.4	10.6	11.9	
	October	10.4	10.1	11.1	10.8	10.4	11.0	4.4	1.1	11.9	
	November	9.9	4.3	10.7	10.9	4.7	6.3	6.3	1.4	2.2	1.7
	December	9.8	5.3	9.4	10.5	4.6	5.5	8.2	2.6	0.1	0.4
	Jan. 1–Mar. 31	9.4	6.0	8.5	9.8	4.1	5.3	7.7	3.6	−0.9	
	April 1–Oct. 31	10.8	10.3	11.2	10.0		10.4	10.8	8.9	10.7	
	Nov. 1–Dec. 31	9.9	4.8	10.0	10.7	4.6	5.9	7.2	2.0	1.2	1.0
90th percentiles	January	12.0	8.6	11.2	11.7	8.8	9.1	11.4	6.9	5.3	5.6
	February	11.1	7.7	10.1	11.7	5.4	7.9	11.4	7.0	2.1	
	March	11.2	8.6	12.4	11.0	6.8	8.5	11.2	7.4	8.8	
	April	11.0	9.9	10.9	10.7		9.4	12.2	9.2	5.2	
	May	12.0	10.6	13.1	10.9	13.3	10.9	14.0	11.5	13.3	
	June	12.4	12.3	14.0	11.4	12.2	12.6	15.4	14.3	17.4	17.9
	July	14.2	14.8	14.7	13.7	15.4	15.3	15.5	14.5	17.6	18.6
	August	14.9	15.0	14.7	13.4	13.9	15.2	16.1	15.2	19.0	19.2
	September	14.8	14.0	13.9	13.7	14.8	13.7	14.8	12.1	16.6	
	October	12.9	13.8	13.5	12.8	14.6	13.3	13.8	11.7	15.3	
	November	12.7	6.9	13.4	12.7	8.4	10.1	10.2	5.9	5.7	4.9
	December	11.5	7.7	13.4	13.3	6.6	9.0	11.5	5.4	5.1	3.1
10th percentiles	January	8.6	1.6	6.1	7.9	0.1	0.4	3.1	−4.0	−5.4	−10.4
	February	6.6	4.0	5.9	8.4	1.3	2.8	3.9	0.9	−6.4	
	March	6.9	4.3	4.3	7.0	1.5	0.6	3.6	1.4	−7.2	
	April	5.0	4.5	6.3	7.0		3.7	4.4	2.0	−3.5	
	May	6.5	5.3	5.6	5.6	7.3	3.4	7.9	6.4	3.6	
	June	8.1	7.4	10.1	7.9	6.5	7.8	9.3	7.6	2.4	1.9
	July	9.5	9.6	10.6	7.8	8.5	10.0	11.7	10.1	9.3	8.4
	August	10.3	11.0	10.6	8.5	9.8	11.1	10.9	9.8	10.6	9.7
	September	10.0	10.2	9.7	9.1	9.4	9.6	10.1	8.0	7.5	
	October	8.1	4.8	8.2	8.4	6.4	8.6	−3.3	−7.7	0.0	
	November	7.4	0.9	6.9	9.0	0.3	2.2	1.6	−4.4	−3.3	−5.7
	December	8.1	2.8	5.5	7.9	2.4	2.2	4.7	−0.7	−3.2	−7.8

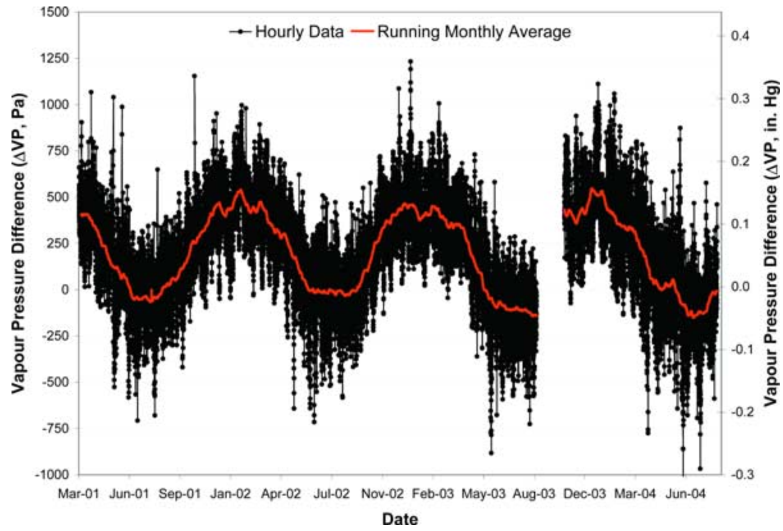

FIG. 13—*Vancouver, Building 1: Vapor pressure difference (ΔVP, Pa).*

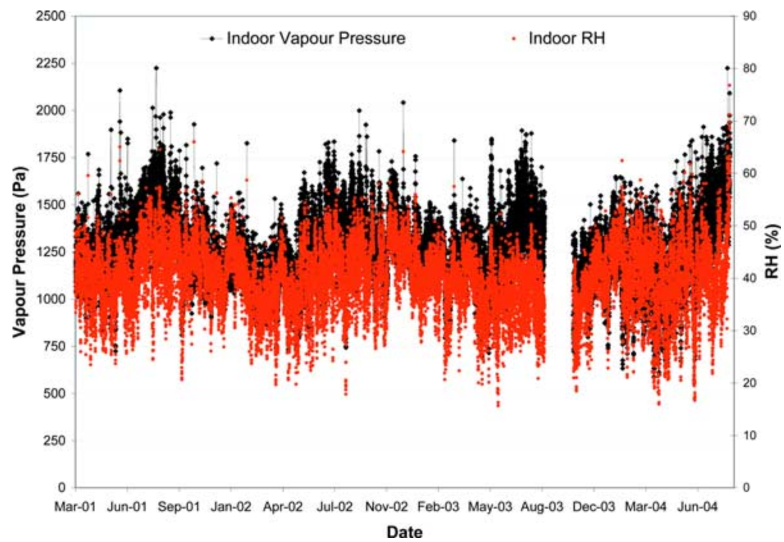

FIG. 14—*Vancouver, Building 1: Indoor vapor pressure (Pa) and RH (%).*

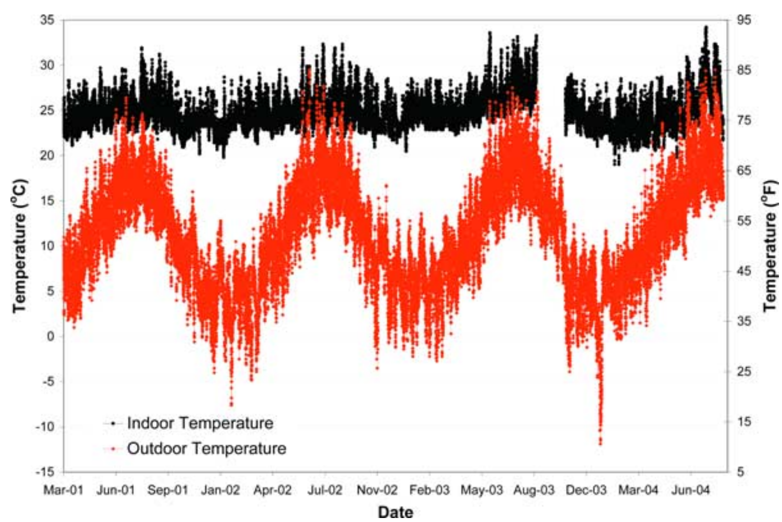

FIG. 15—*Vancouver, Building 1: Indoor and outdoor temperatures (°C).*

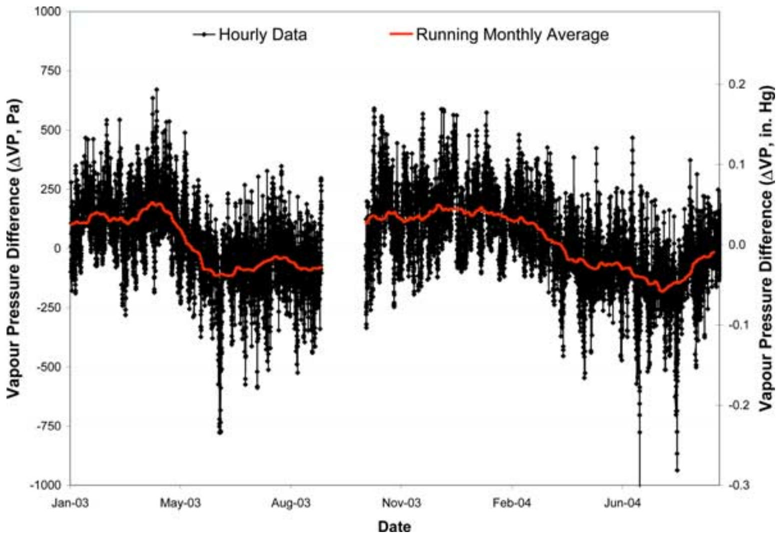

FIG. 16—*Vancouver, Building 2: Vapor pressure difference (ΔVP, Pa).*

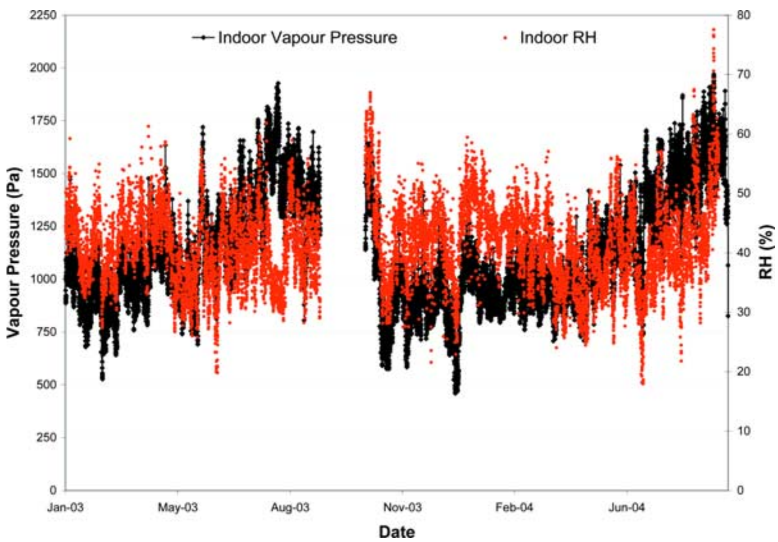

FIG. 17—*Vancouver, Building 2: Indoor vapor pressure (Pa) and RH (%).*

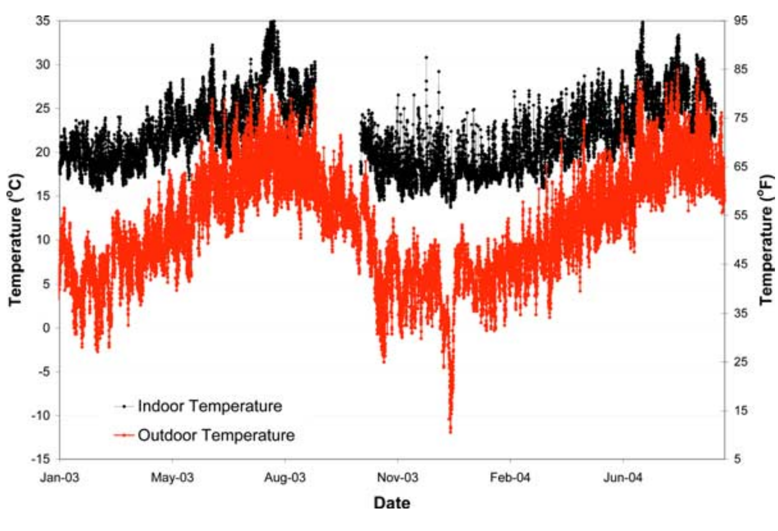

FIG. 18—*Vancouver, Building 2: Indoor and outdoor temperatures (°C).*

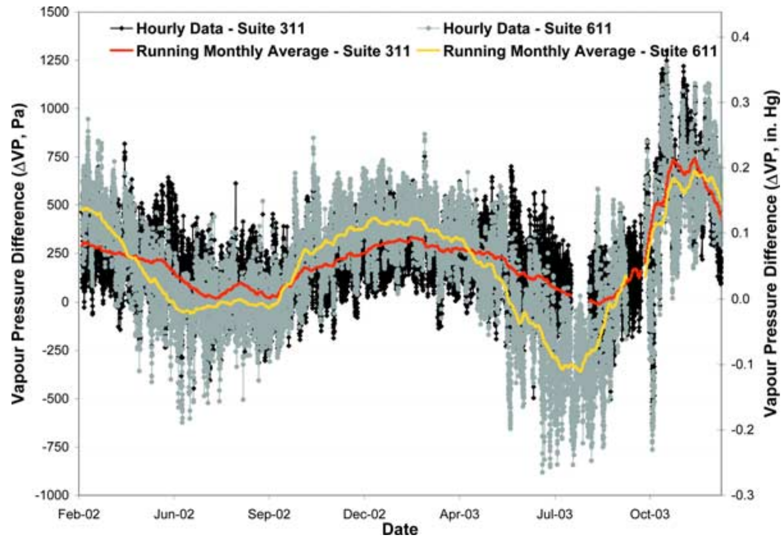

FIG. 19—*Vancouver, Building 3: Vapor pressure difference (ΔVP, Pa).*

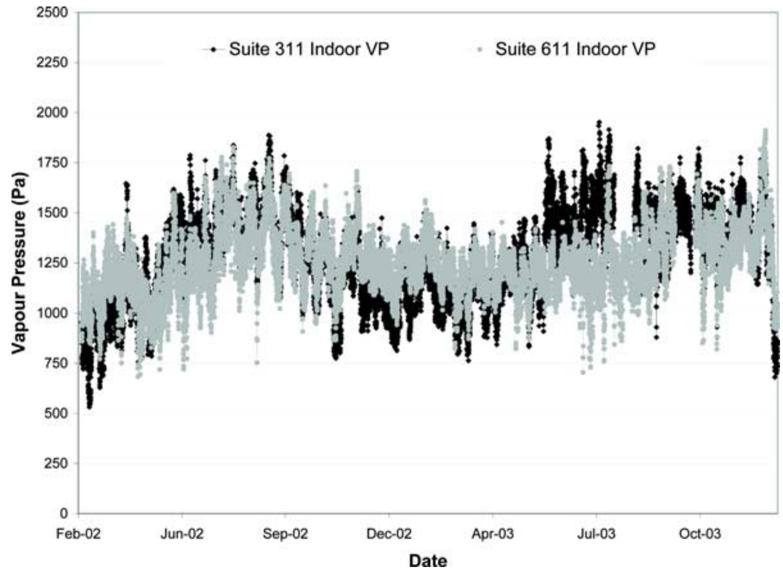

FIG. 20—*Vancouver, Building 3: Indoor vapor pressure (Pa).*

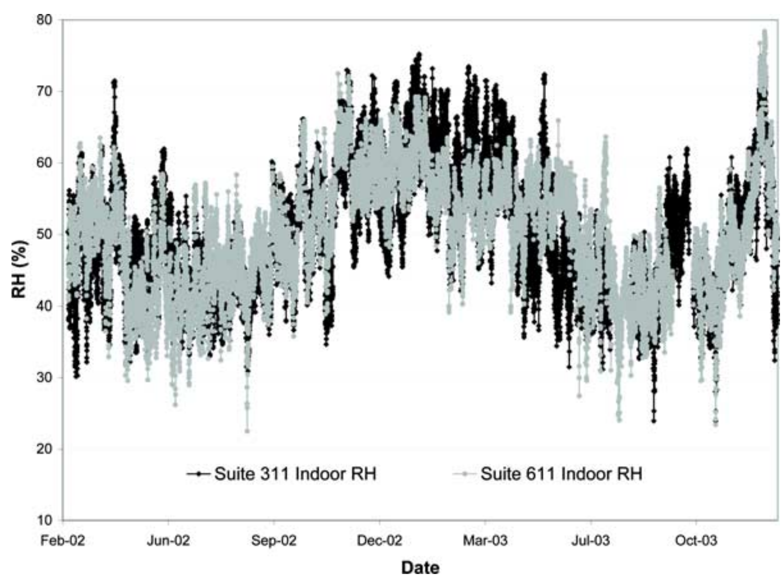

FIG. 21—*Vancouver, Building 3: Indoor RH (%).*

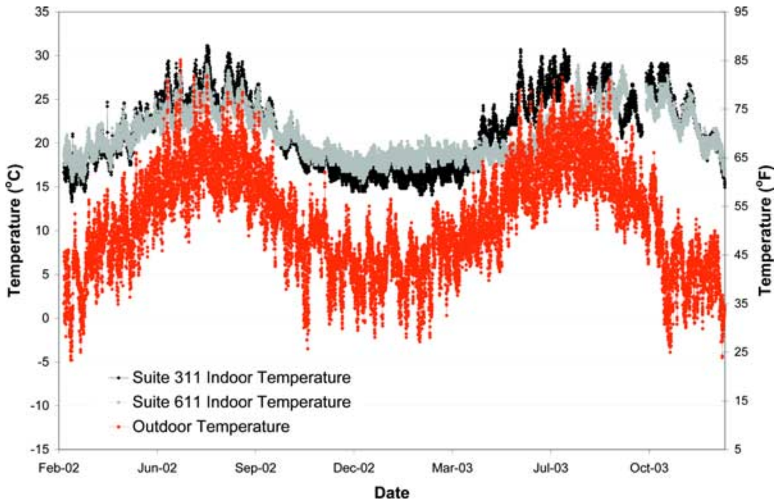

FIG. 22—*Vancouver, Building 3: Indoor and outdoor temperatures (°C).*

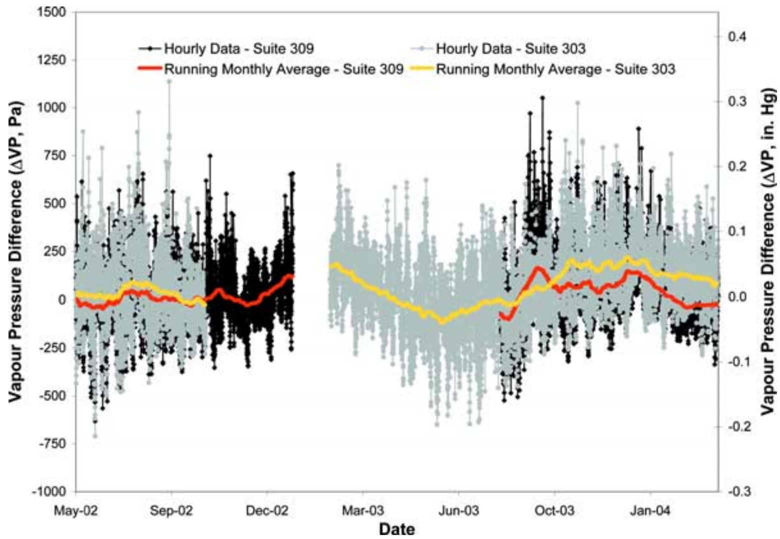

FIG. 23—*Vancouver, Building 4: Vapor pressure difference (ΔVP, Pa).*

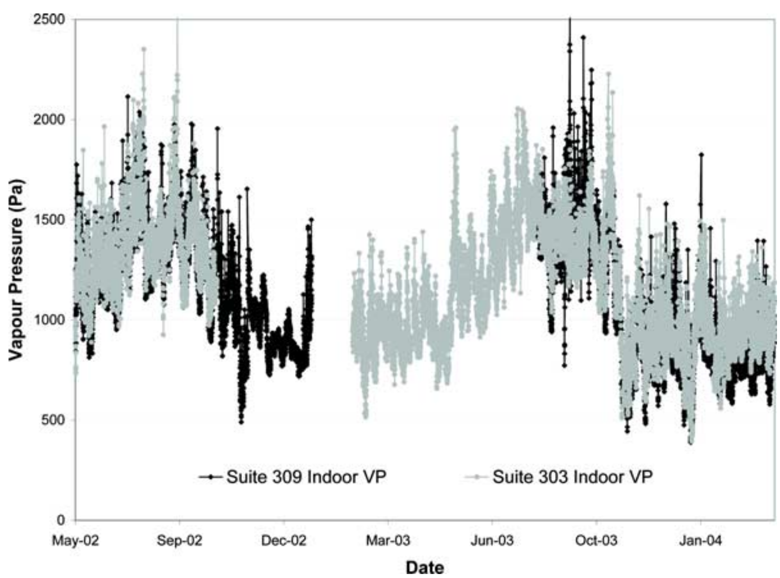

FIG. 24—*Vancouver, Building 4: Indoor vapor pressure (Pa).*

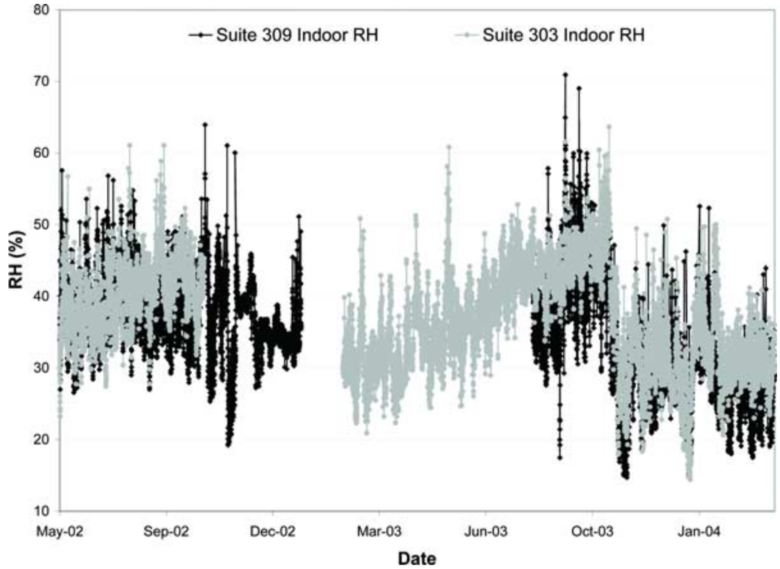

FIG. 25—*Vancouver, Building 4: Indoor RH (%).*

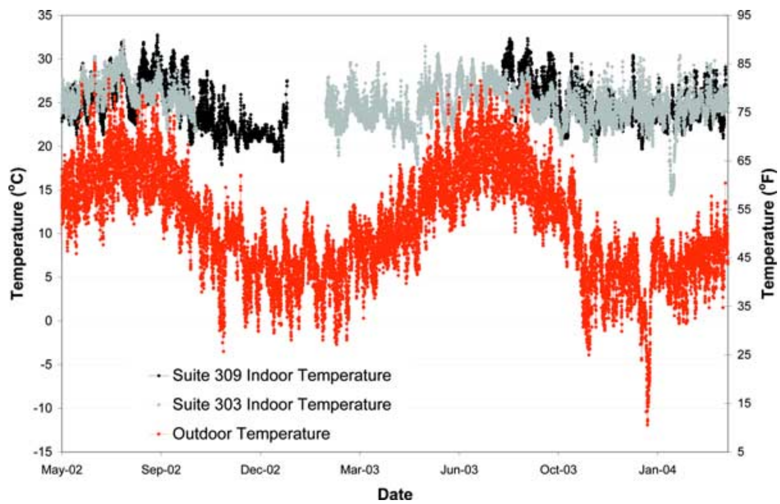

FIG. 26—*Vancouver, Building 4: Indoor and outdoor temperatures (°C).*

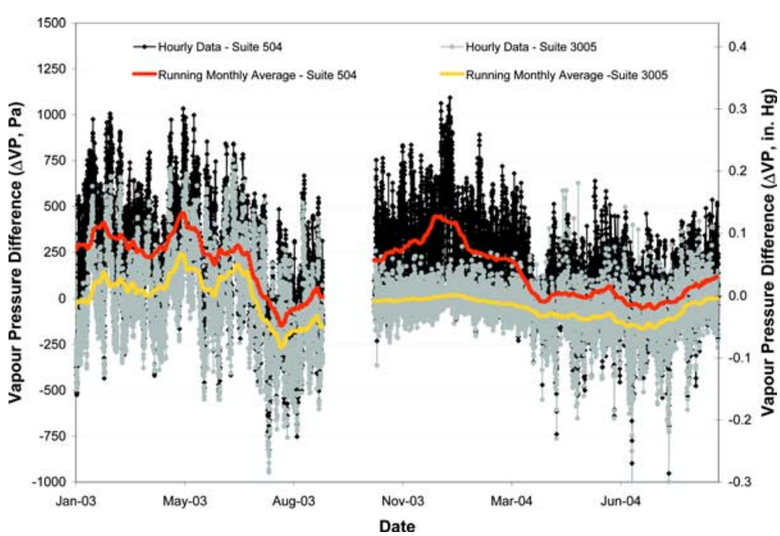

FIG. 27—*Vancouver, Building 5: Vapor pressure difference (ΔVP, Pa).*

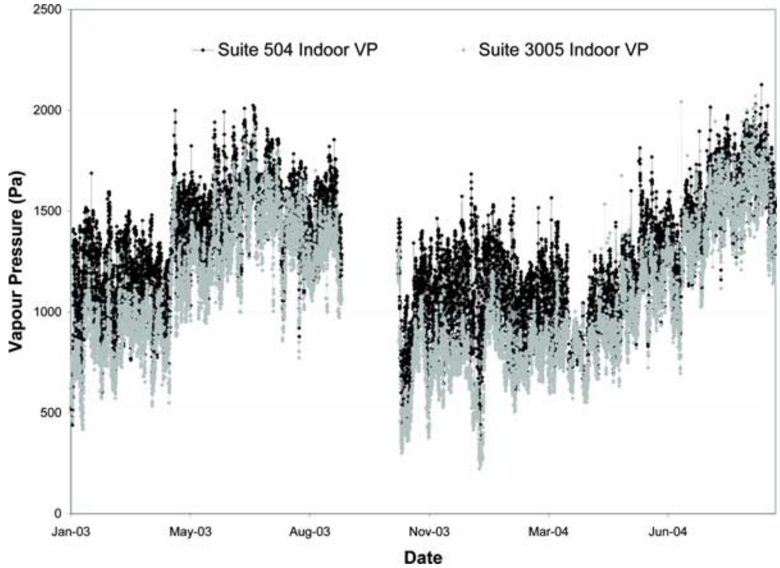

FIG. 28—*Vancouver, Building 5: Indoor vapor pressure (Pa).*

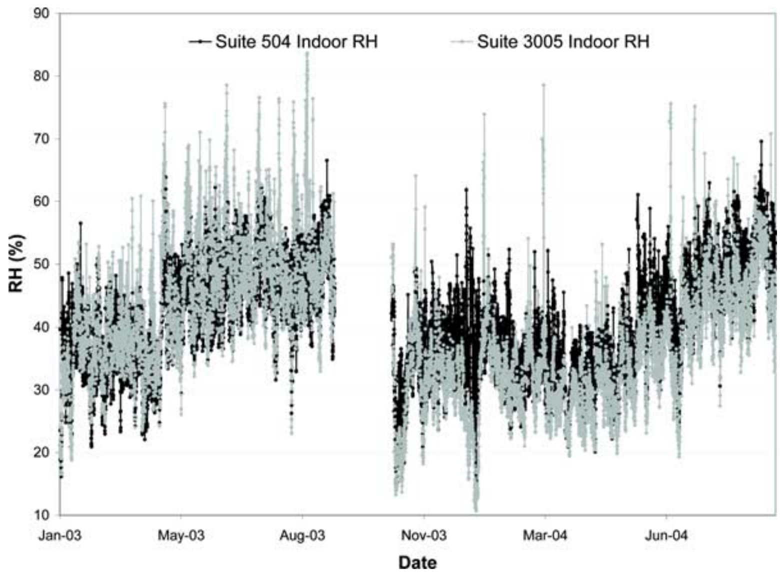

FIG. 29—*Vancouver, Building 5: Indoor RH (%).*

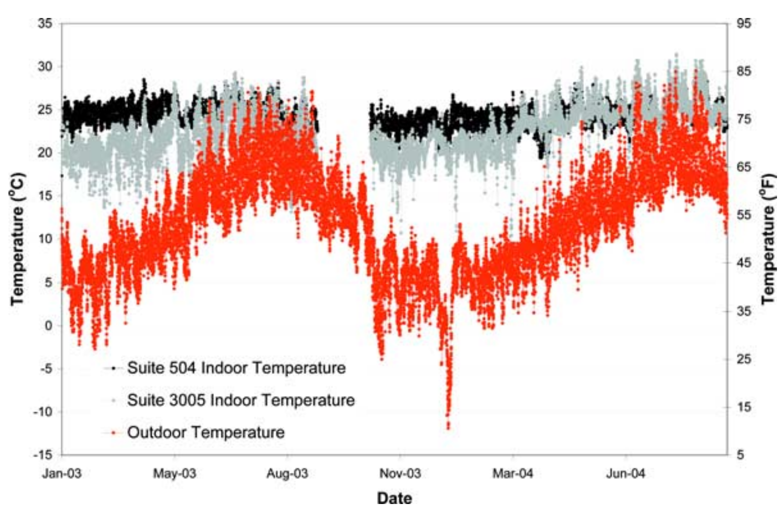

FIG. 30—*Vancouver, Building 5: Indoor and outdoor temperatures (°C).*

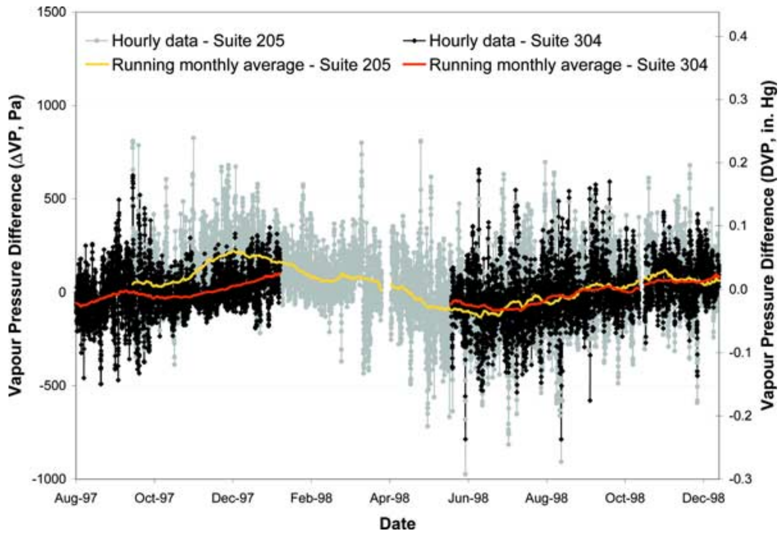

FIG. 31—*Toronto, Building 6: Vapor pressure difference (ΔVP, Pa).*

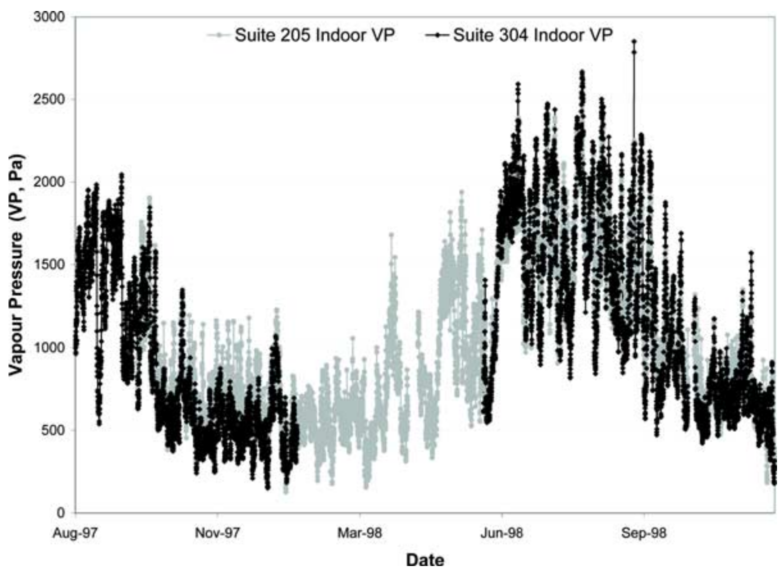

FIG. 32—*Toronto, Building 6: Indoor vapor pressure (Pa).*

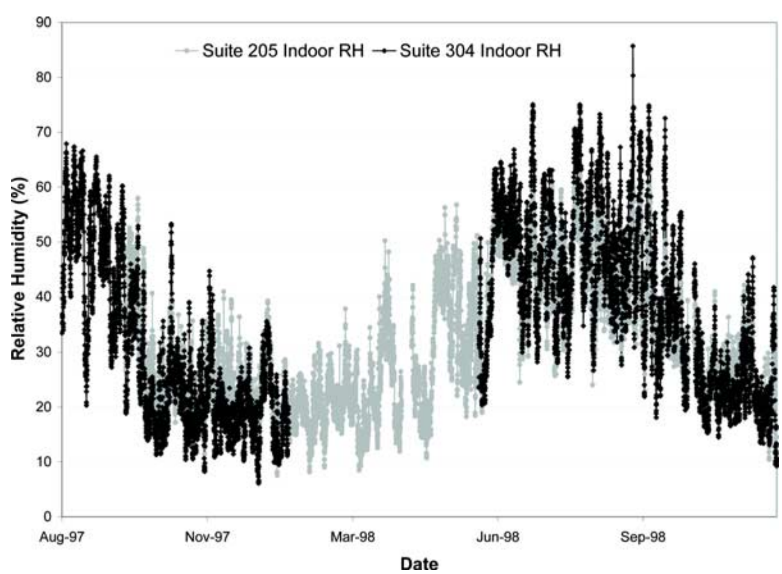

FIG. 33—*Toronto, Building 6: Indoor RH (%).*

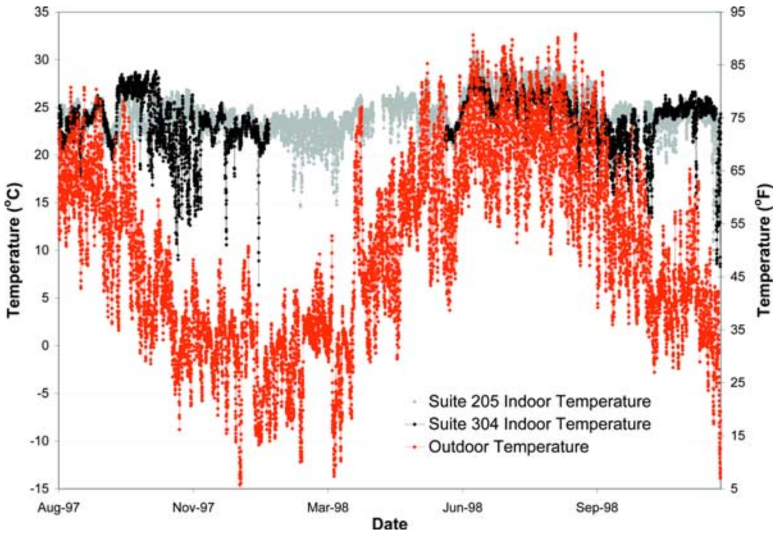

FIG. 34—*Toronto, Building 6: Indoor and outdoor temperatures (°C).*

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