REVIEW OF MOISTURE BALANCE MODELS FOR RESIDENTIAL INDOOR HUMIDITY

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ABSTRACT

Moisture balance models for indoor humidity have been developed and used by researchers and practitioners to generate realistic interior humidity conditions for hygrothermal analysis of building envelopes and to analyze humidity levels and moisture production rates. This paper reviews moisture balance models for residential indoor humidity in cold-climates. We provide background on various simplified approaches to handling water vapor exchange (buffering) with hygroscopic materials in contact with indoor air. We discuss the application of models in actual occupied buildings, comparing modeled indoor humidity values with measured values and describing how models have been used to estimate moisture production rates. We show that there is rather large variability in moisture production rates and argue that the combined uncertainty in moisture production and air exchange rates warrants the use of simple models for moisture buffering. Finally, we evaluate the time scale for which moisture buffering is significant, concluding that the data currently support only short-term effects.

RÉSUMÉ

On a mis au point des modèles de balance de mesure de l’humidité à l’intérieur que des chercheurs et des intervenants ont utilisés pour générer des conditions d’humidité intérieures réalistes, aux fins de l’analyse hygrothermique des enveloppes de bâtiment et de l’analyse des niveaux hygrométriques et des taux de production d’humidité. Ce document examine les modèles de balance de mesure de l’humidité à l’intérieur dans les constructions résidentielles en climats froids. Nous y fournissons les antécédents de diverses méthodes simplifiées permettant de réguler l’échange de vapeur d’eau au moyen de matières hygroscopiques (matériau tampon) mises en contact avec l’air intérieur. Nous traitons également de l’application de modèles dans des bâtiments effectivement occupés, en comparant les valeurs d’humidité intérieure modélisées aux valeurs mesurées et en décrivant comment on a utilisé les modèles pour estimer les taux de production d’humidité. Il est démontré ici qu’il existe une variabilité plutôt importante dans les taux de production d’humidité et avancé que l’incertitude combinée relativement à ces taux ainsi qu’aux taux de renouvellement d’air justifie l’utilisation de modèles simples de capacité tampon. Enfin, nous évaluons l’échelle de temps pour laquelle la capacité tampon de l’humidité est significative et en concluons qu’à l’heure actuelle, les données n’admettent que des effets à court terme.

INTRODUCTION

Proper management of indoor humidity in buildings is an essential aspect of durability. In cold climates, excessive indoor humidity can lead to moisture accumulation with its many unwanted consequences. These include growth of mold and mildew, poor indoor air quality and potential health problems for the occupants, loss of thermal resistance, damage to materials from dimensional changes, failure of paints and finishes, and deterioration of materials to the point of structural failure. Although moisture accumulation in building assemblies from liquid water intrusion can cause the most severe problems, management of indoor humidity is nonetheless critical. Many studies have shown that moisture problems in cold climates often relate to indoor humidity levels in winter (e.g. Hansen 1984, Glass and TenWolde 2007).

Moisture engineering is an emerging discipline that concerns hygrothermal analysis of building envelopes. The discipline typically involves use of advanced models that simulate transient heat, air, and moisture

(HAM) transfer to evaluate the performance of building envelope assemblies. These models have multiple input parameters, among which are boundary conditions or design loads. The results of hygrothermal analyses performed with these models depend strongly on the boundary conditions. In particular, the assumed interior humidity levels have been consistently shown to influence the results of analyses (Ojanen and Kumaran 1992, Tsongas et al. 1995, Djebbar et al. 2001, TenWolde and Walker 2001, Aoki-Kramer and Karagiozis 2004, Karagiozis et al. 2007, Kumaran and Sanders 2008, Holm 2008). Unless measured conditions are available, realistic estimates of the boundary conditions are thus needed. This manuscript reviews a number of approaches to estimating indoor humidity levels in cold-climate residential buildings using moisture balance models.

Moisture balance modeling is based on conversation of mass of water vapor. Models generally consider sources, sinks, and water vapor exchange with hygroscopic materials in contact with the air, including the building structure and furnishings. Models differ in the level of complexity with which they handle these various mechanisms. For example, the ASHRAE draft standard 160P, *Criteria for Moisture-Control Design Analysis in Buildings* (ASHRAE 2008), incorporates three alternative methodologies to arrive at design indoor humidity levels, two of which are based on moisture balance.[1] For simplicity, the "Intermediate Method" accounts for moisture buffering by using 24-h running average outdoor vapor pressures. The "Full Parametric Calculation" option allows the user to employ a more sophisticated model for dynamic hygrothermal response. Both methods require design rates for moisture production and air exchange.

Researchers and practitioners have developed and applied moisture balance models for various intents besides defining indoor humidity levels for HAM analysis. Related applications include predicting whether mold growth or condensation will occur on interior surfaces (Oreszczyn and Pretlove 1999, Lucas and Miranville 2004) and evaluating the relationship between indoor humidity and different methods of ventilation (Barringer and McGugan 1989; TenWolde 1994; Walker and Sherman 2007). Recent work has focused on an integrated approach to whole-building HAM performance, with applications relating to occupant comfort, indoor air quality, energy, and durability (Holm 2008). A great deal of effort has been devoted to advancing whole-building models and precise descriptions of moisture buffering. However, the accuracy of any model prediction depends on the quality of the input parameters.

The objectives of this paper include the following:

1. Review the moisture balance modeling approach and various methods for describing moisture buffering;
2. Compare humidity levels measured in occupied buildings with modeled values and describe how models have been used to determine moisture production rates;
3. Assess the uncertainties in air exchange and moisture production rates and the implications; and
4. Evaluate the time scale for which moisture buffering is significant for modeling humidity levels in occupied houses.

MOISTURE BALANCE MODELS

MODELING APPROACH

The usual approach in modeling indoor humidity is to define a "zone" and to assume that the conditions of temperature, humidity, and air pressure are uniform. While multi-zone models have been developed (e.g. El Diasty et al. 1993, Tsuchiya and Sakano 1993, Plathner and Woloszyn 2002), we limit the scope of our discussion to modeling a single zone, defined as the indoor air of building. When applying conservation of mass to the water vapor in the zone, we need to consider water vapor gains, water vapor removal,

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[1] The "Simplified Method" (not a moisture balance method) prescribes 40% relative humidity (RH) for outdoor temperatures below –10°C (14°F), and 70% RH for outdoor temperatures above 20°C (68°F). This approach is based on measurements in Europe and is similar to European standards. Holm (2008) describes several other simplified methods for defining indoor humidity levels.

and water vapor exchange with hygroscopic materials in contact with the air, including the building structure and furnishings.

Many sources potentially contribute water vapor, including occupants and their activities (respiration, transpiration, showering, bathing, dishwashing, cleaning, cooking, washing and drying clothes), pets, plants, mechanical humidifiers, and evaporation from wet foundations. We lump these sources together into an apparent moisture production rate (kg s–1).

Water vapor removal may also occur through a number of routes. Here we consider only air exchange and denote (m^3 s^{-1}) the effective volume flow rate of outdoor air, including infiltration and mechanical ventilation. We ignore air conditioning and dehumidification equipment, condensation on interior surfaces (e.g. windows), and diffusion through the building envelope. Neglecting diffusion is justified for the majority of North American residences in heating climates because the quantity of water vapor carried by air exchange is in most practical cases much greater than that carried by diffusion (TenWolde 1993).[2]

For water vapor exchange with hygroscopic materials, we define a moisture sorption rate (kg s^{-1}), which is positive for absorption and negative for desorption.

Under non-steady conditions, the moisture balance can be expressed in terms of absolute humidity (water vapor concentration, i.e., mass of water vapor per volume of air) by

$$V\frac{dc_i}{dt} = \dot{m}_{prod} - \dot{V}_a\left(c_i - c_o\right) - \dot{m}_{sorp} \qquad (1)$$

where *V* is the volume of air in the zone (m^3), c_i and c_o are the water vapor concentrations (kg m^{-3}) of indoor and outdoor air, respectively, and *t* is time (s). The left side of equation 1 gives the mass rate of change of water vapor in the zone air, and the right side includes the terms discussed above: the apparent moisture production rate, the rate of water vapor removal by air exchange, and the moisture sorption rate. Equation 1 can be expressed alternately in terms of water vapor pressure or humidity ratio (mass of water vapor per mass of dry air) with the proper transformations. Under steady conditions (where the indoor water vapor concentration is relatively constant), the left side goes to zero.

MODELING MOISTURE SORPTION AND MODEL VALIDATION

The only respect in which models materially differ is how they approximate moisture sorption (aside from the various sources and sinks they include in the moisture balance and whether they assume steady conditions). El Diasty et al. (1992), Jones (1995), Woloszyn and Rode (2008), and Kumaran and Sanders (2008) have summarized a number of approaches with varying levels of complexity. We include here only a brief summary of the models discussed in sections that follow.

The simplest approach is to neglect sorption and assume steady conditions (Loudon 1971):

$$c_i = c_o + \frac{\dot{m}_{prod}}{\dot{V}_a} \qquad (2)$$

This approach is justified when the intent is to model average conditions over a long period (as discussed in sections that follow). However, beginning with Tsuchiya (1980) and Kusuda (1983), many studies have shown that including moisture sorption is necessary for accurate modeling on time scales of hours to days. A slight modification of the Loudon approach is to approximate short-term buffering by averaging the outdoor water vapor pressure p_o. For example, TenWolde and Walker (2001) use a 24-h running average, $p_{o,24h}$:

$$p_i = p_{o,24h} + \frac{\dot{m}_{prod} R_v T_i}{\dot{V}_a} \qquad (3)$$

where p_i is the indoor water vapor pressure (Pa), R_v is the gas constant for water vapor (461.5 J kg^{-1} K^{-1}),

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[2] Diffusion may become significant in the case of airtight buildings without mechanical ventilation and with permeable envelopes (Simonson et al. 2004). An example is a permeable ceiling of gypsum board with latex paint and no vapor retarder below a ventilated attic

and T_i is the temperature of indoor air (K). This model has been adopted by ASHRAE draft standard 160P (2008).

A more detailed approach is to describe the rate of sorption using a driving potential. TenWolde (1988) assumed that the moisture content of materials is related to indoor relative humidity (RH) averaged over a period of time, $\phi_{i,T}$. He expressed the sorption rate as

$$\dot{m}_{sorp} = kA(\phi_i - \phi_{i,T}) \tag{4}$$

where k is a sorption parameter (kg m^{-2} s^{-1}), A is the floor area of the building (m^2), and is the instantaneous indoor RH. The time averaging period and sorption parameter were determined by comparing the model with measured data in a test building. TenWolde (1994) modified his earlier model by exponentially-weighting the time average of the indoor RH, which gives a time constant. Plathner et al. (1998) further modified this approach by assuming two time constants and two sorption coefficients for rapid and slow sorbing materials, based on the work of Martin and Verschoor (1988).

Jones (1993) followed a similar approach in his moisture admittance model, expressing the sorption rate in terms of the difference between instantaneous indoor RH and the surface RH of hygroscopic materials. A mass transfer coefficient and the surface area of hygroscopic materials were lumped into an empirical admittance parameter for absorption,   (h^{-1}). A second parameter for desorption,   (h^{-1}), was essentially   times the surface RH. Expressed in terms of humidity ratio W_i (kg kg^{-1}) of indoor air and of saturated air W_{sat} (at T_i), the sorption rate (kg h^{-1}) is

$$\dot{m}_{sorp} = \rho_a V(\alpha W_i - \beta W_{sat}) \tag{5}$$

where ρ_a is the density of dry air (kg m^{-3}). Jones (1993) suggested that six pairs of admittance parameters would be needed for modeling rooms of varying moisture admittance (high, medium, and low) under summer and winter conditions. However, these values were never determined. The model was partly validated in a test structure (Jones 1993) and an unoccupied residence (Serive-Mattei et al. 1993), giving values of   and   specific to the conditions of the experiments. A further drawback to this approach is that   is set at a constant value, which means that the model does not allow the surface RH to change. While this may be admissible for short periods of time, it is not appropriate for time spans of several weeks or more, when moisture contents of materials can be expected to change appreciably. A constant   essentially implies an infinite storage capacity.

Lu (2003) developed a mathematical method to calculate time-dependent moisture production rates. A polynomial function was used to provide a smooth interpolation between measured values of indoor water vapor content. Moisture exchange was assumed to occur only between indoor air and the building envelope; hygroscopic materials inside the building were apparently neglected. In order to determine the time-dependent moisture production rate, it was necessary to first assume that no moisture was transferred between indoor air and the building envelope. The model was apparently validated using an unoccupied test house over a six-month period, with the average measured air exchange rate and outdoor water vapor content as inputs. There was apparently no mechanical humidification during this period. Predicted and measured indoor water vapor content differed by less than 10%.

APPLICATION OF MODELS IN OCCUPIED BUILDINGS

TenWolde (1988, 1994) monitored indoor temperature and relative humidity in 3 occupied site-built houses and 5 occupied manufactured houses in Madison, Wisconsin, for several months during winter. He determined average air exchange rates for each house using tracer gas measurements periodically over the course of the study. Using the model described above (equation 4), he determined the apparent moisture production rates, sorption parameters, and time constants that best fit the measured temperature and RH data. The moisture production rates and time constants are discussed in sections that follow.

Lu (2003) monitored indoor and outdoor temperatures and humidities over a brief period (24 November – 2 December) at an occupied house near Helsinki, Finland. The model described in the previous section was used to determine the time-dependent moisture production rate. The assumption that no moisture was transferred between indoor air and the building envelope was then evaluated. Calculated transfer rates between indoor air and the envelope were found to be negligible compared with moisture production rates. However, because the model did not include moisture exchange with hygroscopic materials inside the building, the calculated moisture production rates likely include the effects of absorption and desorption. Indoor water vapor contents calculated with these time-dependent moisture production rates compared well with measured values. In addition, the study applied the model to evaluate the effect on indoor humidity of using a variable (time-dependent) versus a constant moisture production rate. It was found that the difference in indoor humidity, whether absolute humidity (water vapor content) or relative humidity, was minor. Therefore, calculations may be simplified by the use of a constant moisture production rate without significant loss of accuracy.

Several studies have compared measured indoor humidity with predictions from various models in the literature. Oreszczyn and Pretlove (1999) measured temperature and relative humidity at 1-h intervals in 36 residences near London, UK, over one heating season. The sample included detached houses and multi-family units. Some of the buildings were newly-constructed, and some were older buildings, not all of which had insulated walls. Moisture production rates were estimated using assumed values for various sources and information about the occupants' lifestyles. It is unclear how air exchange rates were determined. Measured RH values were compared with predicted values from the Loudon (1971) model and the Jones (1993) model. For the former, the predicted RH was within ±5% of the monitored RH for 65% of the data points and within ±10% of the monitored RH for 95% of the data points. The Jones model did not predict as well as the Loudon model; it generally overestimated, except at high RH (70% RH and above). Oreszczyn and Pretlove (1999) suggested that the agreement was poor because the Jones (1993) model "is more appropriate for use in a transient situation where changes in relative humidity are determined over periods considerably shorter than monthly or seasonal periods." While this is true (see previous section), it should also be pointed out that the Jones (1993) model was not validated for heating season conditions. The desorption parameter is a constant, which keeps the surface RH constant at 70%. Hygroscopic materials thus act as an infinite source whenever the indoor relative humidity is less than 70%. This explains why the model generally overestimated indoor relative humidity levels, except when these levels were high.

Roppel et al. (2007) compared the model predictions of TenWolde and Walker (2001) and Jones (1993) with measured hourly indoor humidity conditions for a multi-unit residence in Vancouver, British Columbia, over a period of several years. The building was not air-conditioned and humidity was not controlled. The air exchange rate during the heating season was estimated from measured CO_2 levels and exhaust fan capacity and operation. The air exchange rate outside the heating season was not known; occupants apparently indicated that they kept windows open regularly outside the heating season. The measured data showed that the difference between indoor and outdoor water vapor pressure reached a maximum in winter and minimum (near zero) in summer. Using a constant moisture production rate and values of the air exchange rate and admittance parameters that varied for the heating season, the transition periods, and the non-heating season, the authors were able to make the Jones (1993) model correspond closely with measured data. It should be noted that the admittance parameters that gave the best agreement between the model and measured data might be peculiar to the building and not generally applicable, as the approach was tested with only one data set.

Cornick and Kumaran (2008) compared several models with measured data from 24 occupied houses in three locations in northwestern Canada: Prince Rupert, British Columbia; Inuvik, Northwest Territory; and Carmacks, Yukon Territory. The houses were thought to be typical of North American construction methods in the 1970s, 80s, and 90s. Measured data were selected from each location for one month that was typical of extreme winter conditions. Temperature and RH were monitored in two locations in each house (usually a bathroom and another location, in many instances the kitchen). Hourly predictions were made using four models, including two moisture balance models: Jones (1993) and TenWolde and Walker (2001). Moisture production rates were assumed to be the design values given by TenWolde and Walker (2001), and air infiltration rates were calculated from wind and stack effects (ASHRAE 2005), with average monthly wind speed instead of hourly values. The model of TenWolde and Walker (2001) exhibited the lowest mean bias, mean absolute, and root mean square errors. The Jones (1993) model generally overestimated RH, with large positive mean bias errors as well large root mean square errors. The authors concluded that the admittance parameters given by Jones (1993) are not appropriate for the types of houses and climates studied. This conclusion agrees with that of Oreszczyn and Pretlove (1999) discussed above.

UNCERTAINTY IN INPUT PARAMETERS

Here we assess the uncertainties in air exchange rates and moisture productions rates and discuss the implications for modeling indoor humidity.

AIR EXCHANGE RATES

The air exchange rate is defined as the volume of outdoor air that enters the building per unit time divided by the building volume, expressed as air changes per hour (ASHRAE 2005). This includes leakage through the building envelope (infiltration and exfiltration) and mechanical ventilation. Pressure differences drive infiltration; they can be induced by wind, stack effect, and mechanical systems. Air exchange depends on a number of factors including the height of the building, the distribution and size of leaks, wind speed and direction, exposure, the difference between indoor and outdoor temperature, and the size and performance of mechanical ventilation equipment.

Tracer gas techniques can provide fairly accurate measurements of air exchange rates over short periods, which depend largely on the weather conditions at the time of measurement (ASHRAE 2005). For modeling indoor humidity, one would ideally have ongoing tracer gas measurements to monitor the air exchange rate over time. However, such measurements are labor intensive and cost-prohibitive.

There are several ways to approximate air exchange rates. One alternative is to take the average of a number of tracer gas measurements acquired at different times. For example, TenWolde (1988) monitored air exchange rates in 3 occupied houses for several months during winter. Each house was equipped with a heat recovery ventilator (HRV) controlled by a timer, and sulfur hexafluoride tracer measurements were carried out with the HRV on and off. On average, 5 measurements were made per house. With the HRV off, the coefficient of variation (COV, standard deviation divided by mean) determined for each house ranged from 13% to 72%. With the HRV on, there was generally less variability; COVs were between 14% and 19%. TenWolde (1994) used the same method to characterize 6 manufactured houses during winter. These were not equipped with whole-house mechanical ventilation, and COVs were between 55% and 82%. In theory, the air infiltration rate should be a function of wind speed and the difference between indoor and outdoor temperature. For both studies, however, the correlation between measured air exchange rate and these variables was poor. The lack of agreement may have been due to variations in the distribution of leakage paths, differing degrees of shelter from wind due to terrain and surrounding buildings, and discrepancies between local conditions and those recorded at the weather station (as distant as 32 km in some cases).

An additional method is the passive perfluorocarbon tracer (PFT) technique. The tracer is emitted from a source at a rate that depends on the temperature and the permeance of the container, and the time-weighted average tracer concentration is monitored passively over the period of interest using adsorption tube samplers. The tracer concentration, which is related to the average air exchange rate, is determined from the samplers in a laboratory by gas chromatography. Säteri et al. (1989) found that the uncertainty of this method when applied in occupied buildings is approximately 20%.

Another alternative is to characterize the airtightness of the building envelope using a fan pressurization test and to employ a model that relates air infiltration to wind and stack effects (ASHRAE 2005). Two single-zone models discussed below are the model developed at Lawrence Berkeley National Laboratory (LBL, Sherman and Grimsrud 1980) and the Alberta Infiltration Model (AIM-2, Walker and Wilson 1990a). Several studies have investigated the accuracy of these models.

Modera et al. (1983) undertook an extensive experimental and theoretical examination of the accuracy of the LBL model. They compared model predictions with tracer gas measurements of air exchange collected in a mobile test structure, which essentially was a 4.9 m × 2.4 m × 2.4 m box with calibrated leakage panels. The structure was placed on two sites with uniform wind exposure in Reno, Nevada, and air exchange measurements were acquired over two winter seasons. When compared with measured rates, the air exchange rates predicted by the LBL model were higher on average (biased) by 10%, and the standard deviation of the errors (short-term fluctuations or "scatter") was 28%. These error estimates are not generally applicable, since they are based on one well-characterized test structure in a particular climate zone. In practice, significant errors may arise when applying the model to any given building. Several key parameters (which were known for the test box) may be difficult to estimate: floor and ceiling leakage distribution parameters, neutral pressure level, terrain class, and shielding class. In practice, constant leakage through all envelope surface areas is usually assumed. Furthermore, the model assumes that shielding is identical in all directions and that wind-induced infiltration can be represented by averaging the values for all wind directions. These assumptions may produce significant errors if a particular wind direction is dominant.

Walker and Wilson (1990a,b) showed that including chimney leakage in the AIM-2 model separate from ceiling leakage significantly improved the agreement between model predictions and air exchange rates determined by tracer gas measurements. In some cases, the predictions of models that grouped chimney leakage with ceiling leakage differed from measured values by more than a factor of 3. Walker and Wilson (1998) also showed that for two well-characterized test houses in Alberta, typical differences between measured air exchange rates and AIM-2 model predictions were about 10%.

Palmiter and Francisco (1996) compared air exchange rates predicted by the LBL and AIM-2 models with tracer gas measurements in 10 houses in California and the Pacific Northwest. For two different assumptions about the leakage distribution parameters, the AIM-2 model had a mean error of 16% or 27%, and the LBL model had a mean error of 26% or 46%. Wang et al. (2009) compared the same models with tracer gas measurements in 16 detached houses in Ottawa, Ontario. They found that on average, the AIM-2 model had an error of 19% while the LBL model had an error of 25%.

The infiltration models discussed above, however, do not provide information about mechanical ventilation rates; these must be measured independently. Moreover, for unbalanced mechanical ventilation systems, the manner in which mechanically-induced, wind-induced, and stack-induced airflows combine is nontrivial and depends on the leakage distribution (ASHRAE 2005).

In summary, air exchange rates measured by any method are subject to uncertainty. Tracer gas techniques as described above have a lower bound to the uncertainty of 10–20%. Over long periods, the minimum uncertainty is about 10% using an infiltration model for a well-characterized building; the uncertainty over short periods is about 25%. In most situations, though, the uncertainty in infiltration model predictions will be greater.

MOISTURE PRODUCTION RATES

Two methods have been used for quantifying moisture production rates in residential buildings: (1) Summation of estimates for moisture production from individual sources based on assumed occupancy schedules and activity scenarios; and (2) Calculation of overall moisture production rates based on measurements of indoor humidity, outdoor humidity, and air exchange rates. The latter method may involve moisture balance modeling to account for buffering as discussed previously, or may neglect buffering when the measurement period is sufficiently long. The accuracy of this method depends primarily on the accuracy of the air exchange measurement. The accuracy of method 1 depends on the quality of the estimates for individual moisture sources and for the occupants' schedule and behavior. TenWolde and Pilon (2007) showed that moisture release from wet foundations is potentially a large source but is currently poorly characterized.

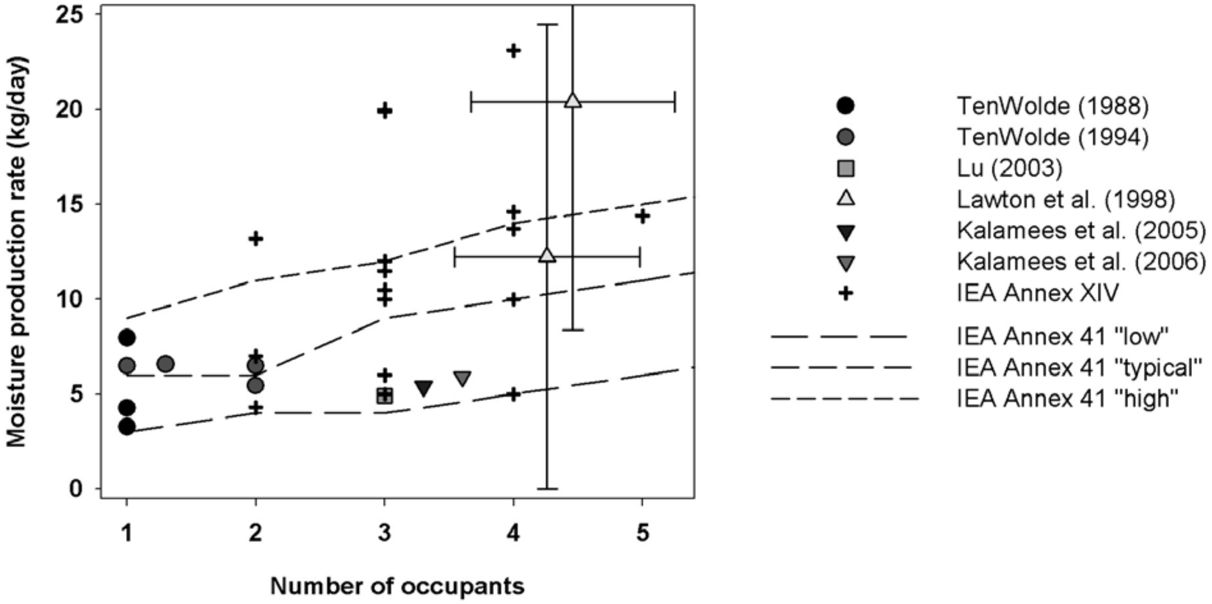

FIGURE 1: moisture production rates from the literature.

Historical data for residential moisture production rates are summarized in the IEA Annex XIV Sourcebook (IEA 1991). It is unclear how some of the data were obtained. In certain cases, though, it is clear that the values were summed (method 1 above). IEA Annex 41 has taken a similar approach, giving probable values of moisture production rates for "low", "typical", and "high" water usage (Kumaran and Sanders 2008). These values are shown in Figure 1 as a function of the number of occupants (dashed lines and crosses), augmented with moisture production rates determined from measurements in occupied houses (method 2 above, colored symbols). These include estimates for a number of individual houses as described previously (TenWolde 1988, 1994; Lu 2003). In addition, several studies have calculated average moisture production rates for large groups of houses with pooled occupancy (Table 1). Lawton et al. (1998) monitored temperature and humidity in a group of 55 single-family detached houses in Wallaceburg, Ontario, for a weeklong period in winter. They measured air leakage characteristics of each house and calculated moisture production rates based on modeled air exchange rates. Similarly, Kalamees et al. (2005, 2006) measured indoor and outdoor conditions for detached houses in Estonia and Finland. They calculated the average moisture production rate in each house over the winter period (December through February) from the measured air exchange rate and the average difference between indoor and outdoor water vapor concentration. Sanders (1996) summarized several studies and gave moisture production rates at the 10th, 50th, and 90th percentile (Table 2) but did not relate these rates to the number of occupants.

Reference	Group	No. houses	No. occupants per house	Mean moisture production rate (kg/day)
Lawton et al. (1998)[a]	“low-biological”	20	4.26 ± 0.72	12 ± 13
	“high-biological”	35	4.46 ± 0.79	20 ± 12
Kalamees et al. (2005)	all	27	mean = 3.3	5.4
Kalamees et al. (2006)[b]	$\Delta v < 1.5$ g m^{-3}	38	≤3	4.6
			>3	5.8
	$\Delta v > 3$ g m^{-3}	36	≤3	5.8
			>3	7.5
	all	101	≤3	5.1
			>3	6.8
			mean = 3.6	5.9

TABLE 1: mean moisture production rates for pooled occupancy

[a] Houses were classified on the basis of measured microbiological contamination of air and dust; number of occupants and moisture production rates are given as mean ± standard deviation

[b] v is the average difference in absolute humidity (water vapor concentration) between indoor and outdoor air during the period when outdoor temperature was less than 5°C

Country	Group	Moisture production rate (kg/day)		
		10%	50%	90%
Canada	Detached houses (28)	3.0	8.7	21.0
Denmark	Flats/mechanical ventilation	2.5	5.8	10.0
	Detached houses/mechanical ventilation	3.5	8.0	13.5
	Detached houses/natural ventilation	3.0	6.5	13.0
Sweden	Detached houses (580)	4.6	8.7	15.7
	Multi-family dwelling units (500)	2.4	5.6	11.0

TABLE 2: moisture production rates by percentile (Sanders 1996)

Based on a simple statistical analysis of the historical data available at the time, TenWolde and Walker (2001) arrived at a design moisture production rate, which was expected to be exceeded in 32% of the population. It is important to note that design values are not average values, but are meant to be more severe (i.e. higher). This analysis resulted in the design values in Table 3, which was adopted for inclusion in ASHRAE draft Standard 160P (ASHRAE 2008).

Number of Bedrooms	Number of Occupants	Design Moisture Production Rate
1	2	8 kg/day
2	3	12 kg/day
3	4	14 kg/day
4	5	15 kg/day
Additional bedrooms	+1 per bedroom	+1 kg/day

TABLE 3: Design Moisture Production Rates (TenWolde and Walker 2001)

Figure 1 shows that moisture production estimates vary significantly. For example, the standard deviations in the data of Lawton et al. (1998), depicted as error bars, show large variability within the two groups of houses. Additionally, the IEA (1991) estimates for 3 to 4 occupants vary by more than a factor of 4. In contrast, the data of TenWolde (1988, 1994), Lu (2003), and Kalamees et al. (2005, 2006) are quite similar; the average release rate based on this limited data set is 5.7 kg/day, considerable less than the majority of historical published rates. TenWolde and Pilon (2007) revisited individual moisture sources within the home, and concluded that moisture release from cleaning and clothes washing can be ignored in today’s household. Clothes washing especially contributed significantly to the totals reported in the older literature. The calculated production rate for a family of five, based on an assumed occupancy scenario was between 6.6 and 10.2 kg/day, depending on indoor humidity level. This agrees well with the estimates in Kumaran and Sanders (2008) for low and typical building use categories. However, it is significantly below levels reported in IEA (1991) and other sources. Recent anecdotal evidence also suggests that the IEA Annex

XIV (1991) values may be high (Aoki-Kramer and Karagiozis 2004, Roppel et al. 2007). Collectively, these observations point toward a need for additional measurements to determine whether moisture production rates should be revised downward.

To show the potential impact on design moisture production rates, we followed a similar procedure to the one used by TenWolde and Walker (2001). We performed a Student distribution analysis, based on the data published by TenWolde (1988, 1994). The average of this subset is 5.8 kg/day and the 32% exceedance level for moisture production from 1 to 2 persons is 6.6 kg/day. This is 1.4 kg/day lower than the design value of 8 kg/day in TenWolde and Walker (2001).[3] It is clear that more data and analysis are needed to ascertain what the design values should be. TenWolde and Walker (2001) also concluded from the historical data that the first child adds 4 kg/day to the production rate, but the measured data by Lu (2003) and Kalamees et al. (2005, 2006) indicate that this addition may be too high. Moreover, moisture release from extra showering/bathing and respiration/transpiration would indicate an additional 1 to 1.5 kg/day (rather than 4 kg/day). This becomes very important if the design rate remains based on the number of bedrooms in the home, as proposed in ASHRAE Standard 160P (ASHRAE 2008), because these days very few single bedroom homes are built.

CUMULATIVE UNCERTAINTY AND IMPLICATIONS FOR MODELING INDOOR HUMIDITY

When a model is applied to an individual building (as opposed to a group of buildings), the uncertainties in moisture production rate and air exchange rate are large, and both these errors contribute to the error in the indoor humidity calculation. We provide rough estimates here of lower limits to this cumulative error. First we consider short time scales (on the order of hours). Based on tabulated data from Lu (2003), the variability in the ratio of the instantaneous moisture production rate to the air exchange rate in an occupied house can be described by a COV of 32%. This value represents a lower limit to the combined error in the moisture production and air exchange rates, the latter being determined from tracer gas measurements. In cases where the air exchange rate is calculated from pressurization measurements and an infiltration model, we take a COV of 28% as the minimum error in hourly infiltration estimates, as reported by Modera et al. (1983). We consider it a minimum because the measurements were done on a well-characterized test structure, not an occupied house. A rough estimate of the error in moisture source rate can be glimpsed from a subset of the data in Figure 1: the COV of moisture production rates determined by TenWolde (1988, 1994) for homes with up to two occupants is about 26%. This produces a COV in calculated instantaneous indoor humidity of about 38%, roughly consistent with the value of 32% calculated above from the data of Lu (2003). For long periods (on the order of weeks), we take the lower limit of the COV for the air exchange rate to be 10% (determined from either tracer gas measurements or an infiltration model) and for the moisture production rate to be 26%, as above. This gives a COV for long-term indoor humidity predictions of about 28%.

As discussed above, the results of HAM analyses of building envelopes depend strongly on the assumed interior conditions. For design analysis pertaining to long-term durability, it is reasonable to select interior conditions that are more severe than average, but not overly severe. Given the uncertainties in moisture production and air exchange rates, the role of moisture buffering is rather insignificant, and simplified modeling approaches are justified. Further measurements of moisture production rates in occupied buildings are needed to better characterize design values.

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[3] TenWolde and Walker (2001) used the moisture production rates of TenWolde (1988) adjusted for the occupant being home 100% of the time. Here we use the actual unadjusted rates instead, which explains why our analysis yields a lower design value.

TIME SCALE OF MOISTURE BUFFERING

The idea of a time constant for absorption or desorption of moisture in response to a change in indoor humidity has been addressed in several models. TenWolde (1988) modeled the rate of sorption using the difference between the instantaneous RH and a time-averaged RH (see equation 4). By comparing the model with measured data in a test building containing a large exposed surface area of wood, TenWolde (1988) found that the best agreement was attained with a back-averaging period of 6 weeks, although the results were not very sensitive to this parameter. The model was also applied to 3 wood-frame houses, all of which were fit best with a back-averaging period of 1 week. TenWolde (1994) modified his earlier model and introduced an exponentially-weighted time average of the indoor RH. This model yielded a time constant of 3 days for all 3 of the wood-frame houses. In addition, the model was compared with data from 6 manufactured houses, yielding time constants between 9 h and 24 h.

Although it is possible that moisture storage occurs on a seasonal time scale, it would be very difficult to prove this. Kurnitski et al. (2007) recently showed by simulation that moisture exchange between indoor air and interior hygroscopic surfaces occurs on an hourly, daily, and weekly time scale but is negligible on a monthly or seasonal scale. Their advanced model accounted for heat, air, and moisture transport within the building envelope and its coupling with the indoor air. Nevertheless, the concept of seasonal storage has been suggested in the literature to explain certain observations. We discuss these cases below.

Kalamees et al. (2006) acquired temperature and humidity data for 101 single-family detached wood-frame houses in Finland. They plotted the difference between indoor and outdoor water vapor concentration, v, as a function of weekly average outdoor temperature between –15°C and 10°C. They found that v was about 4.0 g m^{-3} prior to mid-winter and about 3.5 g m^{-3} after mid-winter. They attributed this change in v of 0.5 g m^{-3} to seasonal moisture storage: moisture that had been stored in materials during summer (high indoor RH) was released during fall; in contrast, materials that had dried out in winter (low indoor RH) began to absorb moisture in spring. In light of the simulation results of Kurnitski et al. (2007) discussed above, we suggest that other explanations are more likely.

One possibility is that the foundation is responsible for the seasonal effect observed by Kalamees et al. (2006). Several studies have shown that building foundations, including basements, crawlspaces, and slabs-on-grade, can contribute significant amounts of moisture to indoor air (Lawton et al. 1998, Rose 1988, TenWolde 1988, Carll et al. 2007). TenWolde and Pilon (2007) showed that evaporation from foundations depends on the foundation temperature and the indoor humidity. The temperature of the soil and the foundation are higher on average prior to midwinter than after midwinter because of thermal inertia; the foundation could therefore act as a larger source prior to midwinter. However, the foundation could also act as a seasonal buffer, giving off moisture prior to midwinter and absorbing moisture after midwinter. Another possible explanation is that the air exchange rate varies over time. Kalamees et al. (2006) apparently measured the air exchange rate for each house at one time during the heating season with a tracer gas technique. The variation of the air exchange rate over time was not characterized, and a variation of less than 15% would account for the observed trend.

Roppel et al. (2007) found good agreement between measured data in a multi-unit residential building in Vancouver, British Columbia, and the model of Jones (1993) with input parameters selected for different seasons (see above). This model, which includes terms for moisture absorption and desorption, apparently fit the data better than the model of TenWolde and Walker (2001), which approximates short-term buffering by using a 24-h running average of the outdoor water vapor pressure (equation 3). Although this could lead to an impression that moisture storage occurs on a seasonal time scale, drawing such a conclusion cannot be justified. As noted by the authors (Roppel et al. 2007), there were too many parameters with a large degree of uncertainty to determine whether seasonal moisture buffering was the physical explanation.

CONCLUSIONS AND RECOMMENDATIONS

Based on our assessment of the literature, we make the following conclusions and recommendations:

- Over long periods, the minimum uncertainty in air exchange rates is about 10% using an air infiltration model for a well-characterized building; the minimum uncertainty over short periods is about 25%. In most situations, though, the uncertainty in air exchange rates predicted by infiltration models will be greater.
- Tracer gas techniques for measuring air exchange rates, as used in studies related to indoor humidity, have a lower limit to the uncertainty of 10–20%.
- The combined uncertainty in moisture production and air exchange rates warrants the use of moisture balance models with simplified descriptions of moisture buffering for predicting indoor humidity as a boundary condition for hygrothermal analyses of building envelopes.
- The data relating to the time scale for moisture buffering in actual buildings support only short-term effects, on the order of hours to weeks rather than months or seasons.
- Design moisture production rates are currently based on a rather limited data set. Additional data on the distribution of moisture production rates as a function of the number of occupants are needed to establish more confidence in design rates. The first step in this direction would be to measure indoor humidity, outdoor humidity, and air exchange rate over periods of at least one month in different types of occupied residences in a variety of climatic regions.

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