Water Vapor Generation in Residential Buildings: Comparing Probabilistic Simulations and Field Measurements

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ABSTRACT

Indoor humidity levels in buildings affect the quality of indoor air, the health and comfort of the occupants, and the durability of the structure. Interior water vapor generation is an important consideration in building design analysis. In this paper we compare two methods for quantifying water vapor generation rates in residential buildings. The first involves Monte Carlo simulations that consider time varying interior sources using statistical survey data. Typical sources include humans, pets, plants, showering, bathing, cooking, washing, etc. The second approach involves field measurements of indoor vapor pressure, outdoor vapor pressure, and air exchange rates for a sample of occupied dwellings, followed by calculations based on mass balance. Probability distributions of total daily water vapor generation as a function of the number of occupants are compared between the two methods, using simulations of single-family detached houses in Sweden and the United States, and field measurements in Finland. Water vapor generation rates generally increase with the number of occupants, though some anomalies are found in the Finnish sample, likely because of the limited number of houses. Probability distributions for houses with two or three occupants agree closely across the different countries, but houses with four or five occupants in Finland consistently have lower generation rates than those in Sweden and the US. Generation rates had broader distributions for US houses than for Swedish houses, which likely reflects differences in lifestyle. We discuss the advantages and limitations of both methods. Finally, we identify research that would advance the state of the art.

INTRODUCTION

Indoor humidity levels in buildings affect the quality of indoor air, the health and comfort of the occupants, and the serviceability of the structure. Indoor dampness and microbial growth have been consistently linked with adverse health effects (IOM 2004; WHO 2009; Mendell et al. 2011). Moisture accumulation can lead to deterioration of structural materials and finishes (ASHRAE 2019a, 2019b, 2021d).

Following dissipation of moisture from building materials after construction, interior humidity levels during normal building operation vary over a range of time scales, from fluctuations on the scale of minutes (e.g., showering) to daily and seasonal changes driven by exterior weather and climate. The primary factors influencing interior absolute humidity in residential buildings are the rate of water vapor generation (influenced mainly by the number of occupants and activities such as showering, bathing, cooking, washing, etc.); occupant density; exterior absolute humidity; air exchange rate (including infiltration and mechanical ventilation); mechanical humidification or dehumidification; and vapor uptake and release by

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hygroscopic materials (TenWolde 1993; TenWolde and Walker 2001; Glass and TenWolde 2009; ASHRAE 2021d).

The rate of interior water vapor generation is an important parameter in building design analysis. Residential cooling load calculation methods (ASHRAE 2021b; Rutkowski 2016; Winkler and Booten 2016) include internal gain of water vapor in the calculation of latent loads and provide a basis for design of mechanical air-conditioning systems. Numerical models for transient heat, air, and moisture (HAM) transfer are used to simulate moisture and temperature conditions within building envelope assemblies over time (Hens 1996; Trechsel 2001; ASHRAE 2021c). This can help identify potential durability risks. However, the need for specific moisture control design features often depends on the assumed moisture loads, and simulation results can be highly sensitive to interior humidity levels. Several standards provide methods for estimating interior humidity levels for the purpose of design analysis, including EN 15026 (2007), EN ISO 13788 (2012), and ASHRAE 160 (2021a). A method that has received considerable attention is quantifying the difference between indoor and outdoor absolute humidity (also known as "moisture excess" or "moisture supply"; see Ilomets et al. 2018; Vinha et al. 2018; and references cited therein). Another approach is quantifying the rate of interior water vapor generation, which can be used for estimating indoor humidity levels by mass balance modeling (Tenwolde and Walker 2001; Glass and TenWolde 2009). The rate of interior generation is also a necessary input for whole building HAM models, which have been used in parametric studies to examine the relations between interior water vapor generation, ventilation, moisture buffering, dehumidification, indoor humidity levels, and energy consumption (Künzel et al. 2005; Walker and Sherman 2007; Woloszyn and Rode 2008; Holm 2008; Fang et al. 2011; Tariku et al. 2011; Geving and Holme 2012; Rudd et al. 2013; Martin 2014; Napp et al. 2016; Winkler et al. 2018).

Total water vapor generation rates in residential buildings have been quantified in the past with two different methods. The first involves summing estimates of individual sources according to occupancy schedules and activity scenarios. Typical sources include humans, pets, plants, showering, bathing, cooking, washing, and cleaning. Several references list estimates for individual sources (Sanders 1996; Kumaran and Sanders 2008; Christian 2009; ASHRAE 2021d). The second method involves calculating an effective total rate based on measurements of indoor absolute humidity, outdoor absolute humidity, and air exchange rate (TenWolde 1988, 1994; Sanders 1996; Lu 2003; Kalamees et al. 2006; Ilomets et al. 2018; Martin et al. 2021). This method has been used in conjunction with mass balance modeling to account for buffering, although buffering may be neglected when the measurement period is sufficiently long (Glass and TenWolde 2009).

Despite the importance of indoor humidity, water vapor generation rates in residential buildings are poorly characterized and vary widely with occupant behavior. For example, estimates for a family of four have ranged from less than 5 kilograms per day ($kg \cdot d^{-1}$) (11 $lb \cdot d^{-1}$) to greater than 20 $kg \cdot d^{-1}$ (44 $lb \cdot d^{-1}$) (Tenwolde and Walker 2001; Glass and TenWolde 2009). This high degree of variability implies that water vapor generation rates need to be characterized with a probabilistic approach. Recent measurements by Ilomets et al. (2018) characterized the variability in water vapor generation rates within bedrooms across a large sample of residential buildings in Estonia. Research conducted within International Energy Agency Annex 55, *Reliability of Energy Efficient Building Retrofitting-Probability Assessment of Performance and Cost*, included a subtask on gathering stochastic data (Ramos and Grunewald 2015). Notably, Johansson et al. (2010) developed statistical distributions of residential water vapor generation rates based on published literature and survey data in Sweden. Pallin et al. (2016) applied similar methods to develop probability distributions for houses in the United States. Both studies indicate that generation rates are strongly correlated to the number of occupants in the dwelling. The tools developed in these studies have been used for modeling indoor humidity and evaluating durability of the building envelope (Pallin et al. 2011; Boudreaux et al. 2016; Buechler et al. 2017). Although probabilistic simulation is an important advancement, questions remain about the accuracy of the input data. Johansson et al. (2010) suggested that results need verification using measurements or improved statistical surveys.

The primary objective of this paper is to compare probability distributions for water vapor generation in single-family detached houses, as a function of the number of occupants, based on two different methods. First, we consider probabilistic simulations using survey data (Johansson et al. 2010; Pallin et al. 2016). Second, we analyze measurements including indoor temperature and relative humidity (RH), outdoor temperature and RH, and air exchange rates from a sample of houses in Finland (Kalamees et al. 2006). A secondary objective of this paper is to evaluate the advantages and limitations of both methods and identify research that will advance the state of the art.

PROBABILISTIC SIMULATIONS BASED ON SURVEY DATA

This section provides an overview of the approach used by Johansson et al. (2010) and Pallin et al. (2016) to characterize residential indoor water vapor generation for the housing stock in Sweden and the United States, respectively. The intent of this approach is to understand and quantify variation in water vapor generation across the population as a function of the number of occupants and time of day. It is recognized that occupant behavior differs between weekdays and weekends and in some cases between seasons (e.g., use of humidifiers during winter). In addition, differences between single-family and multi-family dwellings are accounted for.

The general framework of the approach is shown in Figure 1. Each individual source of water vapor is identified and characterized according to the following factors: the time of day that the source (or "event") begins; the duration of the event; and the associated rate of water vapor generation on an hourly basis. The following sources are considered: bathing, showering, saunas, whirlpools, meal preparation, dishwashing by hand and appliance, laundry, ironing, floor mopping, toilets, faucets, humans, pets, aquariums, plants, and humidifiers. Because certain sources are not present in every household, each source is weighted according to its incidence within the population. Monte Carlo simulations are used to generate the total rate of water vapor generation based on the input data described above.

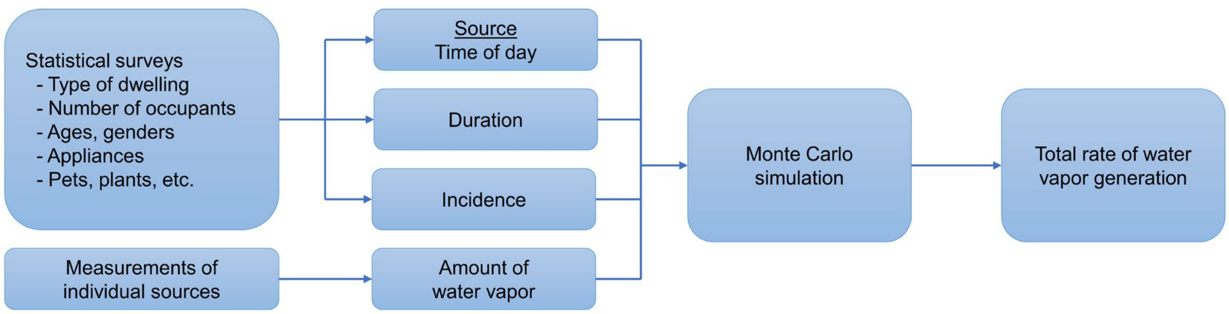

Figure 1 Framework of the probabilistic simulation approach (adapted from Pallin et al. 2016).

Sources of primary data include statistical housing surveys, energy consumption surveys, census data, and literature characterizing various sources of water vapor. Take showering as an example. The time distribution of showering is plotted in Figure 2 based on a survey in California (CARB 1990). In addition, US survey data indicates that 99.7% of dwellings have a shower (De Oreo and Mayer 2012); a showering event has a mean duration of 7.8 min and standard deviation of 3.5 min (Wilson et al. 2010); and the incidence of each occupant showering on a given day varies seasonally (CARB 1990). The amount of water vapor generated during a 5 min period from showering, based on studies in the literature, is in the range 0.20–0.38 kg (0.44–0.84 lb), which can be transformed into an estimated distribution (Pallin et al. 2016).

Probability distributions of the rate of indoor water vapor generation from these studies for single-family dwellings in Sweden (Johansson et al. 2010) and the United States (Pallin et al. 2016), expressed as a daily total ($kg \cdot d^{-1}$ or $lb \cdot d^{-1}$), will be presented in the Results section.

FIELD MEASUREMENTS AND CALCULATIONS

Water vapor generation rates are calculated here based on measurements in 101 single-family detached houses in the metropolitan areas of Helsinki and Tampere, Finland (Kalamees et al. 2006). The houses are grouped according to the number of occupants, and analysis focuses on probability distributions. Pertinent details of the houses, measurements, and calculations are summarized below; full details can be found in the original study (Kalamees et al. 2006).

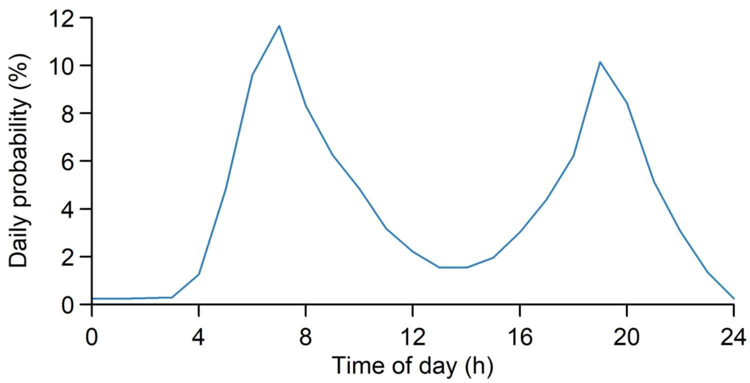

Figure 2 Example of statistical data: probability of showering vs. time of day (adapted from Pallin et al. 2016; based on CARB 1990).

House Characteristics

Houses were relatively new at the time of the study; most had been constructed less than five years prior to measurements. Some older houses without mechanical ventilation were included for comparison. Year of construction ranged from 1979 to 2003 (median: 2000). Most of the houses had been occupied for at least one heating season prior to monitoring. Foundations were primarily slab-on-grade; less than 15% of houses were constructed with wood-frame floors over crawl spaces, and none of the houses had basements. Structures were lightweight wood-frame except for two log houses. Mean floor area was 153 m^2 (1647 ft^2). Houses were ventilated in one of three ways: passive stack or natural ventilation (11%), mechanical exhaust ventilation (28%), or balanced (supply and exhaust) mechanical ventilation (61%).

Temperature and Relative Humidity

Interior temperature and RH were monitored at 1-h intervals with data loggers over a period of one year in each house, which included the winter of either 2002–2003 or 2003–2004. Sensors were placed in the bedroom of each house and in the living room of some houses. Exterior temperature and RH were either monitored outside the house with a data logger or obtained from the nearest weather station. Temperature measurement error was ±0.3 °C to ±0.5 °C (±0.5 °F to ±0.9 °F). Relative humidity measurement error was ±2.5% to ±3% RH. Accuracy of the sensors was checked before and after each monitoring period. Error introduced by the assumption that exterior conditions at the house were identical to conditions measured at the nearest weather station could not be evaluated.

Air Exchange Rate

Air exchange rates were measured with the passive perfluorocarbon tracer (PFT) method in 74 of the houses, over a period of three weeks during winter (Kurnitski et al. 2005). These 74 houses were included in the analysis. The distribution of measured air leakage rates at 50 Pa (0.2 in. wc) depressurization and the air exchange rates based on PFT measurements are shown in Figure 3.

In houses with mechanical ventilation (either exhaust-only or balanced supply/exhaust), airflow rates were measured in the exhaust ducts at all fan speeds. Duct airflow rates corresponding to measured values at the fan speed reported by the occupants in a questionnaire were found to differ from PFT airflow rates, with substantial deviations in some cases. The PFT method is considered more reliable; the uncertainty associated with the PFT method when applied in occupied buildings is approximately ±20% (Säteri et al. 1989). Deviations between PFT and duct airflow measurements may be attributed to several factors. The ventilation systems may have run at lower or higher flow than reported by the occupants, or the systems may have run intermittently rather than continuously. Wind- and stack-induced infiltration would be reflected in PFT measurements but not in duct airflow measurements. Finally, air exchange rates may vary from room to room within the house; PFT measurements reflect local air change effectiveness at the sampler.

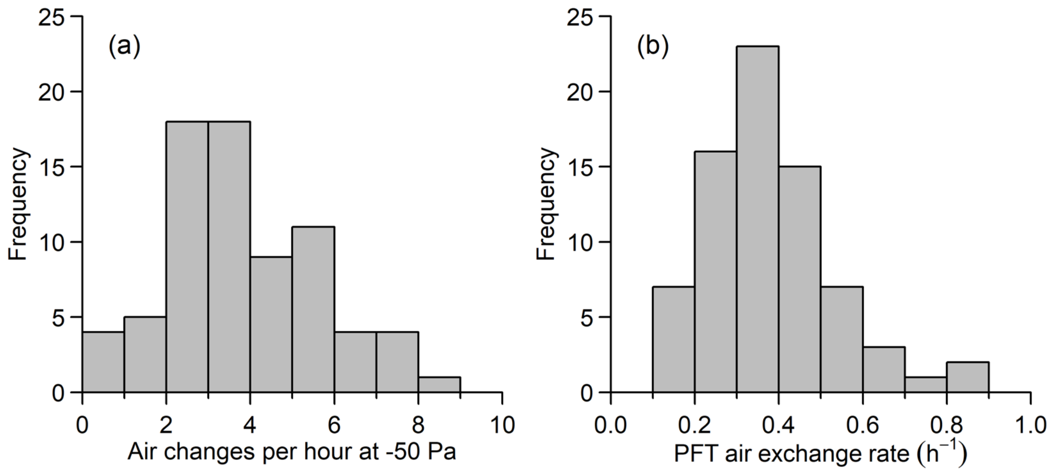

Figure 3 Histograms of (a) measured air leakage rates at depressurization of 50 Pa (0.2 in. wc) and (b) in situ air exchange rates determined by PFT measurements.

Calculations

The partial pressure of water vapor ("vapor pressure") interior and exterior of each house, p_{in} and p_{ex} (Pa or psia), respectively, were calculated from measured hourly values of temperature and RH using an empirical psychrometric equation. For houses in which temperature and RH were measured in both the bedroom and living room, p_{in} was calculated as the mean of the two rooms. The mean difference between interior and exterior vapor pressure, $\langle p_{in} - p_{ex} \rangle$, was calculated over the winter period defined as December 1st through February 28th. Similarly, the mean absolute temperature of indoor air $\langle T_{in} \rangle$ (K or °R) was calculated over the same period (averaging bedroom and living room if both were measured). The effective rate of water vapor generation, r_{eff}, expressed as a daily value (kg·d^{-1} or lb·d^{-1}), was calculated as

$$r_{eff} = \frac{\langle Q \rangle \langle p_{in} - p_{ex} \rangle}{R_v \langle T_{in} \rangle} \tag{1}$$

where $\langle Q \rangle$ (m^3·d^{-1} or ft^3·d^{-1}) is the rate of airflow from interior to exterior (based on PFT measurement and interior house volume) and R_v is the specific gas constant for water vapor (461.5 Pa·m^3·kg^{-1}·K^{-1} or 0.5957 psia·ft^3·lb^{-1}·°R^{-1}).

Several assumptions are built into Equation (1). First, each house is assumed to be a single zone with uniform interior temperature and vapor pressure. In many cases sensors in different rooms within the same house gave similar readings (close to the sensor measurement error). However, in roughly 25% of the houses, sensors in different rooms varied considerably, presumably because moisture sources and air exchange were not spatially uniform (not because of sensor error). Second, the air exchange rate is assumed to be constant over the winter period and equivalent to the value measured by the PFT method. Third, air exchange is assumed to be the only mechanism by which water vapor is transferred from indoor air. Equation (1) thus neglects water vapor exchange with interior hygroscopic materials (moisture buffering), possible condensation on interior surfaces (such as windows), and diffusion through the building envelope. Neglect of moisture buffering is clearly justified when averaging over a period of three months (Glass and TenWolde 2009). Occurrence of window condensation was reported in questionnaires by about 10% of occupants, but this was likely of short duration and would not introduce significant error over the three-month period. Neglect of diffusion through the building envelope is justified for most houses in heating climates because the quantity of water vapor transferred by air exchange is usually much greater than that transferred by diffusion (TenWolde 1993). Most houses included in this analysis had air exchange rates greater than 0.3 h^{-1} (Figure 3) and were constructed with vapor-tight envelopes. Approximately 30% of the homes were constructed with vapor-open envelopes, having a vapor permeable membrane as the air barrier. In these cases, vapor diffusion could have been non-negligible. However, a study of a house with vapor-open walls in a cold climate, for which air exchange rates in winter were typically 0.2–0.3 h^{-1}, found that the transfer of water vapor from indoor air by diffusion through above-grade walls was generally less than 10% of that by air exchange (Boardman and Glass 2015).

RESULTS

The effective water vapor generation rate for all 74 houses in Finland is plotted in Figure 4 as a histogram and an empirical cumulative distribution function. As expected, considerable variation is present across this sample. The houses range from one occupant to six occupants. Given the expected influence of the number of occupants, the houses were further analyzed accordingly. Houses with one occupant or six occupants were excluded from further analysis because of small sample size (only three houses and five houses, respectively).

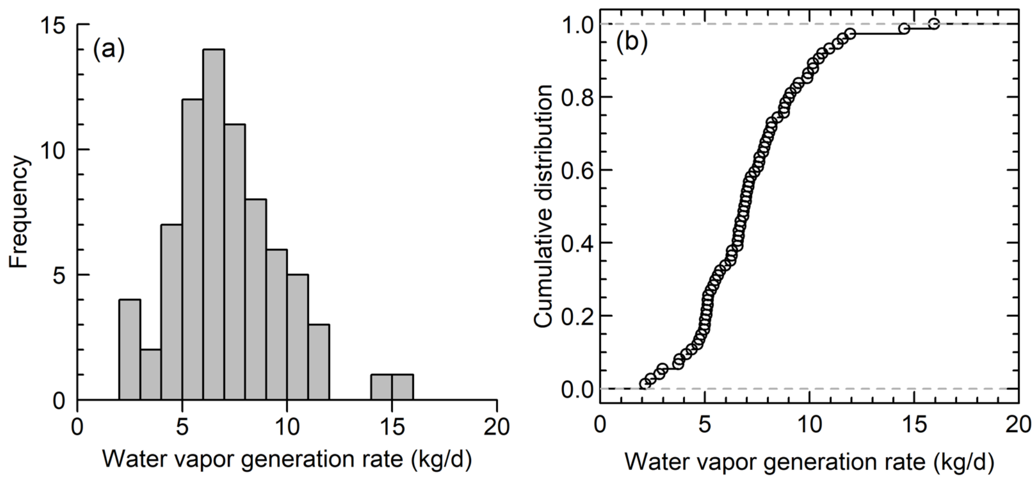

Figure 4 Water vapor generation rates calculated over the winter period for 74 houses in Finland plotted as (a) histogram and (b) cumulative distribution.

Water vapor generation rates based on the field measurements in Finland are compared with rates based on probabilistic simulations for detached houses in Sweden and the US in Table 1 and Figure 5. Overall, the values are relatively close for houses with two or three occupants, but houses in Finland with four or five occupants have consistently lower values than those in Sweden and the US at the 25th percentile and above. For example, the median values for two or three occupants differ by 0.8 $kg \cdot d^{-1}$ (1.8 $lb \cdot d^{-1}$) or less, whereas the difference is 2.0 $kg \cdot d^{-1}$ (4.4 $lb \cdot d^{-1}$) for four occupants and 3.0 $kg \cdot d^{-1}$ (6.6 $lb \cdot d^{-1}$) for five occupants.

While the simulated rates (Sweden and US) increase monotonically with the number of occupants for any given percentile, the field measurements (Finland) show unexpected behavior where the median value for three occupants is greater than that for four and five occupants. On the other hand, 90th percentile values do increase monotonically with the number of occupants. Anomalies are likely related to the limited number of houses in the study, which might not be representative of the larger population. Differences are also apparent in the simulated distributions for Sweden and the US: for a given number of occupants, the US has a broader distribution of generation rates than Sweden (Figure 5). This may indicate differences in lifestyle between the populations related to water vapor generating activities and time spent indoors. The US simulation model is based on the Swedish model but further developed to better account for correlations between occupants' behavior.

Table 1. Comparison of Water Vapor Generation Rates

Occupants	Location[a]	Rate, kg·d⁻¹ (lb·d⁻¹)					
		10th Percentile	25th Percentile	50th Percentile	75th Percentile	90th Percentile	95th Percentile
2	Finland (18)	4.1 (9.0)	5.0 (11.0)	5.9 (13.0)	6.6 (14.6)	8.2 (18.1)	8.8 (19.4)
	Sweden	5.0 (11.0)	5.3 (11.7)	6.0 (13.2)	6.9 (15.2)	7.9 (17.4)	8.6 (19.0)
	US	2.9 (6.4)	5.1 (11.2)	6.7 (14.8)	8.5 (18.7)	10.1 (22.3)	11.2 (24.7)
3	Finland (12)	3.3 (7.3)	6.0 (13.2)	8.0 (17.6)	9.7 (21.4)	10.2 (22.5)	10.4 (22.9)
	Sweden	6.4 (14.1)	6.8 (15.0)	7.5 (16.5)	8.8 (19.4)	10.2 (22.5)	11.3 (24.9)
	US	3.5 (7.7)	5.7 (12.6)	7.4 (16.3)	9.3 (20.5)	11.0 (24.3)	12.4 (27.3)
4	Finland (22)	4.9 (10.8)	5.7 (12.6)	7.0 (15.4)	8.8 (19.4)	10.4 (22.9)	11.2 (24.7)
	Sweden	7.8 (17.2)	8.2 (18.1)	9.0 (19.8)	10.4 (22.9)	11.9 (26.2)	13.0 (28.7)
	US	4.3 (9.5)	6.6 (14.6)	8.4 (18.5)	10.1 (22.3)	11.7 (25.8)	13.8 (30.4)
5	Finland (14)	5.0 (11.0)	6.9 (15.2)	7.8 (17.2)	9.0 (19.8)	10.7 (23.6)	11.7 (25.8)
	Sweden	9.4 (20.7)	9.9 (21.8)	10.8 (23.8)	12.4 (27.3)	14.2 (31.3)	15.2 (33.5)
	US	5.4 (11.9)	7.7 (17.0)	9.6 (21.2)	11.4 (25.1)	12.8 (28.2)	15.0 (33.1)

[a] Finland: calculations based on field measurements (Kalamees et al. 2006); value in parentheses indicates number of houses. Sweden: simulations by Johansson et al. (2010). US: simulations by Pallin et al. (2016).

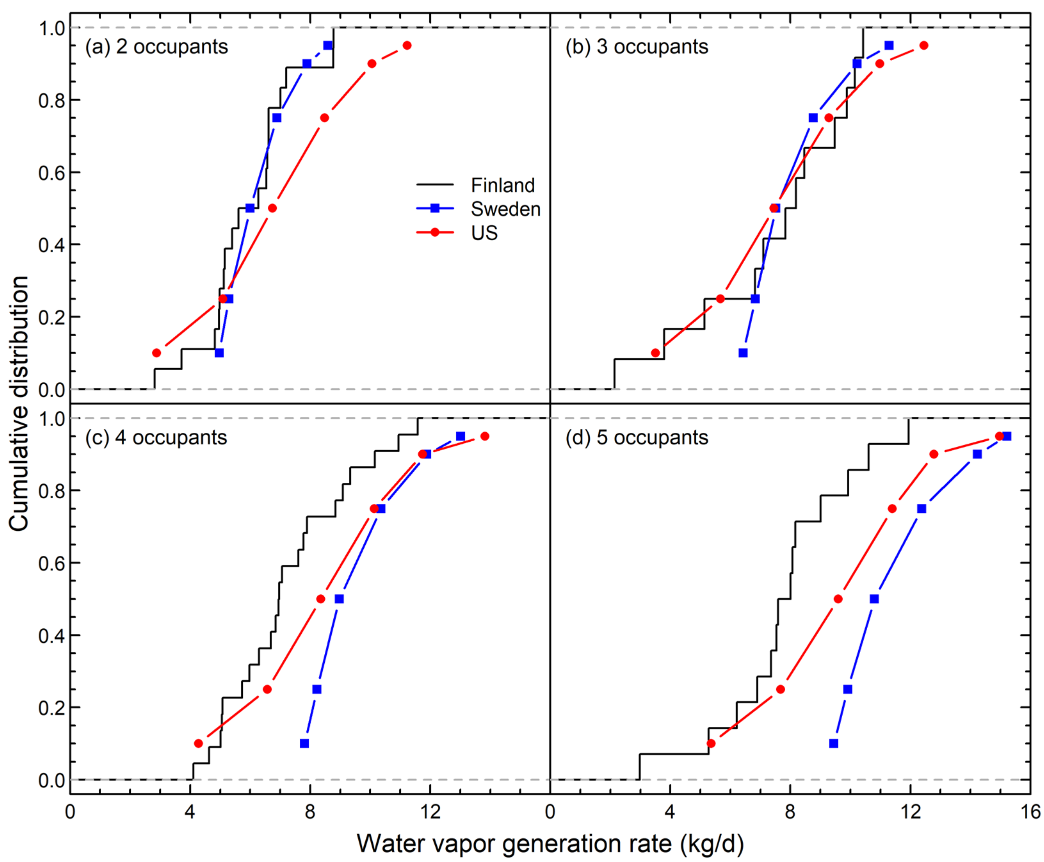

Figure 5 Comparison of water vapor generation rates by number of occupants for the sample of detached houses in Finland based on measurements, and for detached houses in Sweden and the United States based on probabilistic simulations (Johansson et al. 2010; Pallin et al. 2016).

DISCUSSION

The field measurement approach provides an effective daily generation rate based on measured data in real buildings. In principle it can be used to validate other methods. However, several limitations need to be recognized. First, if the aim is to characterize the variation in occupant behavior across a population, then a much larger sample size would be necessary for meaningful statistical analysis. Second, combined measurement uncertainty can be more than 20% considering the uncertainties in air exchange rates and indoor and outdoor vapor pressures. In humid climates, where interior water vapor is removed by air-conditioning or dehumidification equipment, condensate measurements are needed, which may introduce additional uncertainty (Martin et al. 2021). On the other hand, if no systematic errors were present, the impact of random error would diminish as the sample size increased. Third, several assumptions necessary for calculating generation rates may be questionable, such as assuming the house interior is a single well-mixed zone and neglecting vapor diffusion through the building envelope. Fourth, the field measurement method is typically unable to resolve generation rates on shorter time scales (e.g., hourly) because of the difficulties involved in accounting for moisture buffering.

The probabilistic simulation approach has several advantages. It is based on statistical data from surveys, which generally have a sufficiently large random sample to be representative of the population. The survey data allow for granularity in time according to hour of the day, weekday vs weekend, and season. The data also provide granularity in location within a building (e.g., kitchen, bedroom, bathroom), which can be useful in whole building simulations. Nevertheless, several limitations remain. This approach relies on measured generation rates for individual sources, each having associated measurement uncertainty, so the total generation rates include cumulative uncertainties that are difficult to quantify. For certain sources of water vapor, available survey data is often limited, outdated, or of questionable applicability. The studies in this paper reflect survey data available in Sweden as of 2010 and the United States as of 2016. Some of the original survey data come from the 1980s. Lifestyles have changed significantly since then. Broad trends, such as a larger percentage of the population working from home even before the COVID-19 pandemic, would not be reflected in older survey data. Given the major shift associated with the pandemic, new survey data are needed to accurately model water vapor generation rates in residential buildings.

CONCLUSIONS AND RESEARCH NEEDS

This paper compares two methods of quantifying the rate of water vapor generation in residential buildings, using data for single-family detached houses. The first is probabilistic simulations based on survey data from Sweden (Johansson et al. 2010) and the United States (Pallin et al. 2016). The second approach involves mass balance calculations based on field measurements of a sample of houses in Finland (Kalamees et al. 2006).

Probabilistic simulations indicate that water vapor generation rates increase monotonically with the number of occupants. For a given number of occupants, the US had broader variation than Sweden. This was most likely a result of differences in lifestyle between the populations.

Generation rates based on field measurements also increase with the number of occupants. However, the increase was not always monotonic. The limited number of houses in the study was likely the source of anomalies.

Probability distributions for water vapor generation in houses in Finland with two or three occupants agreed closely with simulated distributions for houses in Sweden and the US. However, generation rates for houses with four or five occupants in Finland were consistently lower than those in Sweden and the US at the 25^{th} percentile and above. It is not clear whether discrepancies were a result of lifestyle differences between populations, uncertainties in each method, or the limited number of houses studied in Finland.

The mass balance approach has the advantage of being based on measured data in real buildings. However, given the need for a large sample size and inherent measurement uncertainties, research using this method may be more effective when targeted at validation of specific models rather than broad characterization of occupant behavior.

The probabilistic simulation approach has the advantages of being based on representative statistical data and accounting for variation in water vapor generation by hour of the day, day of the week, season of the year, and location within the building. However, survey data are outdated. Lifestyles have changed significantly because of the COVID-19 pandemic. Research is needed to accurately account for current occupant behavior in residential buildings. In addition, research is needed to better characterize the rate of water vapor generation from individual sources.

ACKNOWLEDGMENTS

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