STOCHASTIC MODELING OF MOISTURE SUPPLY IN DWELLINGS BASED ON MOISTURE PRODUCTION AND MOISTURE BUFFERING CAPACITY

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ABSTRACT

The indoor moisture production is of great interest when simulating the indoor air humidity. Surface materials in an apartment will buffer some of the moisture produced depending on the features of the materials. Monte Carlo simulation of stochastically chosen moisture production rates in dwellings coupled to the moisture buffering capacity of surface materials, the ventilation rates and the outdoor climate define the moisture supply in a dwelling. The resulting distribution and variation of the indoor moisture supply are critical when designing moisture safe and durable buildings.

INTRODUCTION

The present need of energy retrofitting measures in the existing building stock in Europe increases the risk of damages in the construction. Approximately 66% of all Swedish buildings have damages in some way according to the Swedish National Board of Housing, Building and Planning. 45% of the damages that were discovered were defined as moisture damages, mostly in crawl spaces and in attics. The durability of the construction and the indoor climate are affected by the moisture damages (Boverket, 2009). Indoor air humidity is one of the most important parameters when designing building envelopes. Therefore, it is import to generate realistic design values for the indoor air humidity (TenWolde & Pilon, 2007). In order to take the random variations of, for instance, the indoor moisture production in account already in the design phase, simulation tools based on random variations are needed (Stein et al., 2011).

Interior material surfaces in a room buffer some of the moisture produced in the dwelling. Previous studies (Derluyn et al., 2007; Janssen & Roels, 2009; Svennberg et al., 2004) have shown that materials facing the indoor air have potential to buffer moisture depending on the properties of the material. For instance, paper and books buffer a larger part of the excess moisture compared to textile fabrics.

This paper develops a detailed simulation model of the moisture supply in a dwelling presented in (Johansson et al., 2011; Pallin et al., 2011) with regard to the moisture buffering of materials in the dwelling. The simulations are based on Monte Carlo simulation of stochastically chosen moisture production rates in Swedish dwellings. The moisture buffering capacity of surface materials, the ventilation rate and the outdoor climate are used to define the distribution and variation of the indoor moisture supply. An analytical solution to the step response of moisture buffering is used to model the buffering capacity of the material surfaces in the dwelling. Furthermore, the results are compared to measured data of the moisture supply in Swedish dwellings.

SIMULATION ALGORITHM

The simulation algorithm of the indoor air humidity is presented in Figure 1. First the type of dwelling, number of family members and the household composition are simulated for 1000 randomly choosen dwellings based on statistical data. The simulation results are then used to simulate the user behaviour based on new statistical data to estimate the occurrence and expected duration of an activity. Measurements of moisture production rates from typical residential moisture sources are also required to simulate the level of moisture generation. The result is stochastic variations of the hourly indoor moisture production in Swedish dwellings.

Further, the distribution of the indoor moisture production is used together with the moisture buffering capacity of the material surfaces in the dwelling. Expected variations of the ventilation rate in the randomly chosen dwellings together with the outdoor climate are used as inputs in the simulation model of the indoor air humidity. The end result of the algorithm is a distribution of the hourly indoor air humidity in households based on stochastic variations of the input parameters.

The effect of the hygroscopic moisture buffering is likely to reduce the influence of the excess moisture on the vapour content of the indoor air. If the water vapour pressure is higher in the material surfaces than in the air, moisture from the air will be absorbed in the material surfaces. If instead the water vapour pressure is higher in the material surfaces, moisture from the materials will be released into the air.

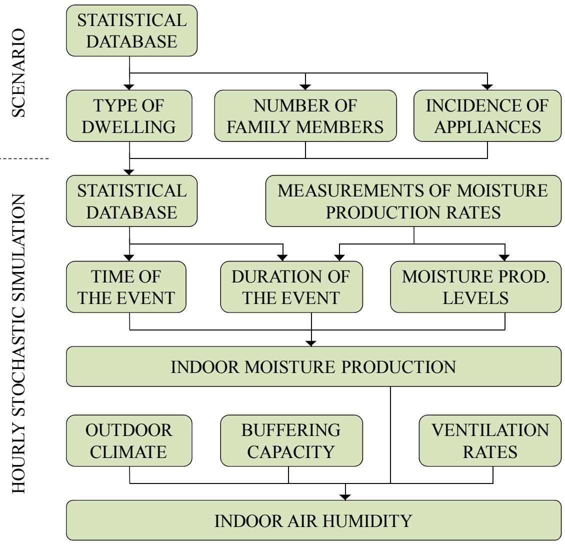

Figure 1 Statistical data create a scenario where a specific number of occupants inhibit a dwelling with a specific number of moisture generative appliances. The scenario together with another set of statistical data and measurements of moisture production levels decide at what time an event takes place, the duration of the event and the produced moisture level. The resulting moisture production, outdoor climate, buffering capacity in materials and ventilation rate are used to calculate the resulting indoor moisture supply.

Household composition

The variations of the indoor moisture production in dwellings depend on a number of conditions. Human behaviour together with the occurrence of technical appliances and installations will affect the moisture production rates. There are two types of dwellings: multi-family and single-family houses. The type of dwelling together with the number of bedrooms will influence the number of people living in the household and the household composition. The probabilities of a certain household composition, at specified conditions, can be obtained from statistical surveys of the building stock. This study uses statistical data from Statistics Sweden (2010) of household composition and dwelling areas.

An estimation of the total indoor moisture load requires the incident frequencies of human behavior (Christian & Trechsel, 1994). The activity pattern of the individuals can be obtained from statistical information, such as time user surveys (HETUS, 2005-2007).The user frequiencies of appliances and other moisture generative activities can be derived from the composition of the household .

Moisture from appliances and activities

There are a large number of moisture generative activities inside a dwelling. Table 1 presents common moisture sources in households and predicted variations of the moisture production levels. The variations are based on several studies summarized by Johansson, Pallin and Shariari (2010).

Table 1

Common indoor moisture sources in households together with expected variations of the moisture production (Johansson, et al., 2010).

INDOOR MOISTURE SOURCES	
	[kg/Event]
Bathing	0.06-0.16
Showering	0.20-0.40
Sauna bathing	0.00-1.28
Whirlpools	0.12-0.32
Tumble drier	0.00-0.70
Unvented drying	1.25-3.50
Ironing	0.00-0.60
Floor mopping	0.30-5.00
Breakfast	0.13-0.52
Lunch	0.25-1.75
Dinner	0.47-3.86
Hand dishwashing	0.10-0.60
Dishwashing machine	0.20-0.40
	[kg/day]
Humans	0.50-2.00
Pets	0.10-1.20
Aquarium	0.40-1.40
Plants	0.10-0.50

There is a large difference between the expected peak values in the presented moisture sources. Concerning the moisture generation from making lunch and dinner, the amount of moisture released varies greatly with the cooking methods (Angell & Olson, 1988). For example, the cooking process used in China generates a large amount of moisture due to stir-frying and boiling (Yik et al., 2004).

The moisture generation from unvented drying mainly depends on the accumulated water and vapour within the fabric of the clothing. All moisture released during the drying process will be excess moisture supplied to the indoor air. The moisture generation rate depends on the amount and type of clothing, the indoor relative humidity and the temperature of the indoor air. The drying process when performing unvented drying may last between 7 to 15 hours, while about 20% of the total moisture generation occurs during the first hour (Yik, et al., 2004).

Simulations of the indoor moisture production, based on the expected variations of moisture generation rates, require knowledge of the user behaviour of the occupants. Concerning moisture production, there are three noise factors, i.e. uncertainties, which will affect the moisture sources. The three noise factors are time, duration and level, see Figure 1. The time of the moisture source refers to at what specific time the moisture production initiate. The duration defines how long period of time the moisture source proceeds and the level defines the expected moisture generation rate per time step.

The computer model designed for simulating the indoor moisture production must be able to work with multiple distributions of parameters. Once the distributions have been defined, the model must choose likely values of the parameters. The model must also be able to work with correlations in the parameters. Example of a correlation concerning the indoor moisture sources are the activity from food preparation and dishwashing.

This study uses Monte Carlo simulations to simulate the indoor moisture production. The Microsoft Office Excel add-in @Risk satisfies the previously stated requirements and is used to perform the Monte Carlo simulations to create a number of possible outcomes based on the spread among the input parameters (Palisade, 2011).

Moisture buffering

The material properties that determine the buffering capacity can be described by the vapour permeability, δ_v (m^2/s), and the moisture capacity, ξ (kg/m^3). Depending on the present relative humidity and earlier state of relative humidity in the air, the absorption or desorption properties of the material can be decided, these parameters are varying with the relative humidity. In this study, the average properties for relative humidity between 30% and 80% are used. The properties for timber, gypsum board and textile carpet are presented in Table 2.

Table 2

Vapour permeability and moisture capacity for timber, gypsum board and textile carpet (IEA, 1991).

MATERIAL	**VAPOUR PERMEABILITY** δ_v **(m^2/s)**	**MOISTURE CAPACITY** ξ **(kg/m^3)**
Timber	$7.1\cdot10^{-7}$	75
Gypsum board	$25\cdot10^{-7}$	23
Textile carpet	$1.0\cdot10^{-7}$	13

The material properties together with the exposed surface area of each material determine the amount of buffered moisture. A survey (Svennberg, 2006) of the surface area of moisture buffering materials in 16 rooms in six three-room apartments in two buildings in Växjö, Sweden is used to estimate the buffering capacity of material surfaces inside the dwelling. Table 3 displays the percentage of each material with hygroscopic buffering capacity found in a random apartment.

Table 3

Percentage of exposed materials in Swedish apartments (Svennberg, 2006).

MATERIAL	**PERCENTAGE**
Wood – untreated	0.5
Wood surface – treated	14.6
Synthetic flooring	8.3
Wallpaper	33.4
Painted surfaces	20.8
Textile carpets	4.2
Textile furnishings	18.2

To estimate how large the total buffering surface area is in a randomly chosen apartment, the average floor area of a Swedish three-room apartment have been used (SCB, 2010). The average floor area is 81 m^2 and the total examined area in (Svennberg, 2006) was 1115 m^2. The relation between the buffering surface area and floor area in a random apartment is:

$$\frac{A_{buff}}{A_{apartment}} = \frac{1115}{16\cdot\frac{81}{3}} = 2.58 \text{ m}^2/\text{m}^2 \tag{1}$$

In the simulation model the residential floor area of each apartment is based on measurements (Boverket, 2009). The areas multiplied with the factor in Equation 1 together with the percentage of each material are used to obtain the total buffering capacity of the materials in the apartments.

The ventilation rate used in the model is obtained from (Boverket, 2009). An additional factor for unintended air leakage of 0.05 l/m^2/s and airing of 0.35 l/m^2/s is added to the ventilation rate. The factor for airing is only added when the indoor temperature rises above 23°C until it drops below 21.5°C (Eliasson & Lindström, 2009). Indoor temperature is modelled based on the outdoor temperature as specified in EN 15026 (CEN, 2007). The model uses a fixed ventilation rate for all hours, in this case the yearly average ventilation rate.

The step change solution, due to a unit change in the moisture production G (kg/s), for a ventilated room with the ventilation rate R_a (m^3/s), with moisture buffering of the surfaces into semi-infinite materials is denoted *f(t)*. The case neglecting surface resistances and considering the air fully mixed is:

$$v(t) = f(t)\cdot\Delta v \qquad f(t) = \left(1 - e^{\gamma^2 t}\cdot\operatorname{erfc}\left(\gamma\sqrt{t}\right)\right)$$
$$\Delta v = \Delta v_e + \frac{\Delta G}{R_a} \tag{2}$$
$$\gamma = R_a\sqrt{v_s(T)}\,\frac{1}{\sum_{n=1}^{N} A_n\sqrt{\delta_{v,n}\xi_n}}$$

where, A_n (m^2) represents the area, $\delta_{v,n}$ (m^2/s) the vapour permeability and ξ_n (kg/m^3) the moisture capacity of surface number n. Δv_e (kg/m^3) is the change in outdoor vapour content and $v_s(T)$ (kg/m^3) is the saturation vapour content in air with temperature T (°C).

An approximation of *f(t)* is used (Hagentoft, 2001):

$$f(t) = \left(1 - e^{\gamma^2 t} \cdot \operatorname{erfc}\left(\gamma \sqrt{t}\right)\right) \approx 1 - \frac{2 + \gamma\sqrt{t}}{2 + (1 + 4/\sqrt{\pi}) \cdot \gamma\sqrt{t} + \sqrt{\pi} \cdot \gamma^2 t} \quad (3)$$

Let us assume that the humidity by volume in the indoor and outdoor air is v_{e0} at time zero. At time 0, Δt, $2 \cdot \Delta t$, ... there are changes in Δv. We have:

$$\Delta v_i = \Delta v_{e,i} + \frac{\Delta G_i}{R_a} \quad (4)$$

In Figure 2, the step change in the moisture production each hour is illustrated:

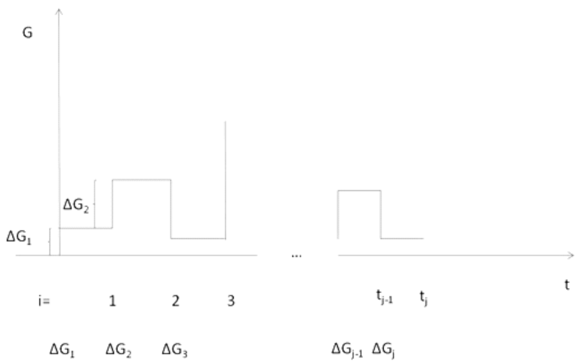

Figure 2 Moisture production each hour.

We would like to determine the humidity in the ventilated room with moisture buffering materials at time t_j:

$$t_j = j \cdot \Delta t \quad (5)$$

Using superposition, we then get:

$$\begin{aligned} v(t_j) &= v_{e,0} + \sum_{i=1}^{j} f(t_j - t_i) \cdot \Delta v_i \\ &= v_{e,0} + \sum_{i=1}^{j} f(t_j - (i-1) \cdot \Delta t) \cdot \Delta v_i \\ &= v_{e,0} + \sum_{i=1}^{j} f((j - i + 1) \cdot \Delta t) \cdot \Delta v_i \\ &= v_{e,0} + f(t_j - 0) \cdot \Delta v_1 + f(t_j - 1 \cdot \Delta t) \cdot \Delta v_2 \\ &+ f(t_j - 2 \cdot \Delta t) \cdot \Delta v_3 + \ldots + f(2 \cdot \Delta t) \cdot \Delta v_{j-1} + f(\Delta t) \cdot \Delta v_j \end{aligned} \quad (6)$$

Figure 3 illustrates how the buffering function in Equation 3 will look like in hour t_j.

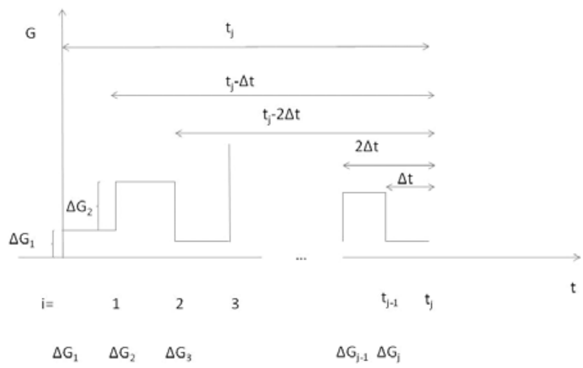

Figure 3 Moisture production each hour and the buffering capacity for each hour back in time.

Influence of climatic conditions

The outdoor climate used in the simulations are derived from the climate computer software Meteonorm (Meteotest, 1999). The climate represents the best reference year used in energy calculations. The purpose of the best reference year is to find the extreme conditions when calculation the heating demand in buildings. The outdoor vapour content in the climate file has been adjusted to the air volume expansion that takes place when the air enters the dwelling:

$$v_i = \frac{T_e}{T_i} \cdot v_e \ \text{ kg/m}^3 \quad (7)$$

where T_i (K) and T_e (K) are the temperatures indoor and outdoor respectively.

RESULTS AND DISCUSSION

The occupants and their user behaviour influence the simulation result of the indoor moisture supply each hour in a dwelling. This section presents the simulation results and a comparison with measured data.

Indoor moisture production

The indoor moisture production has been simulated using the algorithm in Figure 1. The data consists of 1000 scenarios of plausible Swedish households with hourly variations of the moisture production rate for each household during one year. The expected distributions and variations of the indoor moisture production are defined by the variations in the simulated input data. Previous studies of the indoor moisture production using the simulation model that is used in this paper shows good correlation with measurement data of the moisture production in dwellings (Johansson, et al., 2010).

The hourly variations of the indoor moisture production rates for the yearly average during the day and night are presented in Figure 4. For each hour, the mean values together with the variations of the 10th and 90th percentiles are presented. The shape of the distributions of the mean value and the 90th percentile shows good agreement. There are three local maximum values at 07:00, 12:00 and 18:00 for the two curves, and the absolute maximum occurs at 18:00. The mean moisture production rate at maximum is about 300 g/h and 50 g/h at minimum.

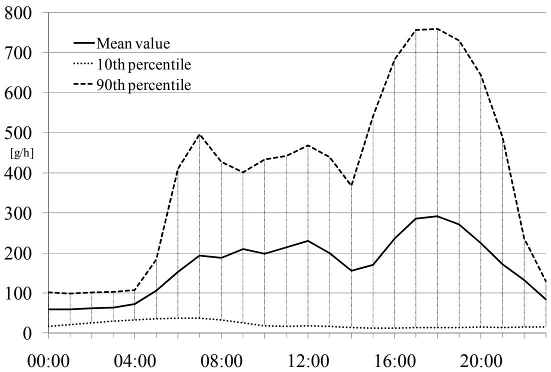

Figure 4 Hourly variations of the indoor moisture production based on simulation of 1000 Swedish household during one year. The graph is presenting the mean value, 10th and 90th percentiles on an average yearly daily basis.

Indoor moisture supply

The indoor moisture supply is defined as the influence of moisture productive activities on the indoor air. Simulations of the indoor moisture supply is performed using variations of ventilation rates, moisture buffering capacity of material surfaces, the indoor moisture production and the outdoor climate of a reference year in Gothenburg, Sweden.The hourly variation of the indoor moisture supply is based on 365000 values each hour which are presented in Figure 5. The two curves in the figure are presenting the hourly mean values with and without consideration of the hygroscopic moisture buffering capacity in the material surfaces. Both curves have a maximum mean value at 18:00 which is in correlation with the distribution of the indoor moisture production in Figure 4. The slope of the distribution with hygroscopic moisture buffering is smaller than the distribution without buffering. Consequently, the latter case results in more sudden changes in the indoor moisture supply because of a faster response to the differences in moisture production. The daily mean value of the indoor moisture supply is 1.6 g/m^3 for both cases.

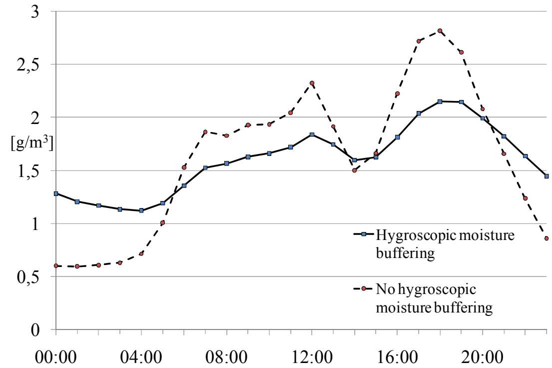

Figure 5 Hourly variations of the indoor moisture supply with and without consideration of hygroscopic moisture buffering capacity of surface materials. The graphs are presenting hourly mean values based on simulation of 1000 households during one year.

The moisture content in the air can be expressed as the relative humidity if available data of the indoor air temperature exists. By using the outdoor temperature and the relation between indoor and outdoor temperature defined in (CEN, 2007), the relative humidity can be calculated. Figure 6 shows the relative humidity in Swedish multi-family dwellings based on the simulations. The graph represents the hourly distributions of the mean value, 10th and 90th percentiles between the 22nd and 26th of February. The relative humidity is based on simulations of the best reference year in Gothenburg, Sweden with consideration of hygroscopic moisture buffering in the material surfaces in the dwelling. Typically, the expected mean value ranges between 50% and 60% during the defined period. The absolute maximum for the 90th percentile is 72% and the minimum value of the 10th percentile is 48%.

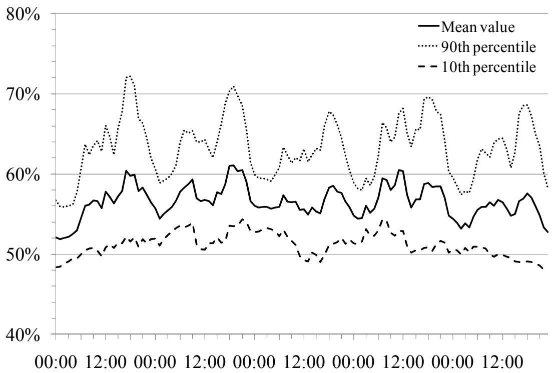

Figure 6 The variation of the simulated indoor relative humidity between the 22nd and 26th of Ferbuary in Gothenburg, Sweden. The graphs are presenting the hourly mean values, 10th and 90th percentiles with consideration of hygroscopic moisture buffering.

An analysis of the differences in the indoor relative humidity with and without the effect of hygrocopic moisture buffering is presented in Figure 7. The graph represents the hourly mean values of the relative humidity between the 24th and 26th of February. As predicted, the differences in the relative humidity in the dwellings are larger for the case of neglecting hygroscopic buffering compared to when the hygroscopic moisture buffering is taken into account.

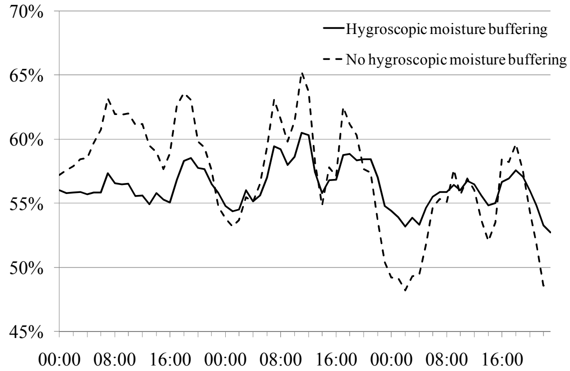

Figure 7 The indoor relative humdity between the 24th and 26th of February in Gothenburg, Sweden. The graph is presenting hourly mean values with and without condsideration of hygroscopic moisture buffering capacity of material surfaces.

A comparison of the resulting indoor moisture supply from the simulations in this study with measurements performed in the extract air in Swedish multi-family dwellings show good agreement. Figure 8 presents the results of measurements of the indoor moisture supply which are comparable to the simulated values presented in Figure 5.

A comparison with Figure 5 and Figure 8 gives important information on the distribution of the moisture supply in the dwelling on average during day and night. In the measurement results from spring and autumn, there is a clear minimum around 6:00 and a maximum value around 18:00. This is also the case for the simulated values presented in this study. During the winter, the distribution of the moisture supply in the apartments varies slightly less during the day but with a higher mean compared to autumn and spring. The summer is not included in the comparison due to other important factors, e.g. airing behaviour during summer, which will influence the indoor air humidity.

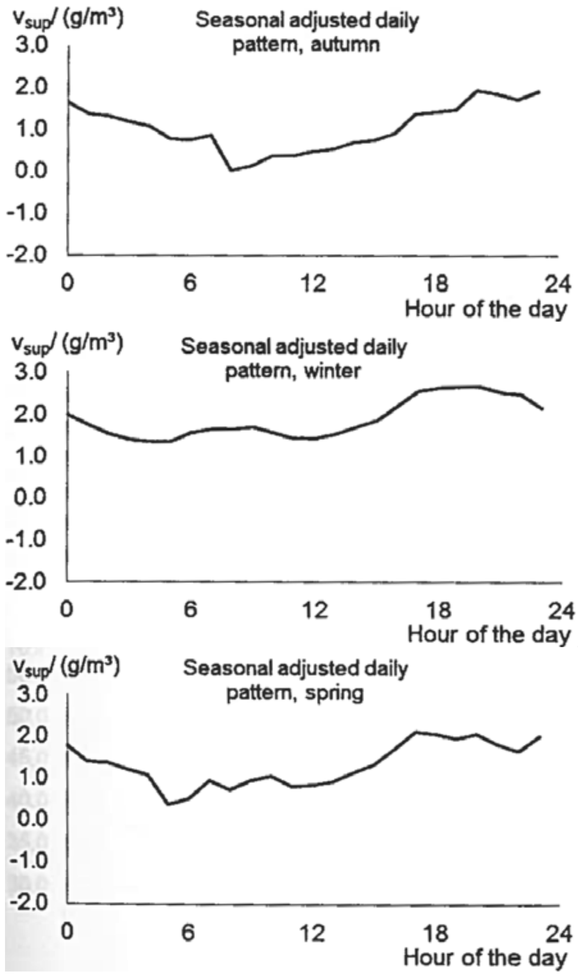

Figure 8 Indoor moisture supply, measured in Swedish multi-family dwellings in the extract air compared to the moisture in the outdoor air for autumn, winter and summer (Bagge, 2011).

CONCLUSIONS

This study uses a previously developed model to simulate the indoor moisture production in Swedish dwellings based on stochastic simulations of statistical data. The model has been developed to also take the hygroscopic moisture buffering capacity of interior material surfaces into account. Together with the ventilation rate and outdoor climate, the indoor moisture supply is simulated for 1000 random households to find the extreme design values for the indoor moisture supply.

The hygroscopic moisture buffering in the material surfaces influences the moisture supply in the dwelling. A comparison with the case when neglecting the hygroscopic moisture buffering shows that the difference is larger during the night than during the day. This consequence is coupled to the lower moisture production during the night. Hence, the moisture that has been absorbed by the material surfaces during the day is released during the night.

Measurements of the indoor moisture supply show good agreement with the seasonal average distributions of day and night for the autumn and spring. For summer, there are less evident daily variations in the measured data than in the simulation results. One possible explanation to this is the fact that the simulations do not consider the increased ventilation rate during summer due to airing behaviour. The simulation model needs to be more advanced in order to consider the airing behaviour.

The 90th percentile values of the indoor moisture supply presented in this study can be used in heat, air and moisture, HAM simulations. These data are useful in the design phase of building components to make sure the design is robust enough to withstand the extreme moisture loads from the indoor environment. If making more thorough HAM simulations or risk assessment of the building envelope, the complete distribution of the indoor moisture supply is preferably used to get the response also to the lower moisture loads.

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