The buffering effect of heavy timber constructions on the indoor moisture dynamic

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***KEYWORDS**: Heavy timber construction, indoor moisture dynamic, moisture buffer capacity.*

***SUMMARY**:*
Since the renewal of the fire regulations in the 90s, an alternative to the traditional light-weight timber frame structures particularly suitable for multi-storey dwellings has recently emerged in the Scandinavian countries under the generic name of massive wood construction or heavy timber construction. This concept provides manifold architectonic possibilities for the use of wood as a building and structural material, with the particularity among others of creating large areas of wood surface being directly exposed into an indoor environment. Regarding the hygroscopic properties of wood materials, this calls upon the possibility of buffering the indoor environment in term of moisture fluctuations by making use of the structure as a passive system. This paper discusses some insights and thoughts round about the notion of moisture buffer capacity through the examination of the indoor moisture dynamic registered into four apartments during the year 2003 at the Vetenskapsstaden multi-storey dwelling located in Stockholm. Numerical results are also provided to ascertain and highlight the holistic approach lying behind this concept where the control of the indoor moisture dynamic requires taking simultaneously into consideration several aspects of the building as the ventilation strategy, the structure configuration, the building use and the outdoor climate.

1. Introduction

The worldwide orientation of nations toward a sustainable development of societies generates nowadays a tremendous task still to be accomplished within the building sector regarding the achievement of healthy and comfortable indoor environments from low-cost, energy-efficient, and environmentally friendly solutions. These sustainable issues are understandable since human beings spend more than 90% of their time indoor, and recalling that the world building heritage consumes around one third of the total energy demand. It has to be recognised that a huge amount of research has endeavoured to achieve good indoor thermal comfort and energy-efficient solutions leading to more or less successfully implemented commercial applications during the second half of the twentieth century. Concerns to reduce the energy consumption has led to an increase of the thermal insulation level in order to reduce the heat loss transmission from the building structure, and to build airtight envelopes in order to minimise the heat losses arising from air leakage and thus enabling effective heat recovery from the exhaust ventilation system. Furthermore, the benefit gains from the thermal inertia of the building envelopes is largely recognised nowadays in international standard (EN ISO 13786, EN 832), and passive or hybrid systems of low-energy and even low-exergy have already been developed to achieve comfortable indoor temperature. However, when considerations arise concerning comfortable and acceptable indoor humidity levels, they oddly remain restricted to the general agreement that too dry and too wet conditions shall be avoided. Only recently has the impact of dampness on the health of inhabitants and on the Indoor Air Quality been studied more thoroughly (Fang *et al.*, 1998) (Toftum *et al.*, 1998a & 1998b), but research on the indoor humidity dynamic and solutions to control it in an efficient way is still in its infancy. Nevertheless, a general interest from the building practitioners and the scientific community appears more and more clearly to make use of the hygroscopic properties of building materials in order to even out the indoor humidity fluctuations in a similar fashion as one activates the thermal inertia of buildings to even out the indoor temperature fluctuations. It is foreseen that the building structures themselves could have much more to bring that only thermal, structural and aesthetical aspects. It is nowadays recognised that the adsorption and desorption of moisture from the building structure might play a significant role in the behaviour of the indoor moisture dynamics (Simonson *et al.*, 2001) (Plathner & Woloszyn, 2002) (Rode *et al.*, 2003). A concept trying to fix this phenomenon and known under the generic name of moisture buffer capacity has emerged in a recent workshop (Nordtest Workshop, 2003), but it is stressed that no consensus on a stringent definition has been reached yet. According to the opinion of the author, concepts such as effective moisture penetration depth, available water (Padfield, 1998), or still moisture effusivity are different ways of expressing an effective moisture capacity of a building material or envelope when subjected to controlled moisture boundary conditions, but it does not depict a buffer activity. The term moisture buffer capacity is alternatively defined in this paper as a quantification of the building structure ability to absorb and release moisture while maintaining the indoor humidity fluctuations of the specified built indoor environment in an acceptable range (Hameury, 2004). This definition stresses that the moisture buffer capacity shall not be regarded merely as a material properties but it implies a reciprocal interdependence between the building material or envelope considered and the environment into which it is applied. It calls upon an holistic approach of the problem, where different aspects such as the outdoor climate, the building structure, the building use and the HVAC strategy interfere, as shown in Fig. 1.

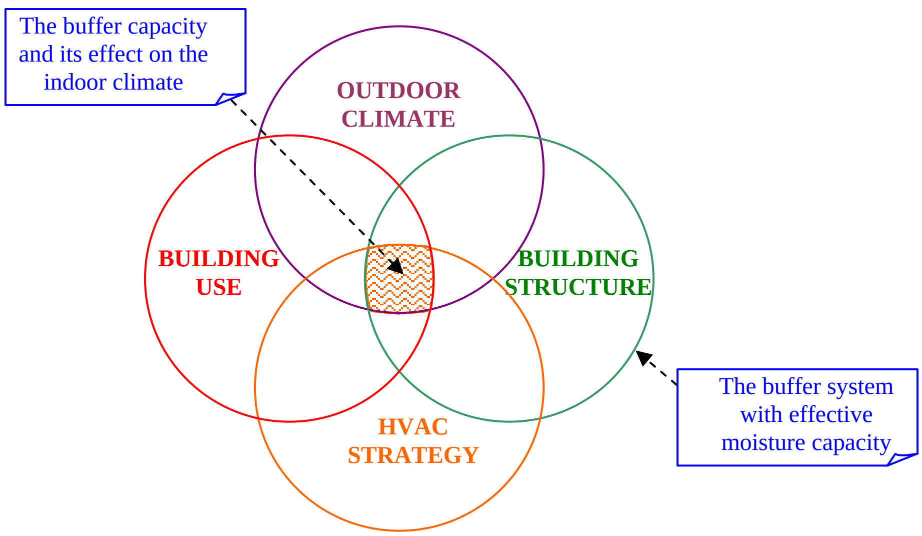

FIG. 1: Illustration of the holistic approach one shall consider when studying the moisture buffer capacity.

The idea of moisture buffer capacity is actually not something new and might be tracked down up to the mid 60s (Horie, 1965). It was also already pinpointed in the early 80s that as much as one third of the moisture loads generated in a room could be buffered by the building envelope ability to absorbed moisture (Kusuda, 1983). It has however been rediscovered recently since nowadays building design are in search of alternative solutions to high ventilation rates while maintaining healthy buildings. Numerical simulations with the implementation of moisture lumped models (Plathner & Woloszyn, 2002) or more sophisticated models with coupled heat air and moisture transport within the building envelopes (Simonson *et al.*, 2001) (Rode *et al.*, 2003) (Künzel *et al.*, 2003) (Hameury, 2005), and where the specified boundary conditions are the only outdoor climate data, all have shown the positive effect of applying hygroscopic materials facing an indoor environment. It has been followed in parallel by experimental investigations in laboratory (Padfield, 1998) and full-scale environmental chamber (Rode *et al.*, 2002) or even by a few in-situ measurement campaigns (Rode *et al.*, 2003) (Hameury, 2004). In this paper, the author further examines the indoor moisture dynamic evolution recorded during the year 2003 within four apartments of a four storey heavy timber dwelling known as the Vetenskapsstaden building, located in Stockholm, Sweden (Hameury, 2004). The moisture buffer effect of this innovative structural system where large area of wooden surfaces are directly exposed to the indoor is evaluated together with numerical simulations to emphasize the parameters of importance.

2. Indoor moisture dynamic and the buffer effect

During the year 2003, an attempt to record the moisture dynamic in four apartments of a multi-storey massive wood building in Stockholm was carried out. Each apartment covers a floor area of $34m^2$. The structure is provided by mineral insulation at the outside and plate-like massive wood panels at the inside, formed by 3 cross-linked wood layers (35mm wood / 22mm air cavity / 35mm wood), and directly exposed into the indoor environment without any coating systems or additional gypsum boards. The ratio of directly exposed wood surfaces including walls, floors and ceiling, to the total surface in each apartment is estimated to 40%. The ventilation rate remains stable at $0.8h^{-1}$. The indoor and outdoor relative humidity and temperature were recorded with a total number of 79 sensors set up to measure the temperature and moisture content at different depths within the structure at different locations. The sampled data were stored every hours in a host computer. A thorough description of the measurement campaign as well as of the Vetenskapsstaden building might be found in Hameury (2004) and will not be further discussed in this paper. The principal idea behind this campaign, in comparison to others (Rode *et al.* 2003), was to directly quantify the moisture buffering capacity of the structure by recording its moisture content dynamic, instead of usually carrying out and comparing 2 sets of measurements, namely one when the indoor is exposed to its structure and one when the structure is closed to moisture diffusion with the application of water vapour tight sheets on the interior surfaces. A second idea during the measurement campaign was to measure the moisture buffering phenomenon when the building was in use with people living inside. However, an important limitation of the method arises from the moisture content recording of the wooden structure since the moisture probes were at best fixed 3mm from the wood surface exposed to the indoor. This limitation hides any direct quantifications of the moisture buffer capacity considering the high frequencies of the indoor moisture fluctuations, i.e. below the daily time periods.

From the results achieved in the four apartments, it has been noticed that the indoor relative humidity fluctuations were relatively independent from the indoor temperature fluctuations, as shown in Fig. 2.

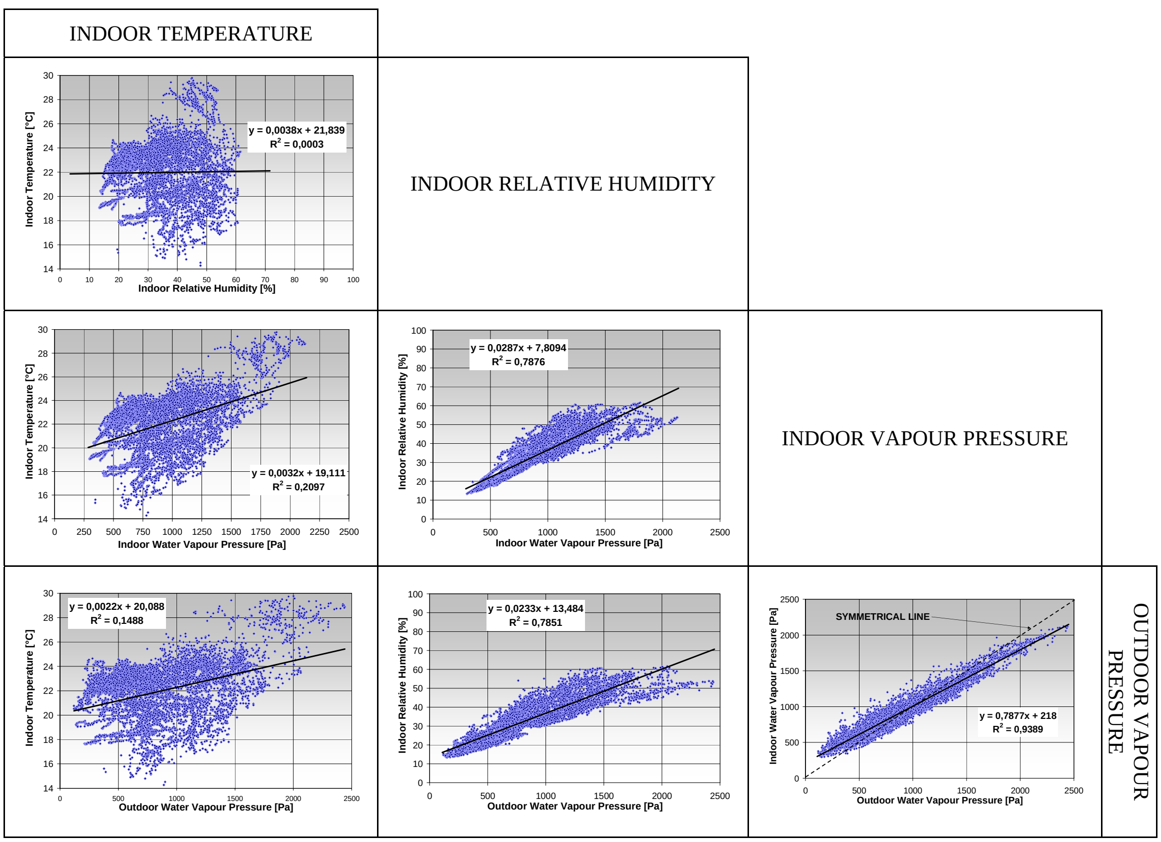

FIG. 2: Snapshot and correlation of the indoor variables recorded in the Apartment 3 situated north.

Similar results have been recorded for the three other apartments. This phenomenon has already been pointed out in the past from some field survey in New Zealand (Cunningham, 1994), where it was stressed that at low ventilation rate, the hygroscopic properties of the building materials facing the room highly influence the indoor relative humidity fluctuation in such a way to prevent any dependence of the indoor the relative humidity to the indoor temperature fluctuation. Another strong evidence of the buffering activity of the massive wood structure and the furniture arises from the dynamical analysis of the indoor water vapour pressure, which often lies below the outdoor water vapour pressure especially during the warm season, as stressed in Fig. 2. This also points out that the buffering effect of the structure is more efficient during the hot and humid periods since it is well known that high moisture and temperature levels are “catalysts” to the ad- and de-sorption of moisture by building materials. It is often underlined that this result might seen *a fortiori* not compatible with the most simple model stated by Equation (1)

$$\frac{\partial p_i}{\partial t} = n \cdot (p_o - p_i) + \frac{S \cdot R \cdot T}{V \cdot M}, \tag{1}$$

where t expresses the time (h), p_i the indoor water vapour pressure (Pa), p_o the outdoor water vapour pressure (Pa), n the ventilation rate (h^{-1}), S the moisture source strength ($kg.h^{-1}$), V the room volume (m^3), M the molecular weight of water, T the indoor temperature (°K), and R the universal gas constant. Here, the indoor humidity fluctuation depends on the ventilation rate and the moisture source strength but not on the moisture flows with the structure or the surface moisture condensations; and therefore a more reliable model should also consider all the above cited physical phenomena.

In a dynamical situation however, it is still interesting to analyse the general analytical solution obtained from the inhomogeneous linear ordinary differential Equation (1), without taking into consideration moisture exchanges with the structure in order to avoid the possible confusion between what could be perceived *a priori* as a moisture buffering effect but which appears to be an intrinsic dynamical effect caused by the indoor air volume and its moisture storing capacity. An elegant and simple way of solving Equation (1) is by the variation of parameters and one obtains:

$$p_i(t) = e^{-n \cdot t} \cdot \left[\int e^{n \cdot t} \cdot \left(n \cdot p_o(t) + \frac{R \cdot T}{V \cdot M} \cdot S(t) \right) \cdot dt + k \right] \tag{2}$$

where k is a constant to be determined by the initial conditions, but it is not of interest here since this additive constant exponentially decays with time and the solution then reaches a stationary state. From the use of complex Fourier transform and the principle of superposition, one analyses the response of the indoor water vapour pressure as a function of frequency. The average level is described by Equation (3) and the amplitude and time lag response to each frequency is extracted from the complex Equation (4):

$$\bar{p}_i = \bar{p}_o + \frac{R \cdot T \cdot \bar{S}}{n \cdot V \cdot M}, \tag{3}$$

$$\tilde{p}_i(w) = \left[\frac{R \cdot T \cdot S_w}{V \cdot M} + n \cdot p_{o\,w} \right] \cdot \frac{1}{n + i \cdot w} \cdot e^{i \cdot w \cdot t}, \tag{4}$$

where S_w and p_{ow} are the amplitude of the moisture strength source and of the outdoor water vapour pressure respectively at frequency w. For the sake of simplicity, the phase between the fluctuations of the moisture source strength and the outdoor water vapour pressure might be neglected. Equation (3) is the well known steady state solution, which suggests that the indoor water vapour remains above the outdoor water vapour differing from a constant. However, one directly see from Equation (4) that the ventilation system acts as a low-pass filter and this is further shown in Fig. 3 (*Left*) depicting the indoor water vapour pressure amplitude as a function of the frequency. It clearly shows that the amplitude of indoor water vapour pressure might be below the one of the outdoor water vapour pressure for low time period. Fig. 3 (*Left*) shows the results for a high moisture source strength with amplitude $66g.h^{-1}$ (i.e. a water vapour pressure amplitude of 125Pa) and decreasing this amplitude will affect and displace to the right the point where the indoor water vapour pressure amplitude crosses the fixed point of outdoor water vapour pressure amplitude. In other words, the less the moisture activity within the building is, the more range of the high frequency spectrum will find amplitudes of indoor water vapour pressure below the one of the outdoor water vapour pressure. However the moisture storing capacity of the indoor air volume is certainly not responsible for the results depicted in Fig. 2 since the power spectrum of the outdoor vapour pressure shown in Fig. 3 (*Right*) indicates that time period below 24h are not strong enough to create such a gap between the indoor and outdoor vapour pressure recorded in the four apartments. The results shown in Fig. 2 shall be thus credited to the moisture buffer capacity of the structure and the furniture.

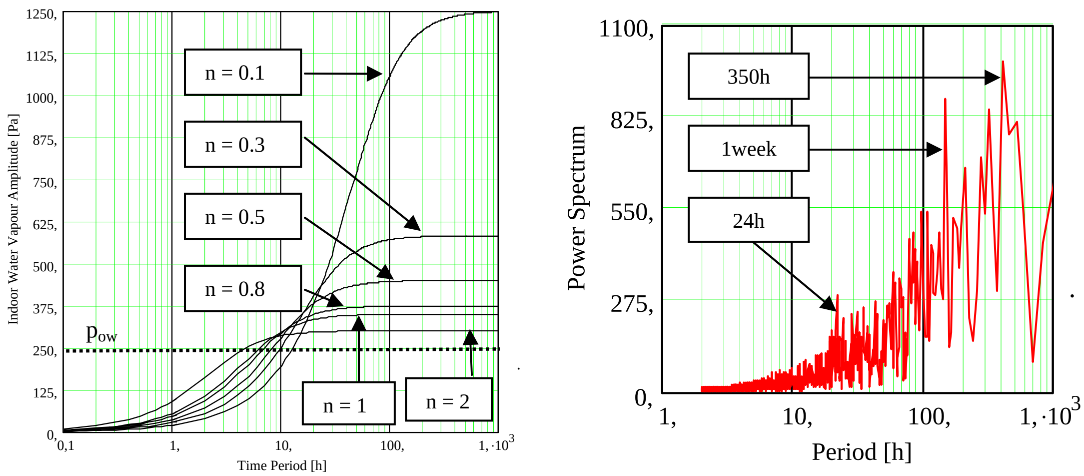

FIG. 3: Amplitude of the indoor water vapour pressure with p_{ow} = 250Pa and S_w = 66g.h^{-1}(Left), and power spectrum of the outdoor water vapour pressure recorded at the Vetenskapstaden building (Right).

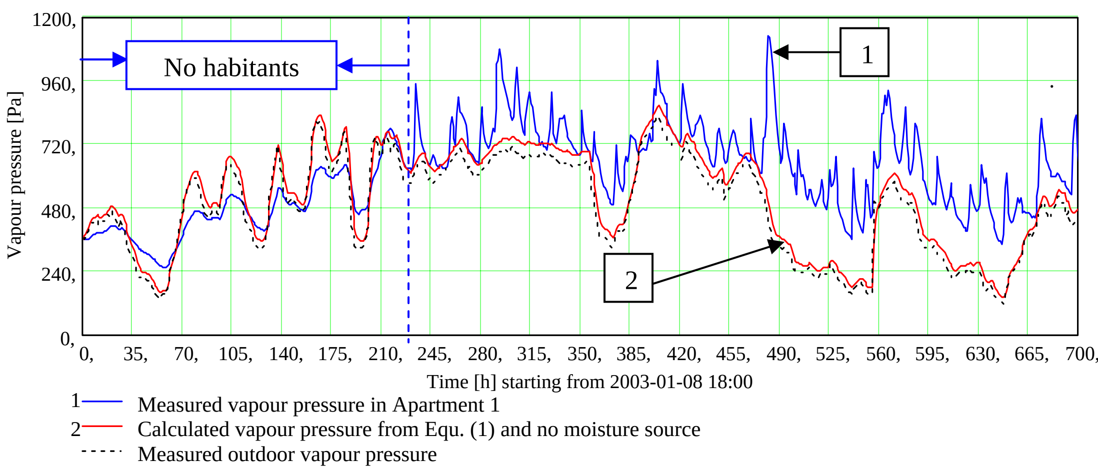

FIG. 4: Measured indoor water vapour pressure compared to the calculated indoor water vapour pressure highlighting the buffer capacity of the structure during the first 200 hours when there are no inhabitants.

From Fig. 4, one might clearly assess the buffering effect of the structure during the first 200 hours by simple comparison of the measured vapour pressure in apartment 1 and the calculated values from Equation (1) neglecting the moisture sources. The numerical result in Fig. 4 provides a clear comparison of what would have been the course of water vapour pressure in apartment 1 if no moisture exchange with the structure would have occurred. A moisture buffer factor can also be computed from a time average of the ratio of the slopes of the two curves. The result provides in this case and for the first 200 hours a moisture buffer capacity factor of 75%, i.e. the fluctuation are reduced by as much as three fourth compared to the case where the structure would be closed to moisture diffusion. This high factor is not surprising considering the small space volume of the apartments and the significant ratio of wood surfaces exposed to the indoor. Furthermore, the present course of vapour pressure recorded during the first 200 hours in apartment 1, would only have occurred with a ventilation rate as low as 0.1h^{-1} if the structure was supposed close to moisture exchange. At this point, it might be interesting to discuss the monthly averages of the difference between the indoor and outdoor moisture water vapour concentration. One can clearly notice in

Fig. 5 that the buffering capacity of the structure and the furniture controls the indoor water vapour concentration even though the ventilation rate is as high as $0.8h^{-1}$.

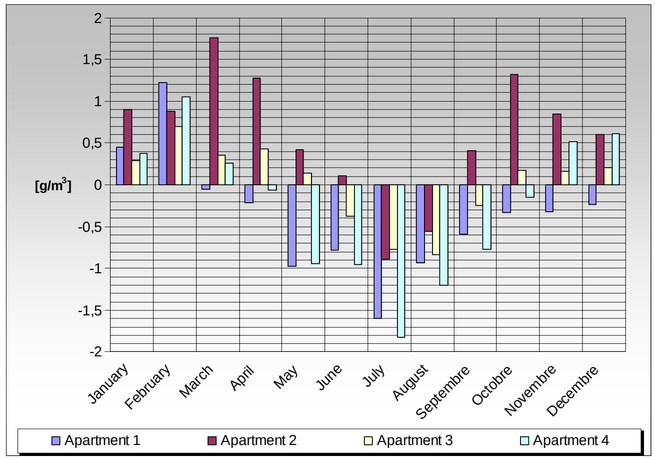

FIG. 5: Monthly average variation of the moisture concentration difference between the indoor and the outdoor environment for the four apartments.

3. Analysis of the perceived Indoor Air Quality within the 4 apartments

The intended goal with passive systems used to even out the indoor humidity fluctuations rests not so much on the possible increased thermal comfort but rather on the possibility to provide healthier indoor conditions with limited time of dryness and dampness and without further feeding the building with extra energy. Fang *et al.* (1998) discovered that the acceptance of the inhabitants towards their perceived Indoor Air Quality (IAQ) is a linear function (5) of the enthalpy H ($kJ.kg^{-1}$) on a scale from -1, where the IAQ is perceived as clearly unacceptable, to +1, where the IAQ is perceived as clearly acceptable:

$$Acc = -0.033 \cdot H + 1.662 \quad (5)$$

The acceptability of the IAQ in the four apartments is depicted in Fig. 6 for the entire year 2003. The results seem fairly good with an average around 0.45 and a limited spread of the values lying mostly between 0 and 1. However, it remains questionable if Equation (5) really depicts the acceptability of the perceived IAQ by inhabitants living in cold climates where dry indoor air conditions occur in winter.

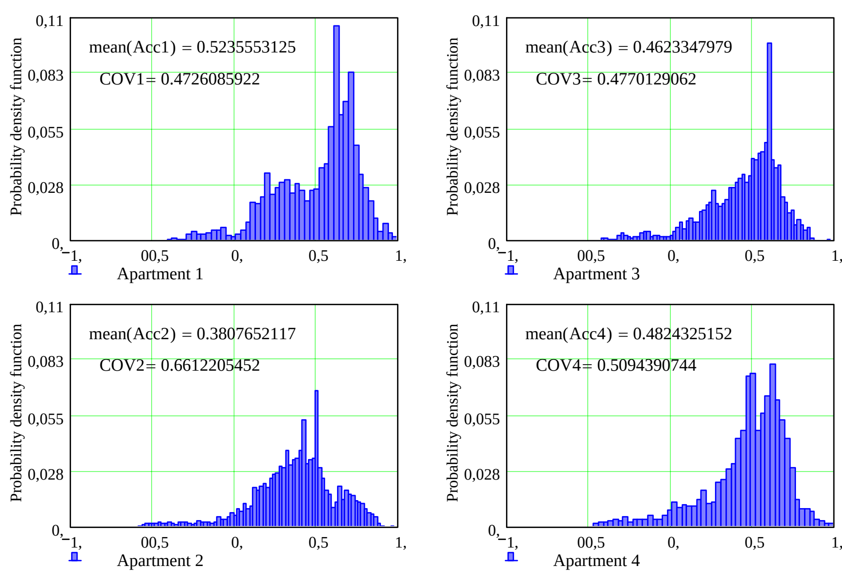

FIG. 6: Distribution of the perceived IAQ with the average and Coefficient of Variation.

4. Moisture dynamic within the massive wood structure

The dynamic of the water vapour pressure recorded within the four apartments has shown predominant fluctuations for the time periods similar to the one of the outdoor water vapour pressure shown in Fig. 3 (*Right*) and yet for 8h and 12h time periods to be credited to the indoor moisture sources. As can be seen in Fig. 7, it is noteworthy how well the massive wood walls respond to the indoor moisture fluctuation. The responses to the 8h and 12h time periods are clearly depicted at 3mm and even seen at 6mm even though to a lesser degree. This is surprising since it is common to state that the effective moisture penetration in wood is only 2mm already for daily time period. Furthermore, the power spectrum of the moisture content recorded at 9mm is not reported here but the first peak detectable lies at daily time period demonstrating that the structure does not interact with the indoor at this depth for time period lower than 24h.

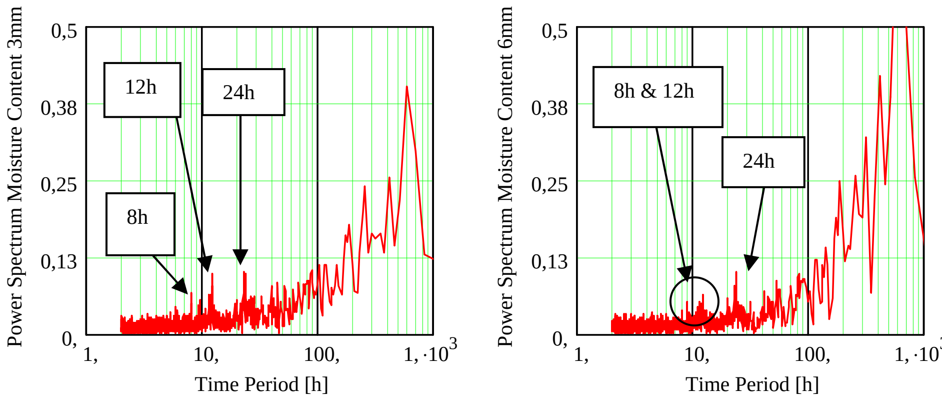

FIG. 7: Power spectrum of the moisture content measured in the massive wood walls at 3mm and 6mm from the indoor surface.

5. Holistic approach highlighted from numerical simulations

It has been stressed in the introduction that the moisture buffer capacity shall be considered from a holistic point of view integrating considerations on the ventilation strategy, the building use, the outdoor climate, and the structure itself. A numerical simulation with typical daily fluctuations of the outdoor climate in Stockholm has been carried out (Hameury, 2004) to illustrate this point and the major results are provided in Fig. 8. The apartment considered is one of the apartments at Vetenskapsstaden, orientated south-west.

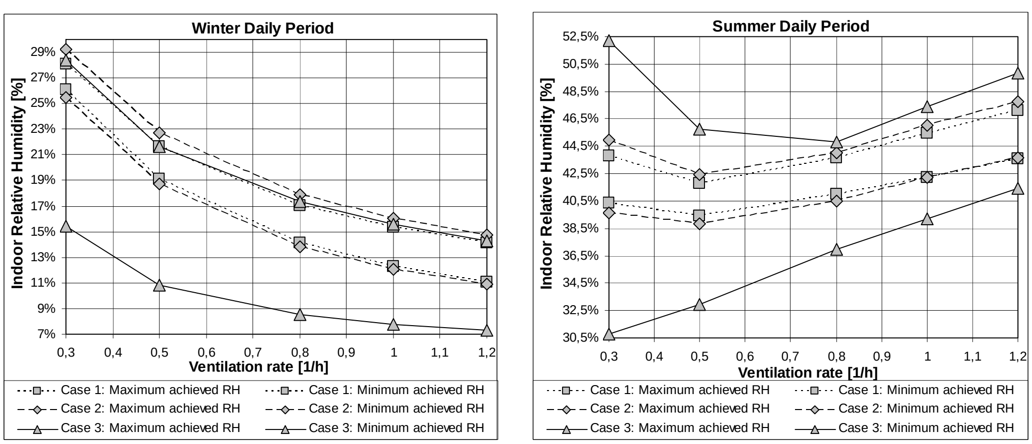

FIG. 8: Maximum and minimum achieved indoor relative humidity during the winter and summer period as a function of the ventilation rate and the moisture resistance at the indoor surface of the massive wood structure

The results provide insight of the sensitivity of the moisture buffer capacity to different settings of the ventilation rate and for three different cases, i.e. the wooden surfaces are directly exposed to the indoor

(Case 1), a highly water vapour permeable coating is applied (Case 2) and the structure is closed to moisture diffusion (Case 3). Benefits for the Case 1 and 2 are noticeable whatever the ventilation rate in winter and the best effect is achieved in summer for the Case 2 when the ventilation rate is set up at $0.5h^{-1}$.

6. Conclusion

In this paper the concept of moisture buffer capacity is discussed together with the holistic approach it implies. Furthermore, it is shown how the massive wood structure substantially evens out the indoor humidity fluctuations even though the ventilation rate is relatively high. It remains however difficult to quantify precisely the phenomenon and the effect in term of comfort for the inhabitants and their health. It is proposed here that the moisture buffer capacity shall refer to a reference case when moisture flow with the structure is blocked. Substantial savings might be achieved from the use of massive wood structures as a passive system against the energy demanding ventilation systems.

7. References

Cunningham M.J. (1994). Using Hygroscopic Damping of Relative Humidity and Vapour Pressure Fluctuations to Measure Room Ventilation Rates. Building and Environment, Vol. 29(4), p.501-510.

Fang L., Clausen G. and Fanger P.O., 1998. Impact of Temperature and Humidity on the Perception of Indoor Air Quality. Indoor Air, Vol. 8, p.80-90.

Hameury S. (2004). Heat and Moisture Buffering Capacity of Heavy Timber Constructions. Licentiate Thesis TRITA-BYMA 2004, KTH, Dept. of Civil and Architectural Engineering.

Hameury S. (2005). Moisture Buffering Capacity of Heavy Timber Structures Directly Exposed to an Indoor Climate: A Numerical Study. To be published in Building and Environment.

Horie, G. (1965). On the Reduction of Humidity Variation in a Room by the Absorption of Wall Surfaces. RILEM/CIB symposium on Moisture problems in buildings, Helsinki.

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

Kusuda T. (1983). Indoor humidity calculation. ASHRAE Trans., Vol. 89, Part 2, p.728-738.

Nordtest Workshop (2003). Moisture Buffer Capacity. Report BYG.DTU R-067, Technical University of Denmark.

Padfield T. (1998). The Role of Absorbent Building Materials in Moderating Changes of Relative Humidity. Doctoral Dissertation. The Technical University of Denmark, Dept. of Structural Engineering and Materials. Series R no. 54.

Plathner P., Woloszyn M. (2002). Interzonal air and moisture transport in a test house. Experiment and modelling. Buildings and Environment, Vol. 37, p.189-199

Rode C., Salonvaara M., Ojanen T., Simonson C., Grau K. (2003). Integrated Hygrothermal Analysis of Ecological Building. In Proceedings of the 2nd International Building Physics Conference, Leuven, Belgium.

Rode C., Mitamura T., Schultz J., Padfield T. (2002). Test cell measurements of moisture buffer effects. In Proceedings of the 6th Symposium on Building Physics in the Nordic Countries, Trondheim, Norway.

Simonson C.J., Salonvaara M., Ojanen T. (2001). Improving Indoor Climate and Comfort with Wooden Structures. VTT Publication 431.VTT Technical Research Centre of Finland.

Toftum J., Jørgensen A.S., and Fanger P.O. (1998a). Upper Limits of Air Humidity for Preventing Warm Respiratory Discomfort. Energy and Buildings, Vol. 28, p.15-23.

Toftum J., Jørgensen A.S., Fanger P.O. (1998b). Upper limits for indoor air humidity to avoid uncomfortably humid skin. Energy and Buildings, Vol. 28, p.1-13.