The effect of structures on IAQ and thermal comfort

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ABSTRACT
This study calculates the effect of permeable hygroscopic structures on IAQ and thermal comfort in a cold climate. Simulations are carried out for a detached house and application of criteria for assessment of indoor climate is given. The results show that hygroscopic structures significantly decreased the fluctuation of indoor relative humidity. In the winter, hygroscopicity had only minor effect on indoor climate, but in the summer, hygroscopicity had some effect on thermal comfort, which was improved at lower ventilation rates. In respect of thermal comfort the ventilation rate was a more important factor than hygroscopicity, as thermal comfort was greatly improved at higher ventilation rates. Hygroscopicity improved considerably perceived air quality in the summer when ventilation rate of 6 l/s/person in the non-hygroscopic case corresponded roughly to 4 l/s/person in the hygroscopic case.

INDEX TERMS
IAQ assessment; Humidity; Permeability; Modelling; Building physics

INTRODUCTION
Besides temperature, relative humidity (RH) is one of the key parameters of indoor climate. RH is determined by the indoor moisture production, air change rate and release or uptake of moisture by the hygroscopic surface materials. The significance of the exchange of moisture between the indoor air and the surface material has been discussed in many studies. Hagentoft (1996) concludes that the ventilation is of major importance for the indoor RH, and only about the first centimetre of the surface material is of some importance for the indoor climate especially for daily variations. Simonson *et al.* (2002) have come to a different conclusion, showing that hygroscopic structure is able to significantly improve perceived air quality. Both these studies are based on the simulation of a room similar to a two-person bedroom.

This study assesses the importance of the moisture exchange on indoor climate by computer simulation providing two new aspects compared to previous studies. First, a comprehensive set of criteria is used for the assessment, and secondly, an advanced model of a detached house comprising three modelled rooms is used.

METHODS
Criteria for Assessment of Indoor Climate
For assessment of the significance of hygroscopicity on indoor climate criteria for RH is needed, as hygroscopic materials mainly decrease fluctuations of RH. Excessively high and low RH has several health and comfort effects and it is not possible to use a single criterion for the assessment of these effects. Based on literature review, three main criteria were chosen for the assessment of hygroscopic effects:

- General criteria for thermal comfort (ISO 7730).
- Acceptability of perceived air quality (Fang *et al.*,1998)
- Health based criteria for excessively low relative humidity (Wyon *et al.*, 2002) and a criterion for the static charge of floorings.

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RH has only slight effect on thermal comfort, as thermal comfort basically means the sensation of cold or warm environment. Nevertheless, this criterion is to be used, because at high temperatures the effect of RH is much stronger as skin gets wet for ensuring evaporation heat transfer. When PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) are calculated according to ISO 7730, values for each hour of the simulated year are obtained. To compare the results of different cases, not the sum of hours exceeding the criterion but the sum of weighted hours is calculated as proposed in (Olesen and Parsons, 2002). Weighting factor is calculated for each hour exceeding the criterion set (20 and 30% PPD criterion is used) and then the results are summed.

$$W_\mathrm{f} = \frac{\mathrm{PPD}_\mathrm{actual}}{\mathrm{PPD}_\mathrm{criterion}} \qquad (1)$$

$$\sum W_\mathrm{f} t$$

where W_f is the weighting factor and t is time (h). Criteria for thermal comfort do not tell about the perception of indoor air quality. It is known that warm and moist air is perceived as stuffy almost independently on air quality, i.e. fresh air changes to stuffy one when it is heated or humidified. Fang *et al.* (1998) have shown that at constant indoor air quality, perceived indoor air quality is a function of enthalpy of the air. At a long-term full body exposure

$$\mathrm{Acc} = 0.7 - 0.012H \qquad (2)$$

where Acc is acceptability for polluted air (full exposure) and H is enthalpy (kJ/kg). According to Gunnarsen and Fanger (1992), the relation between the acceptability and perceived air quality is given by

$$\mathrm{PD} = \frac{\exp(-0.18 - 5.28\mathrm{Acc})}{1 + \exp(-0.18 - 5.28\mathrm{Acc})} 100 \qquad (3)$$

This criterion is very useful for comparison of non-hygroscopic and hygroscopic structures, as air quality is considered to remain the same in both cases (the same ventilation rate, the same pollution load, whereas material emission dependency on humidity is not considered) and only temperature and RH are varied.

In cold climates, low RH in the winter is problematic as it has effect on the skin and upper-airway symptoms. It is shown by Wyon *et al.* (2002) that 15% RH will increase the symptoms relative to 25% RH. In addition, for many flooring materials, limit values of RH leading to static charge are available.

Numerical Model of the Detached House

A half of one-storey house with internal dimensions 9.0 × 13 × 2.5 m (Figure 1) is modelled in IDA/ICE building simulation software (Sahlin, 1996). There is no moisture, air or heat exchange from the modelled part of the building to another part. The conservation of energy and mass equations are solved simultaneously for the indoor air and the structures by IDA/ICE solver. The moisture transfer equation in porous envelope parts uses humidity by volume as a transfer potential. Energy and moisture balances for envelope parts are

$$\rho c_p \frac{\partial T}{\partial t} = -\frac{\partial q''}{\partial x} = \lambda \frac{\partial^2 T}{\partial x^2} + h_\mathrm{vap} \frac{\partial w}{\partial t} \qquad (4)$$

$$\frac{\partial w}{\partial t} = -\frac{\partial g''}{\partial x} = \delta_\mathrm{v} \frac{\partial^2 v}{\partial x^2} \qquad (5)$$

where ρ is the density of the material, c_p is the specific heat capacity of the material (J/kg/K), T is temperature (K), t is time (s), q'' is heat flux (W/m^2), λ is the thermal conductivity (W/m/K), h_{vap} is the latent heat of the vaporization (J/kg), w is the moisture content (kg/m^3), g'' is the moisture flow ($kg/s/m^2$), δ_v is the moisture permeability (m^2/s) and v is the humidity by volume (kg/m^3).

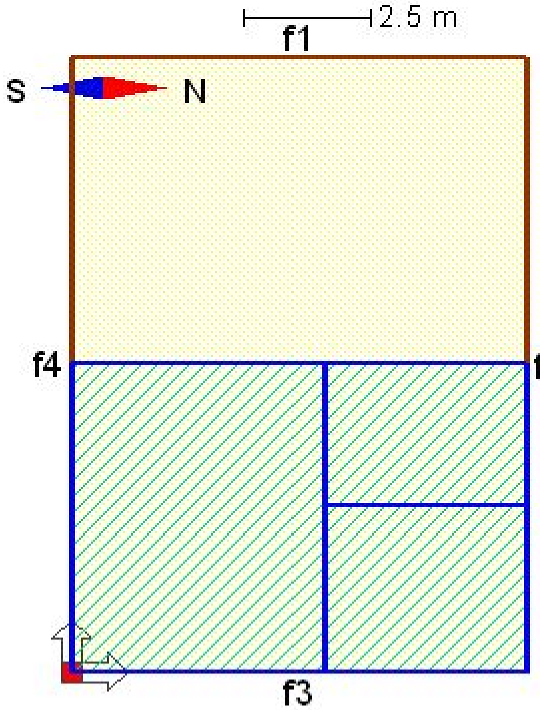

Figure 1 Modelled rooms of the detached house.

Description of the rooms, boundary conditions and structures used are given in Table 1. The climate of the test year (1979) of Helsinki, Finland is used.

Table 1 Description of the modelled rooms

	Living room	Bedroom 1	Bedroom 2
Occupancy	3 pers. at 07–08 and 16–23 working days and at 10–23 weekends	1 pers. at 21–07 working days and at 21–10 weekends	2 pers. at 23–07 working days and 23–10 weekends
Ventilation rate	4, **6** or 8 l/s/pers.	4, **6** or 8 l/s/pers.	4, **6** or 8 l/s/pers.
Intermediate door		0.8 × 2.1 m to living room, **open** or closed	0.8 × 2.1 m to living room, **open** or closed
Window size and direction	4.5 m^2 South	2.2 m^2 North	2.2 m^2 East
Window shading	Blinds between panes		
Hygroscopicity	High hygroscopicity and permeability of the interior wallboard, air barrier and insulation in hygroscopic cases. Moisture transfer in the structures is not calculated in non-hygroscopic cases		

Structures used except for that of the floor are shown in Figure 2. For the floor, moisture transfer is not calculated and a standard model RC-Wall of IDA/ICE is used. The floor consists of 15 mm pine wood, 0.3 mm paper, 80 mm concrete, 100 mm expanded polystyrene insulation and 1 m soil with 10ºC constant temperature at the bottom. All other structures are modelled with moisture transfer model HamWall, which is based on Fick's law and is validated in Kurnitski and Vuolle (2000). From Figure 2, the number of the computational cells in each material layer can be seen. For example, 11 mm fibre board of separated walls is divided into four cells with thickness of 1, 2, 4 and 4 mm. Material properties used are shown in Table 2.

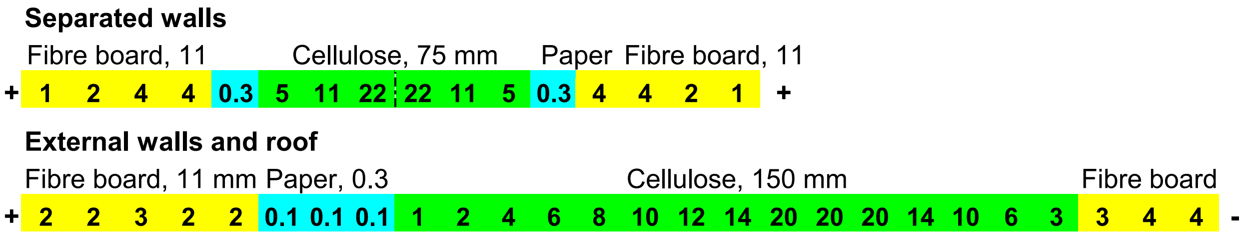

Figure 2 Structures used in the model and thickness of each layer of the material (mm); internal surface in the left side (+ indoor, – outdoor).

Table 2 Material property data

	Wood fibre board	Paper	Cellulose insulation	Pine wood	Concrete	Polystyrene insulation	Soil
Thermal conductivity, W/m/K	0.055	0.165	0.041	0.10	2.7	0.037	1.0
Specific heat capacity, J/kg/K	2100	1250	1400	2390	840	1200	800
Volume weight, kg/m^3	310	840	30	425	2200	20	1500
Moisture permeability[a], m^2/s							
δ_0, m^2/s	2.71×10^{-6}	1.08×10^{-7}	5.41×10^{-6}	–	–	–	–
B, -	5.41×10^{-6}	3.92×10^{-7}	1.69×10^{-5}				
C, -	3.11	3.44	1.57				
Sorption isotherm[b]							
1st point (w_1, kg/m^3; ϕ_1, %)	39; 90	2.8; 90	4.3; 80	–	–	–	–
2nd point (w_2, kg/m^3; ϕ_2 = 100 %)	93	8.6	9.0				

[a] Moisture permeability is given by $\delta_v = \delta_0 + B(\phi/100)^C$, where δ_0, is a constant value at ϕ = 0%, B and C are constants and ϕ is the relative humidity (%).
[b] Sorption isotherm is given by two lines starting at w = 0 kg/m^3 and ϕ = 0% and having a deflection point at (w_1; ϕ_1) and end point at (w_2; ϕ_2 = 100%).

RESULTS

Indoor temperature and RH in the summer are shown in Figure 3. Air change rate is 6 l/s/person and doors of bedrooms are open. In the hygroscopic case, fluctuations of RH are significantly decreased and RH is slightly lower in the living room than in the two-person bedroom. In the non-hygroscopic case, RH is almost the same in both rooms.

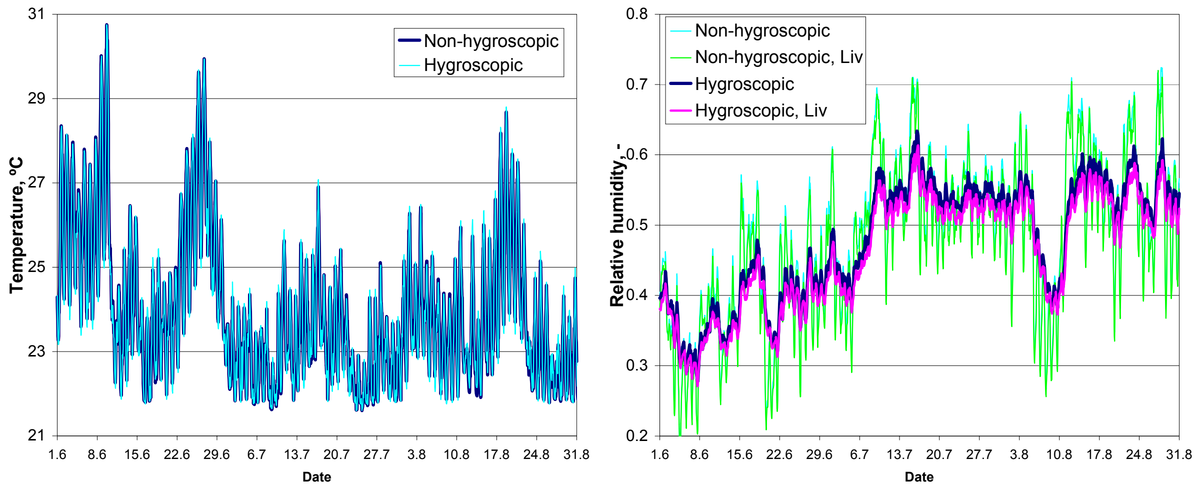

Figure 3 Temperature in two-person bedroom and RH in the bedroom and living room (Liv).

Differences in the temperatures are not significant (cannot be seen from Figure 3), but they are important when studying the behaviour of the moisture model. The moisture exchange has slight effect on the temperature as shown in Figure 4. The temperature tends to fluctuate slightly more in the hygroscopic case, which is explained by the heat of evaporation. Evaporation from the internal surface of walls (negative values) has a cooling effect and moisture uptake (positive values) heating effect.

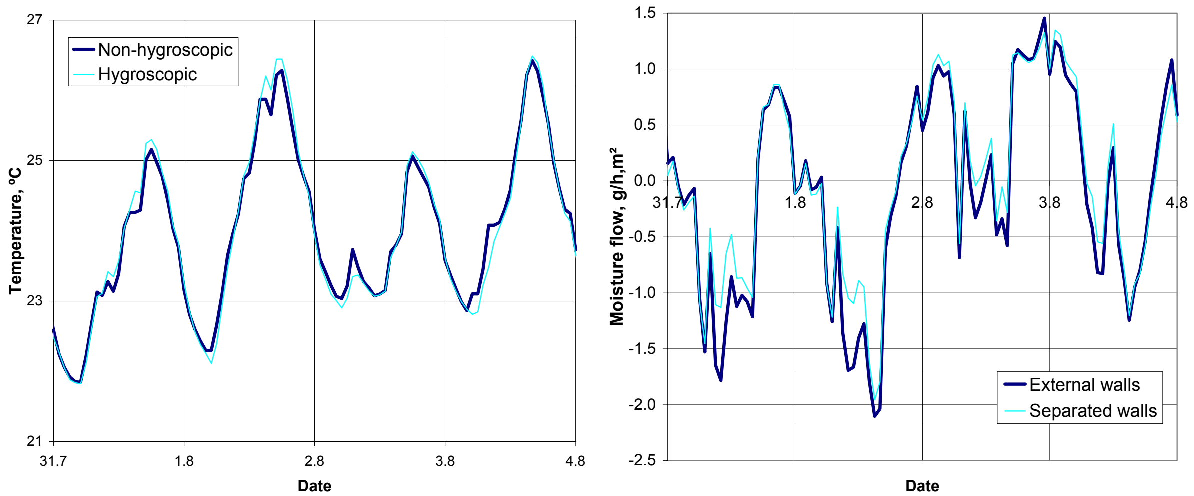

Figure 4 Temperature and moisture exchange between the indoor air and the surface material for external walls and separated walls. The moisture uptake is marked positive.

To compare the duration of RH, occupied hours only are considered. When all the hours of the period are used the results are different especially in the non-hygroscopic case, as shown for summer period in Figure 5(a). In the winter period the effect of hygroscopicity is less significant than in the summer, Figure 5(b). The number of hours RH < 15% during the whole year is 177 h in the hygroscopic case vs. 210 h in the non-hygroscopic case.

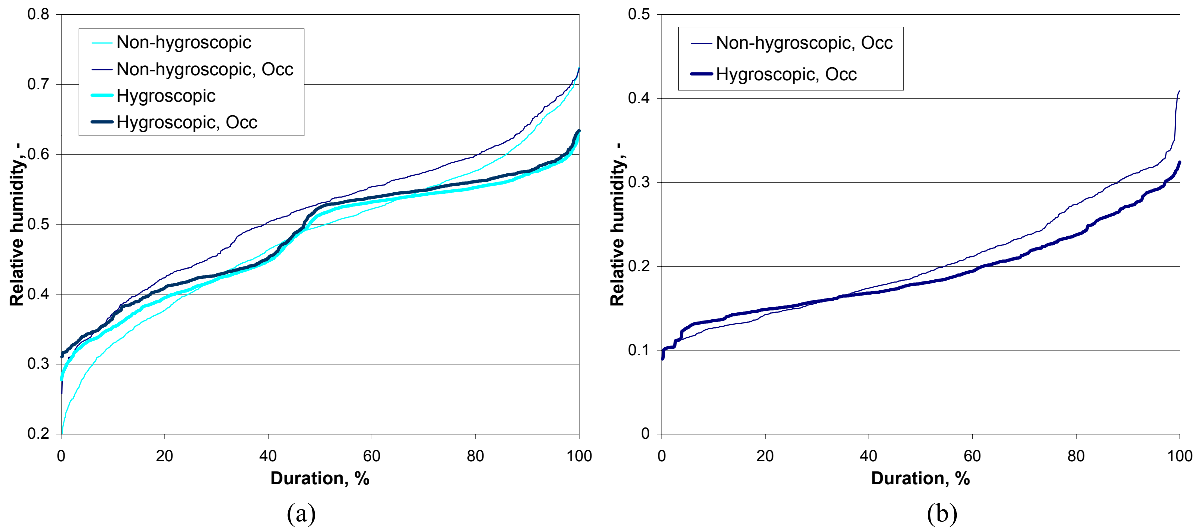

Figure 5. Duration of RH in (a) the summer (1 June to 31 August) and in (b) the winter (1 December to 28 February) when occupied hours (Occ) or all the hours of the period are considered.

To assess thermal comfort and IAQ, PPD and PD are calculated according to ISO 7730 and Eqns (2) and (3). For the assessment of thermal comfort, hours exceeding the criterion are weighted with corresponding PPD values, Eqn (1), and then summed. For the perceived air quality, simply the sum of the excess hours is calculated. The results for two-person bedroom during the whole year are shown in Figure 6. Although the whole year is considered, the excess hours occur in the warm summer period as indoor climate is well controlled during the heating season.

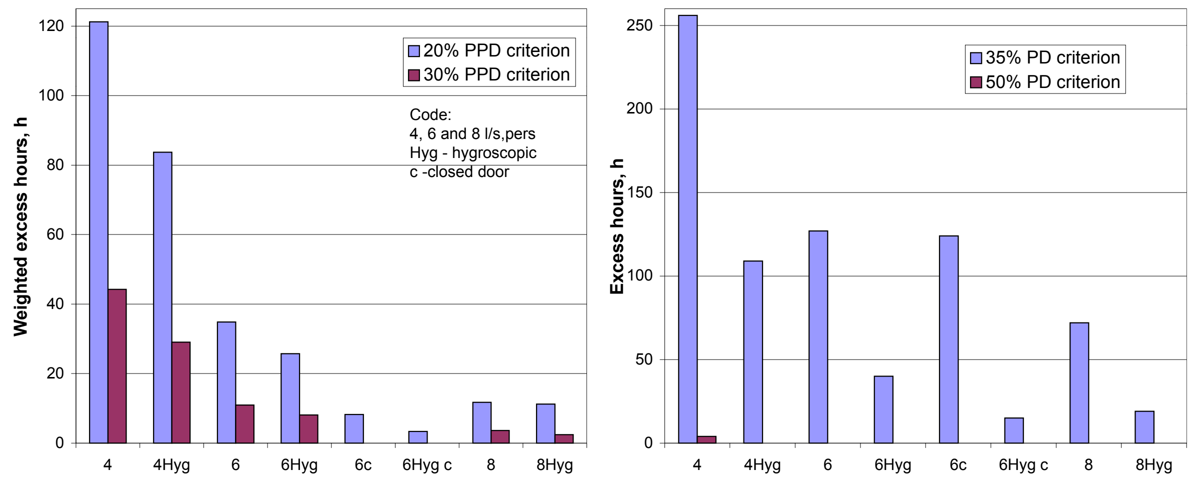

Figure 6 (a) The sum of the weighted hours exceeding the PPD criterion of thermal comfort and (b) the sum of the hours exceeding the PD criterion of perceived air quality.

CONCLUSIONS

Hygroscopic structures studied decreased significantly the fluctuation of indoor RH and decreased the maximum value of RH from about 70 to 60%. As indoor RH was relatively low all year round due to cold climate, the assessment of the significance of hygroscopic structures on thermal comfort and IAQ was complicated. In the winter, hygroscopicity had only minor effect on indoor climate. In the summer, hygroscopicity had some effect on thermal comfort, which was improved at lower ventilation rates. In respect of thermal comfort, the ventilation rate was a more important factor compared to hygroscopicity, as thermal comfort was greatly improved at higher ventilation rates. Hygroscopicity improved considerably perceived air quality in the summer. Ventilation rate of 6 l/s/person in the non-hygroscopic case corresponded roughly to 4 l/s/person in the hygroscopic case, although such comparison is not exactly valid as the same pollution of air is considered in both cases.

ACKNOWLEDEMENTS
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