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HYGROTHERMAL PERFORMANCE BENEFITS OF THE CELLULOSE FIBRE THERMAL INSULATION STRUCTURES

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Abstract *The hygroscopic properties of the cellulose fibre thermal insulations can be best utilized in applications allowing moisture flow between the structures and both outdoor and indoor air spaces. These dynamic, vapour open structures may dry out also to indoor air, which can improve their moisture tolerance especially in climates having strong seasonal temperature variations. The other benefit of the hygroscopic structures is the interaction with the indoor air. The moisture capacity of the material layers can smooth down the humidity peak levels and dynamics of the indoor air and thus improve the thermal comfort of the occupational area.*

This paper presents a survey of research studies already published and also new building physical simulations about the cellulose fibre insulation applications in buildings. Both the moisture performance of the nearly zero energy building structures and their dynamic effect on indoor air humidity and heat flows were evaluated.

Under cold, norther climate conditions the cellulose fibre structures can have as safe moisture performance as those having vapour barrier and non-hygroscopic insulation. The benefits of the vapour open inside layer can be seen also under northern conditions – the summer period humidity peaks on the outer surface of the vapour open air barrier could be 10 % RH lower than those with vapour barrier. Under warm and humid outdoor conditions the benefits of the hygroscopic structures are typically increased.

The hygroscopic structures can significantly smooth down the changes of the indoor air relative humidity under dynamic loads. During the room occupation period moisture tends to flow into the hygroscopic structures that are warmed up due to the latent heat effect. This warming can temporarily change the direction of heat flows, which may still improve the indoor thermal comfort and energy efficiency. When applying high density cellulose insulation on the inner parts, the indoor moisture buffering effect could be improved. Highly insulated structures enhance the humidity interaction with indoor air.

1. INTRODUCTION

Cellulose fiber insulation (cfi) is a form of wood fibre insulation, manufactured typically from recycled newsprint paper that is treated with fire retardants. It is used both in loose form and in blocks. In loose form installations permanent, non-settling insulation layer can be produced with the help of binding agents.

Hygroscopicity of cellulose fibre insulation is the essential factor that has effect on the hygrothermal performance of the building structures containing this material. The material can bind and release humidity allowing moisture buffering effect for the structure. This effect can smooth down the humidity variation, both inside the structure and indoor air during the dynamic moisture load variations.

The moisture capacity of the cfi thermal insulation and other hygroscopic material layers can equalize moisture flows and levels. This makes it possible to replace a typical vapour barrier layer with a more vapour-permeable air barrier that allows moisture transfer (drying) also towards indoor air space. The interaction between indoor air humidity and moisture capacity of the structures can help in maintaining stabile relative humidity levels and comfortable indoor conditions.

This paper presents a collection of the results of earlier studies about the moisture performance of cfi-insulated building structures. Additional numerical simulation studies were carried out to fill in some part of needed information.

Safe moisture performance of cfi-structures having no PE-foil vapour barrier is one key item in the study. The other issue is the interaction between indoor air and structures: What is the effect of latent heat on the heat losses during different phases of moisture flow and how the moisture buffering effect of structures can be utilised to improve the indoor humidity and comfort conditions.

2. SAFE MOISTURE PERFORMANCE

Safe moisture performance is the essential requirement for a building structure. The initial moisture and the moisture entering the structure should dry out without causing any defects for the material layers or the performance of the structure.

Hygroscopic structures under dynamic climate and indoor loads cannot be studied reliably using steady state analysis like dew-point calculations. Suitable analysis tool is a heat and moisture transfer simulation model that takes into account the capacity of materials and the thermal and moisture dependence of the transport properties. In these studies WUFI – simulation model [1] was used.

The criteria for safe moisture performance are the moisture content levels, moisture accumulation and mainly the mould growth. The risks for mould growth can be analysed numerically for different building materials with VTT mould model [2 – 4] that uses the solved hourly temperature and humidity values as input.

Several low-energy cfi-insulated building structures have been studied numerically (for example [5]) and found out to have safe moisture performance under cold northern (Finnish) climate conditions and with indoor conditions typical to dry living spaces in apartments and offices. The cold climate conditions cause high demand for the drying efficiency of the structure. Thus in milder climates the performance of these structures should be on the safe side.

In northern climates the moisture performance of the vapour open cfi-insulated wall structures is about the same as that with non-hygroscopic structures having PE-foil vapour barrier. Only when part of the driving rain was assumed to wet the thermal insulation, the drying took longer with the hygroscopic structure.

Summer condensation - moisture accumulation or high humidity conditions on the outer side of the vapour barrier - can be mostly avoided using the vapour open cfi –structures. Under norther conditions summer condensation is not a real problem. Figure 1 presents the simulated (WUFI 5.3 simulation model [1]) relative humidity levels on the outer side of the vapour barrier or vapour open air barrier during 6 months in Finland. The indoor air was set to be at +20°C temperature, the wall was facing south, had no solar shading and 1 % of the driving rain could penetrate into the thermal insulation. The highest temporary relative humidity levels on the outer side of the vapour barrier surface were 87 % RH. When the outdoor climate is warmer and more humid, like in Central and Southern European climates, the period for inverse moisture flow can be significantly longer. Vapour open cfi –structures can be one solutions for the possible summer condensation problems.

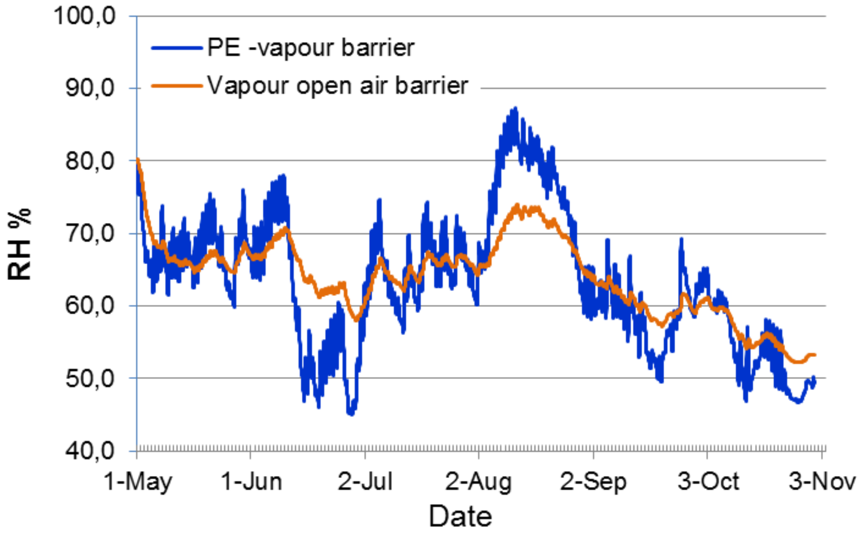

Figure 1. Numerically simulated relative humidity levels on the outer side of the air or vapour barrier during warm season in Finland.

The heat flows between the structure and the indoor air depend also on the moisture flows. Figure 2 shows the heat flux through the inside surface of the structure during one week in August and during one day for the hygroscopic and non-hygroscopic cases. The overall transferred heat was about the same in these cases, but in non-hygroscopic structure the peak heat loads were higher than in the hygroscopic case and they occurred during the afternoon. Additional heat flows into the room increase the risk for indoor overheating. Under these conditions the hygroscopic structure smooths down the variations and decreases the peak values of the heat flux, which can thus reduce the risk for overheating of indoor air.

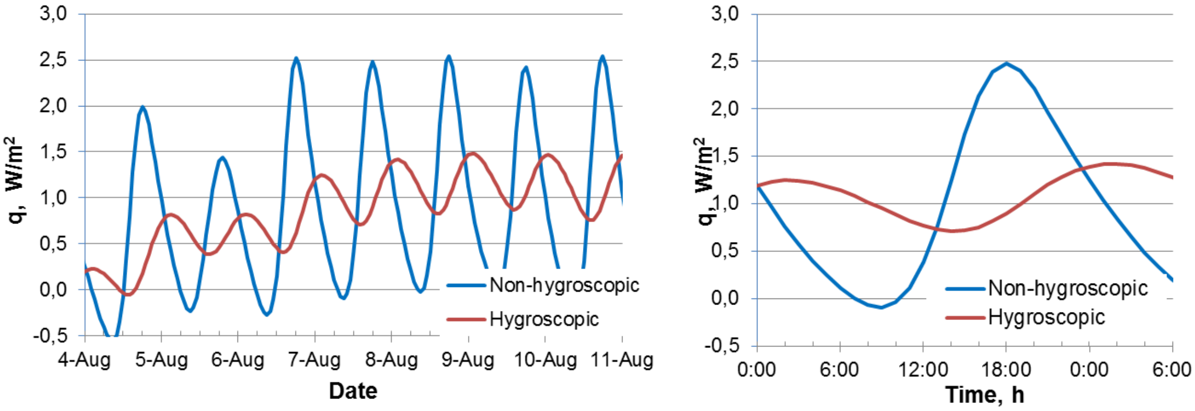

Figure 2. Numerically simulated heat fluxes at the inside surface of the wall structure during one week in August (left) and during 30 hours (right). Indoor temperature maintained at +20 ^{o}C.

The effect of hygroscopic structures on the heat flows will be studied more in the following chapter.

3. INTERACTION WITH INDOOR AIR HUMIDITY

The effect of moisture capacity of structures on indoor humidity has been studied both in field experiments [6] and numerical simulations [7]. Also a Nordic method has been developed to measure and evaluate the effect of different materials and building components [8]. The findings showed moisture capacity of structures can have clear effect on indoor air relative humidity levels especially during daily variations and also under longer load periods. The moisture buffering effect supports the maintenance of indoor conditions in comfort zone. This does not decrease the need for ventilation, but it helps the system to react passively to moisture loads.

One illustrative result from site measurements is presented in Figure 3. In this case the relative humidity of a bedroom was monitored. The room had moisture load during the night corresponding to that of two sleeping persons. The cfi-insulated structure had vapour open plasterboard as inside layer. The measurements were carried out using the vapour open structure as it is and in the non-hygroscopic reference case it was covered with plastic foil. The air change rates of the room had different values from case to case. The test periods cannot be compared directly with each other, because the measurements were affected by weather. Still, the difference between the both stages was clear.

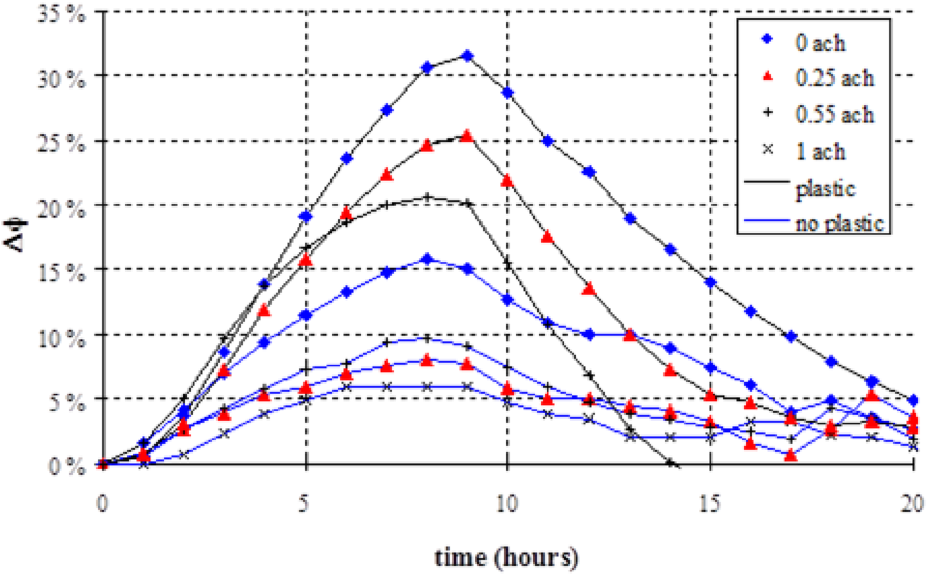

Figure 3. Measured increase of relative humidity of bedroom air at night time, adjusted with different ventilation coefficients (0, 0.25, 0.5 and 1.0 1/h ach), both with plasterboard and either with vapour tight (plastic) or vapour-open (no plastic) inside surface.[6]

According to the results, the growth of relative humidity during the occupation period was significantly higher in case of non-hygroscopic (plastic) structures, compared to the case with hygroscopic structure (no plastic). In the non-hygroscopic case the change of relative humidity during the load period with 0.55 l/h ventilation rate was higher (ΔRH about 20 %) than in the hygroscopic case having no (0 ach) mechanical ventilation (ΔRH about 15 %). In this case the impact of the hygroscopic structures on the relative indoor air humidity was higher than that of the typical ventilation rate 0.5 1/h.

The experienced indoor climate comfort depends among other factors on the air and surface temperatures, air humidity, air flow velocity and air quality. When the other factors are on a normal level, the relative humidity level 30 - 55 % RH normally indicates to comfortable conditions [9 and 10].

Hygroscopic structures may significantly help in maintaining stabile indoor humidity levels, which is the precondition for comfortable indoor conditions. Numerical simulations were carried out for hygroscopic cfi-structures with building paper air barrier and vapour open gypsum board as inside sheathing layer. The reference structure was similar, but with vapour tight inside sheathing layer, thus making the structure non-hygroscopic for the indoor air space. Figure 4 presents the numerically solved hourly temperature and relative humidity values for hygroscopic and non-hygroscopic wall structure cases of a bedroom. Two adults were sleeping in the room for nine hours every night. The air change rate of the room was set to be constant, 0.5 1/h.

In case with non-hygroscopic structures the occurrence of extreme relative humidity values (very dry or very humid air) was more frequent than in case of hygroscopic structures. The extreme relative humidity values were typically outside the comfort area. Reduction of these values improves the indoor air comfort and perceived quality. The effect of hygroscopic structures was even more important in warm Italian climate than in Helsinki, because in non-hygroscopic case occasional condensation conditions were reached, but with hygroscopic structures the maximum relative humidity remained all the time below 70 % RH.

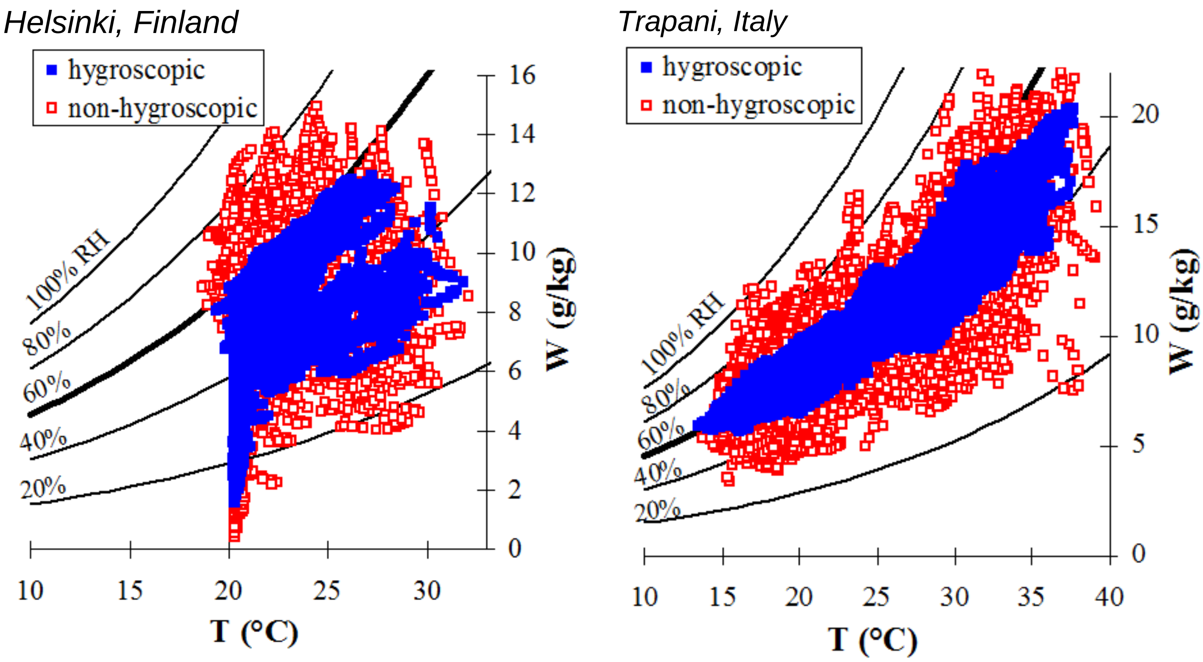

Figure 4. Hourly temperature and relative humidity values of a bedroom simulated under Helsinki, Finland (left) and Trapani, Italy (right) climate conditions. The minimum temperatures vary due to national practices in the use of heating systems.

4. EFFECT ON HEAT FLOWS

Numerical simulations of a simplified case were carried out to study the effect of moisture flow on the heat flows through the inside surface of the structure. The inside surfaces of the structures are considered as control surfaces of the room heat losses and gains. Also, the temperature of the inside surface has a strong effect on the heat radiation and thermal comfort conditions of the inside air space.

In the simplified case a step change of indoor air humidity took place in the beginning of the simulation period. The step change was set to happen from 30 % RH to 60 % RH, or on the other direction, from 60 % RH to 30 % RH. The initial moisture content of the structure corresponded to the initial relative humidity. The objective of these case studies was to find out what effect moisture flow could have on the heat flows between the indoor air and different structures.

4.1. Studied structures

The ventilated wood frame wall structures had from outside: Exterior siding, ventilation cavity, wind barrier layer of porous wood fibre board, 350 mm layer of thermal insulation, vapour or air barrier between the main insulation cavity and a 48 mm thick insulated space for installations of electric cables etc. and a 13 mm gypsum board as inside covering. The inside surface of the gypsum board was assumed to be as vapour open as possible. The studied structures are presented in Table 1.

Table 1. The analysed wall structure cases with the step change of indoor air relative humidity.

Code	Thermal insulation	Thermal insulation	Vapour resistance Sd [m]	
	350 mm space	48 mm space	Vapour/air barrier	Inside surface treatment
CFI40	CFI 40 kg/m^3	CFI 40 kg/m^3	0,70	0,02
CFI70	CFI 40 kg/m^3	CFI 70 kg/m^3	0,70	0,02
Ref_MW	Mineral wool 20 kg/m^3	Mineral wool 20 kg/m^3	50	0,02
Ref_Vapourtight	CFI 40 kg/m^3	CFI 40 kg/m^3	0,70	100

There were two vapour open hygroscopic structures with cfi. The inner thermal insulation cavity (48 mm thick), that is between the internal gypsum board and the airbarrier layer, could have different densities of cellulose fibre insulation: 40 kg/m^3 or 70 kg/m^3. In reference case *Ref_MW* there was 20 kg/m^3 mineral wool on the insulation cavities on both sides of the vapour barrier layer, but the inside surface treatment was as vapour permeable as that of the cfi-structures. The second reference case had vapour tight surface treatment on the inside surface of the otherwise hygroscopic structure (*Ref_Vapourtight*).

4.2. Step change of indoor air relative humidity

In this analysis the indoor air relative humidity had a step change from 30 % RH to 60 % RH while the indoor temperature was constant +20°C. This represents a simplified case for the study of moisture flow and phase change effect on the heat flows. Structures presented in Table 1 were used in the analysis carried out with WUFI model [1].

After the step change of indoor air humidity, the moisture flow from indoor air into the structure had the peak values in the three cases having vapour open inside surface. After that the moisture flow and the sum of moisture that had diffusely transported into the wall started to decrease (Figure 5). The change in the moisture flow depended on the moisture capacity of the inner layers of the structure. With higher moisture capacity it took longer to reach steady conditions, where the moisture flow would be negligible.

Moisture is transported into the structure by vapour diffusion and the absorbed moisture is mainly water that is bound in the material. In the absorption the phase change effect releases heat, the structure will be locally warmed up and this changes the heat flows through the inner surface.

Figure 6 presents the numerically solved heat flux as a function of time for different structures. In the case with reference structure that didn’t have any moisture flow between indoor air and the structure, the heat flux was negative (heat losses through the structure) throughout the 10 day simulation period. With other structures the moisture flow and phase change effect reversed the heat fluxes to positive in the beginning of the period. Like with moisture flows, also the balancing of heat flows took longest with the most hygroscopic structures. The heat gain period (positive heat flows) took 1 – 3 days depending on the properties of the structure.

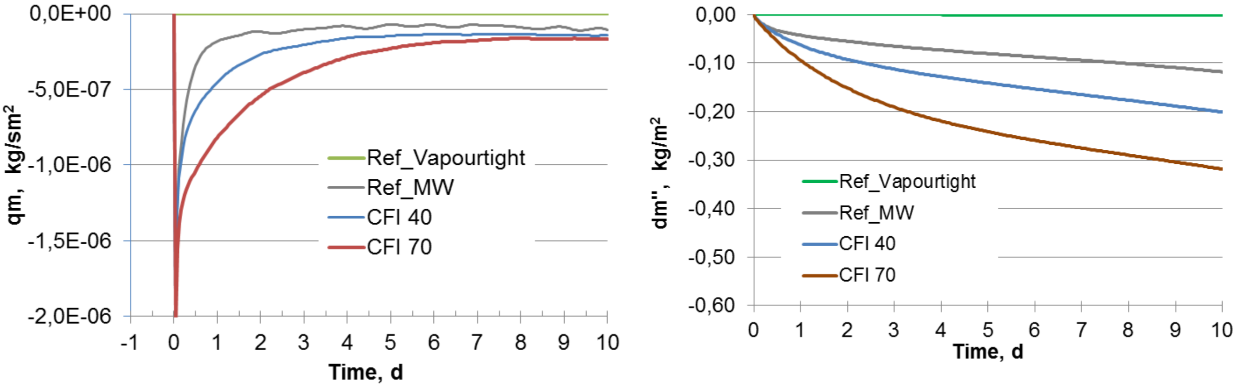

Figure 5. Moisture flux from indoor air into the structure (left) and the amount of moisture transported into the structure (right) after the step change of indoor air (30 % RH to 60 % RH) at time = 0. Negative values refer to the flow out from the room into the structure.

Figure 6 shows also the heat losses calculated for the 10 days after the start of the step change. The heat losses through the wall surface were 0.18 kWh/m^2 in the vapour closed case, 0.16 kWh/m^2 in the case with mineral wool insulation and a vapour barrier and 0.11 kWh/m^2 and 0.05 kWh/m^2 in the cases with 40 kg/m^3 and 70 kg/m^3 cfi-structures, respectively.

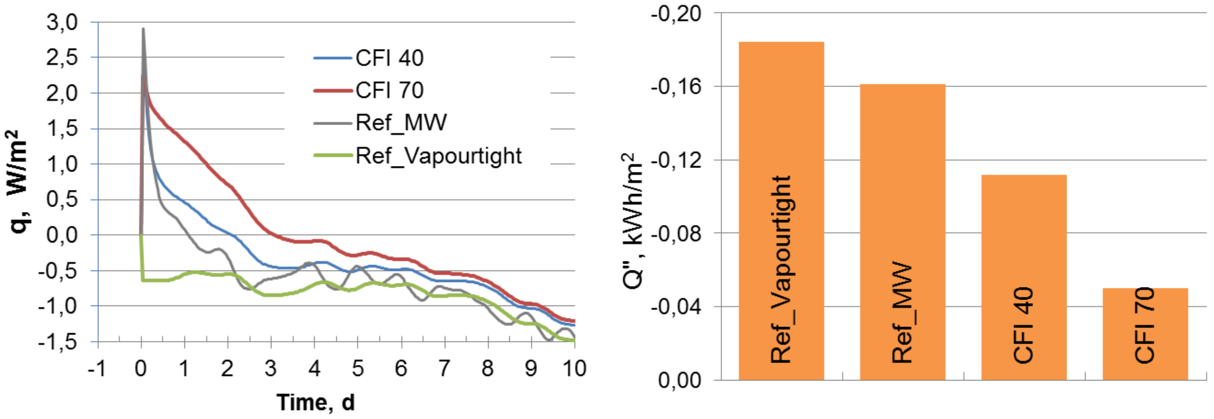

Figure 6. Transmission heat flux through the inside surface of the structure (control surface) (left) and the sum of heat flows into the structure (right) after the step change of indoor air (30 % RH to 60 % RH) at time = 0. Negative values are heat losses, positive heat gains.

The approach of this study is simplified and it doesn’t correspond to the dynamic performance of real room air, but still it gives an idea of the effect of hygroscopic structures on heat flows and the potentials to utilize this effect. The additional heat that reduces the transmission heat losses of the structure comes from the entalphy of the room air that is reduced. Hygroscopic structures offer a possibility to reduce the room air humidity under occupation period and to utilize this latent heat to reduce the heat losses. When the step change takes place from humid

60 % RH conditions (also initial conditions of the structure) to dryer 30 % RH conditions, the effect is inverse. The evaporation of moisture cools down the structure and increases the transmission heat losses through the control surface.

The hourly maximum surface temperature was in the numerically analysed cases about +0.4 ^{o}C higher than the indoor air temperature. Nore [11] has measured significantly higher differences, even +2.5 ^{o}C on wooden panel surfaces during short periods in a case where relative humidity changed from 20 % RH to 90 % RH. The application idea is to utilize the effect in bathrooms: When taking shower the humidity increases fast causing the surface temperature to rise, which improves the thermal comfort and cuts down the heat losses through the control surface of the room. Thus the room air temperature can be kept lower to achieve the same thermal comfort during the occupation period, which saves energy.

In longer period the heat losses and gains are basically in balance, but under short periods there is potential to utilize this effect to reduce the heat losses during room occupation period. Also the potential to reduce the heat gains could be utilized to avoid overheating of the room. The objective was to reveal these potentials, the practical applications still need to be studied and developed.

5. CONCLUSIONS

Moisture transport between indoor air and hygroscopic structures may have a significant effect on indoor air humidity and comfort. Previous studies have shown that that hygroscopic cellulose fibre insulated structures can smooth down the indoor relative humidity variations under dynamic conditions. In field measurements the increase of relative humidity during the occupation period of a bedroom having normal ventilation rate was with non-hygroscopic structures about 30 % RH and with hygroscopic structures about 15 % RH. Even conditions and the lack of extreme levels help in maintaining comfortable conditions.

In addition, the moisture interaction can temporarily change the conduction heat losses during dynamic conditions. High indoor humidity during the room occupation period causes moisture transport into the structure, the latent heat warms the inside material layers and the heat losses can be temporarily reduced or even inversed. Step change of indoor air relative humidity from 30 % RH to 60 % RH could invert the negative heat flows (losses) to heat gains for 1 – 3 days depending on the level of available hygroscopic capacity in the structure. Even the long period heat flows are in balance, the periodical changes could be utilized to improve thermal comfort and energy efficiency. These applications require studies made under different climate and indoor load conditions.

High thermal insulation levels enhance the interaction between indoor air and structures. Even relatively small changes in the temperature and humidity levels can have a significant effect under low temperature and vapour pressure gradients. Due to more even vapour pressure fields it is possible to utilize deeper layers of hygroscopic structure as moisture buffering capacity for the indoor air.

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