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MEASURED MOISTURE BUFFERING AND LATENT HEAT CAPACITIES IN CLT TEST HOUSES

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ABSTRACT

This research investigates the significance of the moisture buffering and latent heat capacities in exposed cross-laminated timber (CLT) walls with the respect to indoor climate and energy consumption. Hygroscopic materials have the ability to accumulate and release moisture due to change in the surrounding humidity. The moisture buffer capacity is regarded as this ability to moderate, or buffer, the indoor humidity variations. Latent heat refers to the heat of sorption due to the phase change from vapour to bound water in the material and the other way around. The indoor relative humidity (RH) is closely related to indoor comfort, more specifically to thermal and respiratory comfort and perceived air quality. Both persistently low RH (<20 %) and high RH (>75 %) can cause health threats for humans such as respiratory infections or the growth of mould. Wood is naturally hygroscopic, which enables it to act passive and efficient to stabilize the indoor humidity and thus, temperature variations. A better understanding and more deliberate implementation of these properties could potentially reduce the need for ventilation and heating without compromising the indoor comfort. A full-scale experimental study compares the responses of two 25 m^2 test houses to an applied moisture load. The test houses are identical constructions made of CLT elements, where the exposed spruce interior in module A is kept as is, while the interior in module B is covered with PE foil emulating an impermeable surface. The moisture load is applied as continuous flow of mist under several various conditions, including different magnitudes of the load and altered air change rates of the ventilation fan. The responses are measured in terms of RH, moisture content in the wood, changes in surface and air temperature and the time needed for the system to restore itself to the initial state. The software WUFI®Plus is utilized to perform a hygrothermal building performance simulation for comparison and evaluation. Both the experimental and calculated results show that exposed wood is an efficient moisture buffer capable of reducing daily fluctuations in RH. The results also show a rise in surface temperature, which is a contribution from the latent heat of sorption.

KEYWORDS

Moisture buffer capacity, latent heat, indoor climate, energy, buildings, exposed wood surface, Cross Laminated Timber (CLT)

1 INTRODUCTION

In the last decades a global "green awakening" has led to new standards and requirements concerning environmental awareness and sustainable development. According to the International Energy Agency (IEA), commercial and residential buildings represent 32 % of the worlds total final energy consumption (IEA 2014). In reducing this figure, the potential is mainly related to reducing the need for heating and cooling. The public and legislative demands for energy efficient building design have led to increased air tightness and insulation in modern dwellings. In these modern buildings, the ventilation accounts for a large amount of the heat loss through air renewal. One solution to keep the energy consumption down whilst providing a comfortable and healthy indoor climate is the use of passive design strategies. In its simplest form, passive methods include considerations such as shape and orientation of buildings to reduce the ventilation, cooling and/or heating demands. Thermal inertia associated with heavy walls is another type of passive design that is actively implemented. Thermal mass design takes advantage of the heat capacity, which enables heavy buildings to heat up and cool down up to three times slower compared to light buildings (Karlsson 2012). Well-controlled HVAC systems or ventilation that is RH or CO_2 sensitive are other options.

Studies on the moisture buffer capacity of hygroscopic materials have shown that these materials have a great ability in terms of moderating the indoor RH levels (Rode & Grau 2008). Moisture buffering is described as the ability of porous materials to buffer changes in the RH by absorbing and desorbing water vapour from the surrounding air. Indoor humidity varies significantly through the day and seasons. Materials that can store and release moisture can reduce the extreme values of these fluctuating humidity levels. This results in improved thermal comfort while keeping the energy consumption low.

Another phenomena closely connected to the moisture buffer capacity, is the latent heat of sorption. In the process of moisture exchange between the hygroscopic material and surrounding air, the humidity undergoes a phase change. The energy associated with this phase change from vapor state in air to liquid water in hygroscopic pores, or vice versa, is the latent heat of sorption (Osanyintola. & Simonson, 2006).

This paper aims to measure the significance of the moisture buffering capacity and latent heat of sorption of exposed spruce CLT in full-scale experimental facilities. The experimental facilities include two test houses: one with exposed spruce interior surface; and one control house with impermeable surface where moisture buffering and latent heat are limited. The responses of the test houses are compared to one another, as well as to results from a computer performed hygrothermal whole building performance simulation using WUFI®Plus (2007) in order to evaluate these models.

2 BACKGROUND

2.1 Indoor climate

The main purpose of air ventilation is to ensure adequate indoor air quality (IAQ) for users with regard to health and comfort (TEK10, 2010), and to keep the indoor humidity at correct levels to maintain the building structure and envelope. The indoor RH is affected by different factors, such as internal moisture sources (human activity and respiration, household appliances and equipment), airflow, leakages and external air moisture content. There is also a significant seasonal impact on the RH, more dependent on outdoor temperature than outdoor humidity. Heated homes are usually dry because the infiltrating cold winter air contains little water vapour. RH reaches its lowest levels during the coldest days. During hot summer days, the outdoor air contains plenty of vapour even if the RH is lower than in winter. But because of high vapour pressure outdoor, vapour generated inside hardly migrates out. (Kubler 1982)

Daily indoor moisture loads due to normal life activities leads to fluctuations and peaks in RH, which easily reaches 80-100 % in airtight spaces, like bathrooms. The moisture production in residences differs among people depending on habits and behaviour. The total moisture generation (sum of respiration and transpiration) of an adult at rest is in the range of 0.8-1.7 kg/day, while the total water vapour production (including daily chores, plants, pets etc.) for a family of five is in the range of 6.6-10.2 kg/day (TenWolde & Pilon 2007).

Keeping the RH at correct levels is vital for both the durability of the building materials and the indoor climate comfort. Surveys show that humans feel most comfortable at certain temperatures and humidities (ANSI/ASHRAE; ISO). The RH is important for skin humidity (Toftum et al. 1998a), respiratory comfort (Toftum et al. 1998b) and perceived IAQ. High RH can be associated with moisture problems in the building envelope, such as mould growth, as well as human health problems, including asthma and allergies. Arlian (Arlian et al. 1999) suggests maintaining mean daily RH below 50 % to effectively restrict population growth of house dust mites.

In a wide variety of commercial buildings the right levels of RH can be of even higher importance. Swimming halls and laundry facilities often have excess humidity, while offices and production facilities with heavy machines tend to be perceived as too dry. Museum and gallery artefacts require specific and steady humidity and temperature levels to minimize deterioration (Janssen & Christensen 2013).

2.2 Energy efficient design strategies

By 2020, the EU Energy Performance of Buildings Directive (2010/31/EU) aims for a 20 % reduction in European primary energy consumption and Nearly Zero-Energy Building norm for all new buildings. Mandatory energy performance certificates are already implemented in commercial property development, and recent studies show that better energy efficiency is rewarded in the market.

The energy consumption in dwellings can be divided into three main categories: electricity for lightning and equipment, room heating/cooling and water heating. In Norwegian households, an estimated 60 % of the consumed energy is used on room heating alone. (Edvardsen et al. 2006) In more southern climates, the cooling and air conditioning in the hot season is the main energy drain. Energy efficient development means utilizing plan strategies where the total purchased energy need for a building is kept at a minimum.

Sustainable development requires that the choice of materials for building take into account the environmental impact of the materials being used, the energy consumption of building and the indoor environment. Manufacture, use and disposal of wood is associated with low energy cost and low emissions. Furthermore, wood used as indoor surface material enables its hygrothermal inertia to act as a passive system regulating the temperature and moisture fluctuations. Hameury and Lundström (2003) describe an experimental study performed in four occupied apartments in Sweden with large areas of exposed massive wood surfaces. The results show evidence of the wood contributing to buffer the indoor temperature.

A Canadian study estimated that applying hygroscopic materials in combination with RH and user presence control of HVAC systems reduces the heating energy consumption with 2-3 % and the cooling energy consumption with 5-30 % in moderate climates. (Osanyintola & Simonson 2006).

Compared with other materials, the heat conductivity of wood is low, especially perpendicular to the fiber axis. This makes (dry) wood a good insulator, but also poses as a limitation for heat storage purposes. Nevertheless, because wood is excellent at holding water, this captured moisture increases its basic heat storage capacity. This gives wood a beneficial compromise between insulation and heat storage. Since the thermal and hygroscopic behaviors of building physics are closely related, the wood moisture content also affects the thermal fluctuations through the material. A high moisture content enhances the heat flux.

2.3 Hygroscopic potential

The total moisture buffer capacity depends on the moisture buffer capacities of each material and furniture in the room together with the moisture production, air change rate and the ratio between the material surface area and the air volume. The materials active thickness, vapor permeability and moisture storage capacity, as well as the thickness of the boundary air layer are factors that determine the moisture buffering.

Moisture content in wood is expressed as a percentage of dry wood mass. Most hygroscopic properties in wood, including the wood surface – ambient air moisture exchange, are related to the hygroscopic moisture range where minimal capillary forces occur (Wood moisture content <30 %). The hygroscopic water is bound to the wood cells via hydrogen bonds, and its amount is limited by the number of sorption sites available and how many water molecules each site can hold. More energy is needed to release bound, as opposed to free, capillary water. As the bound-water content increases, the physical properties of the wood are altered: swelling, decrease in the mechanical strength, increase in thermal and electrical conductivity and higher rate of bound water diffusion (Siau, 1984).

In a hygrothermal simulation, Korsnes (2012) attempted to identify the magnitude of the latent heat exchange in a small bathroom under normal conditions. The comparison of case 1 with wood panels on the walls and ceiling to case 2 with solely impermeable surfaces shows huge advantages to the former. Not only are the values of RH lower and more stable, but there is also an increase in indoor air temperature of 2.5 °C due to the latent heat. In a follow-up laboratory test conducted to verify the hygrothermal simulation, Nore (2014) subjected wood samples in a climate chamber to rapid increase in RH (from 20 % to 90 % RH). Thermography was used to measure the surface temperature change. In a few minutes, the exposed wood sample reached its maximum surface temperature nearly 2 °C higher than the reference sample covered in low-emitting PE-foil.

The latent heat is naturally user controlled in the sense that a space has to be occupied or employed, with a following moisture load, in order to be released. This has potential as local heating in spaces when it is actually needed. For instance, both kitchens, bathrooms and laundry rooms, are only occasionally used during the day. If the operating temperature of a room can be raised with 2 ºC upon being occupied, the set temperature can be lowered accordingly when the room is not in use.

The latent heat of desorption may also be of practical use in building design. Desorption is the opposite process of sorption; here excess moisture in the wood is dried out by energy contribution from the ambient air. This may be applied to buildings which need cooling during the day in hot seasons. By airing the building during the night when the temperature is lower and humidity higher, humidity can accumulate in the indoor surfaces. During day time, this moisture will require heat from the indoor air to vaporize thus lowering the indoor temperature. A known problem to cabin owners in Norway, is the time it takes to heat the wood cabin during winter times; lot of energy is needed to firstly dry out the walls before the indoor temperature rises.

3 METHODOLOGY

This paper assesses the issues of moisture buffering and latent heat of sorption of CLT in two different ways; measurements under controlled conditions in experimental field facilities; and hygrothermal whole building performance simulation with WUFI®Plus. The test houses have been exposed to large moisture loads, 616 g/h and 1232 g/h over a 9 h 25 min. period, in an attempt to aggravate a response with as high RH as possible. The studied scenarios are presented in Table 1. Case I and II are conducted in multiple runs. Case III is only performed in module A, meaning the permeable hygroscopic module. The initial conditions differ in each case, and are here only approximately presented.

Table 1: Presentation of test cases and initial conditions

	Moisture load		**Initial conditions**				**Experimental**		**Simulated**	
Case	Diffusion rate [g/h]	Total load [kg]	Operative temperature [°C]	Indoor RH [%]	WME [%]	ACH [h^{-1}]	A	B	A	B
I	616	5.8	20.2	23-24	7.4	0.5	x	x	x	x
II	616	5.8	20.1-20.5	32-37	7.4	0.3	x	x	x	x
III	1232	11.6	20.2-20.5	31	7.4	0.5	x		x	x

3.1 Field experiment

Figure 1: View of test the houses from northwest. Module B is seen in the front; module A in the rear.

The field facilities consists of two identical test houses, module A and module B (see Figure 1) situated in a meteorological field, *Søråsfeltet*, affiliated to the Norwegian University of Life Sciences (NMBU) in Ås, Norway. The test houses are constructed of CLT made of spruce. The walls are made up 100 mm CLT and externally insulated with 100 mm mineral wool in the south and east directions, and 150 mm mineral wool in the west and north directions. There is a layer of weather resistive barrier between the CLT and insulation, and on the exterior side of the insulation, which can be seen in Figure 1. This barrier is vapour diffusion-open. The ceiling and roof consist of 140 mm CLT and 250 mm mineral wool insulation with a wind barrier in-between, and sheet metal roofing on top. The floor has 14 mm oak parquet over 22 mm chipboard and 100 mm mineral wool insulation. The modules are placed on top of 200 mm Rockwool with vapour barrier inhibiting any moisture to penetrate from the ground. The internal dimensions of the modules are 7.0 x 3.6 metres and 2.2 metres height from floor to ceiling. Table 2 shows the exact materials of the wall assembly.

The test houses do not fulfil the requirements demanded by the Norwegian Building Regulations (TEK 10) in terms of insulation, and are thus not comparable within these standards. Blower door tests ran in module A have shown that the air infiltration *n* is 1.63 and meets the national guideline requirements for residential houses with $n < 2.5$ (Olaussen 2014).

In module A the spruce walls and ceiling are kept exposed and untreated, in direct contact with the indoor climate. In module B the spruce surface has been upholstered with PE-foil to make the ceiling and walls impermeable and limit the effects of moisture buffering and latent heat (Figure 2).

The instrumentation inside the modules includes heat and ventilation flow control; registration of temperature and RH of air into and out the modules; wood moisture content sensors; and energy meter. The instrumentation system is limited to nine parameters in each test house. An additional five freestanding moisture sensors are mounted on small timber

Table 2: Wall assembly

Wall layer	Material
Surface coating	Module B: PE, 0,2 mm, s_d =1500
Indoor surface	Spruce CLT, 100 mm
Weather barrier	Tyvek: water resistant, diffusion open
Insulation	100/150 mm GLAVA mineral wool
Weather barrier	Tyvek, UV resistant

Figure 2: Interior view of module B where the walls and ceiling are upholstered in PE foil.

Table 3: Measured parameters. The placement of the sensors is shown in Figure 3.

	Module A	Specification	Module B
1	RH indoor	DT043 sensor Range 0-100% ±1,5%	RH indoor
2	Extract temperature	DT043 sensor Range -50-100°C ±0,5°C	Extract temperature
3	Air flow	Sensiron SDP	Air flow
4	Operative room temperature	MCP9700/01 Temperature sensor Range -40-125°C, ±4°C	Operative room temperature
5	Surface temperature, ceiling		Surface temperature, ceiling
6	Surface temperature, north wall		Surface temperature, north wall
7	Surface temperature, south wall	DT043 sensor. Range 0-100%, ±1,5%	RH outdoor
8	Surface temperature, floor	DT043 sensor. Range -50-100°C, ±0,5°C	Temperature intake
9	Energy consumption	Energy meter	Energy consumption
10	A1 Surface temperature, RH, WME	Hygrotrac S-900-1, ±0.4°C, ±3.5%RH	B1 Surface temperature, RH, "WME"
11	A2 Extract temperature, RH, WME		B2 Extract temperature, RH, "WME"
12	A3 Surface temperature, RH, WME		

blocks of spruce and placed in the test houses, three in module A and two in module B. Each of these sensors monitors the RH, ambient air temperature and wood moisture content. The 3rd sensor in module A is mounted directly on the CLT element of the south wall. Table 3 displays all the measured parameters and Figure 4 depicts the floor plan.

The indoor air temperature was held at 20°C using an electric heater with temperature control. The extract ventilation system supplies constant air change, controlled by differential pressure sensors. The ventilation is pre-set to $n = 0.5\ h^{-1}$ for both modules, in accordance with Norwegian building regulations (TEK 10), but later adjusted in Case 2. The moisture loads were introduced by ultrasonic evaporative humidifiers, each with a total capacity of 5.8 litres and diffusion rate 616 g/h. To prevent the humidity of being extracted straight out through the ventilation canal, a small table fan was placed on the floor to stir up the air and distribute the moist more evenly in the space. This fan was directed towards the floor to avoid disturbing the laminar boundary layer. (Figure 3) Some assumptions have been made regarding the experimental setup: the moisture load is applied with steady flow. The diffusion rate was measured in a laboratory and divided on the water container capacity to get the moisture load duration.

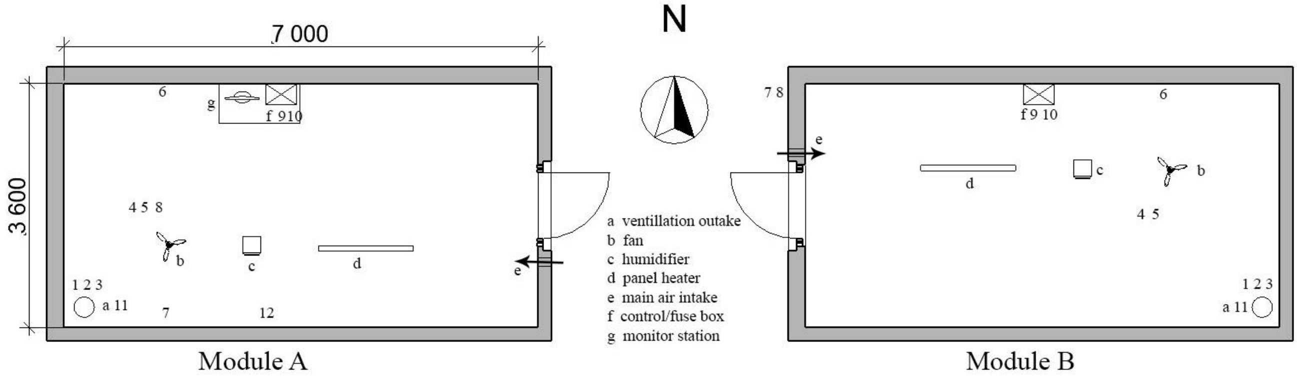

Figure 3: The ground plan of the modules and a schematic figuration of the instrumentation placement.

3.2 Simulation set-up

In the simulation part of this study, the hygrothermal building simulation software WUFI$^{®}$Plus (2007) is used. This software is developed by Fraunhofer Institute IBP, and has been validated through experimental studies. The simulation cases are based on and designed after the real life test houses from the experimental study. The outdoor boundary conditions are the recorded weather data provided from the meteorological station in which the test houses are situated. The indoor initial conditions, including operating temperature, RH and wood moisture content, are set equal to the measured initial conditions from the equivalent experimental case.

4 RESULTS AND DISCUSSION

The results are presented in Figures 4-6, with the permeable cases on the left and the impermeable on the right. The experimental data is depicted with full line and the calculated results with a dotted. A summary of the complete results is presented in Table 4. The values are recorded with 1 minute intervals. A moving average data treatment of 10 steps have been applied to smoothen the all the curves. The exception is the temperature measurements from module B which have been treated with a 30 step moving average smoothing. The reason being an unsteady meter controller in this module making the recorded data flutter.

The RH curve starts rising as soon as the moisture is applied. The RH in the impermeable cases reaches 100 % in a short amount of time. The curves are steep, both increasing and decreasing. Under the permeable conditions, the RH has a lower interval, a gentler slope and delayed peak. In case 1, which is the first case conducted in the wood active module A, the initial RH is the same in both modules due to the fact that they both where dried out a long time ahead. In following experiments the initial RH differs with about 5 % less in the impermeable module, demonstrating clearly the hygroscopic inertia of wood. In Figure 4b the PE covered module B doesn’t seem to reach 100 % RH, which has to do with the built-in hygrostat in the humidifier kicking in. In case 4, which has the same setup, but with the built-in hygrostat being disconnected, this curve looks like the B module RH curve in Figure 5b. The peak in RH in the permeable module is in all cases at the max (end point) of the moisture load. The wood moisture content also reaches its highest value when RH is max. The surface temperature curves follow the same path as the curves for wood moisture content, showing the effect of latent heat of sorption. After case 3 (last case) is conducted and the module is left closed, the wood moisture content reaches its initial state of 7.4 % 60 hours after the moisture load is fully applied.

There is a drop in temperature at the start of every case which is caused by the entrance door opening and shutting while launching the experiment. Temperature prior to this decrease is considered as the initial temperature, thus the increase in temperature due to the latent heat of

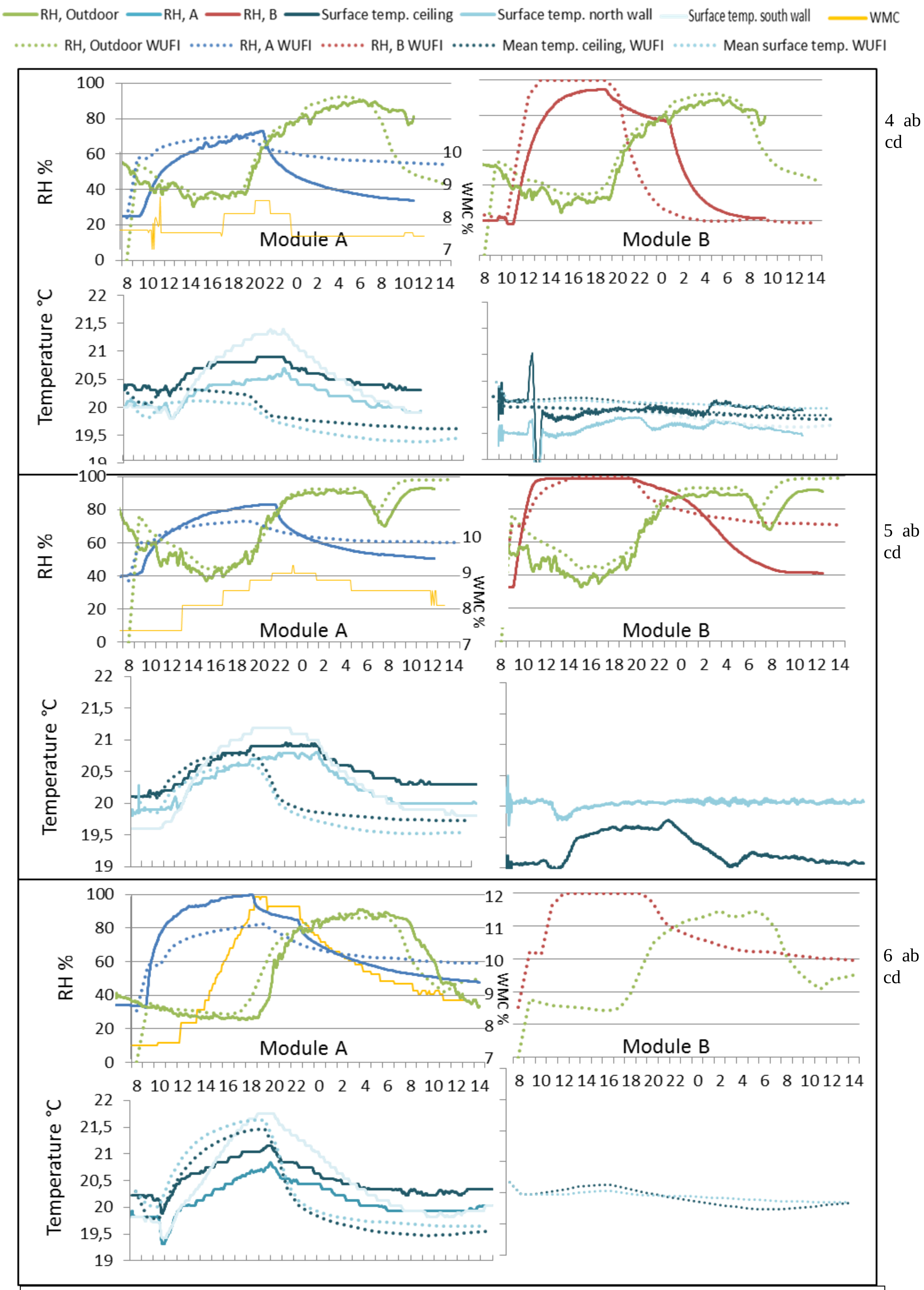

Figure 4-6, a-d: Results from case 1-3 from top to bottom. The wood active module A is depicted on the left side and the PE-covered module B on the right side.

sorption is quite conservatively estimated. The summarized Table 4 shows the initial/max temperatures from the ceiling surface sensor in the experimental tests. This curve was representative in all the cases, not being extreme either ways, as well as being given by WUFI. The temperatures from the different measurement points differ with at least 1 ºC within each case. There are certainly some temperature differences from point to point due to air circulation and humidity not being distributed evenly. The latent heat effect from the south wall is higher in every case, compared to the other surfaces. It is reasonable to assume that the south walls are more dried out than the other surfaces by solar radiation, as well as being less insulated than the north wall. The increases in temperature due to latent heat lies around 0.5-1° C, not taking into account the temperature drop at the start. Nevertheless, there are clear trends regarding the permeable vs. impermeable cases when it comes to temperature rise.

Concerning the simulated cases; the accordance is quite accurate between the experimental and calculated impermeable cases. In the permeable cases however, there is more discrepancy. The max RH is too high in the simulations, and the RH decline to gentle compared to the measured cases. This problem might be linked to the values for the heat and moisture transfer coefficients used by the simulation program. Furthermore, the thickness of the CLT might cause the permeability to become too complex a process. The surfaces temperature curves returned from WUFI®Plus (mean surface and mean ceiling temperatures) do look more cohesive than the experimental results, as can be expected from an ideal computer simulation.

When RH is the primary factor for ventilation, energy savings can be made by reducing the air exchange rate. In situations where humidifying/dehumidifying is necessary, exposed wood can help stabilize the environment and decrease this need. Another option for energy profit includes applying moisture buffering to cooling strategies; moistened exposed wooden surfaces absorb heat from the ambient air during hot days.

Table 4: Summary of the test results

Case				Moisture load				Experimental test					Simulation test			
#	Setup	Date	Ventillation rate [h^{-1}]	Diffusion rate [g/h]	Duration [t]	Total load [litres]		Permeable			Impermeable		Permeable		Impermeable	
1	I	31.3.	0.54	616	09:25	5.8	initial	23.9	20.2	7.4	23.1	20.2	23.9	20.2	23.1	20.2
							max	75.4	20.9	8.6	98.1	20.2	70.4	21	100	20.2
								+51.5	+0.7	+1.6	+75	0	+46.	+0.8	+76.9	0
2	II	11.4.	0.32/0.31	616	09:25	5.8	initial	37.3	20.1	7.4	32.4	20.5	37.3	20.1	32.4	20.5
							max	83.8	21	9.2	100	20.2	73.8	20.8	100	20.5
								+46.5	+0.9	+1.8	+67.6	-0.3	+36.	+0.7	+67.6	0
3	III	15.4.	0.54	1232	09:25	11.6	initial	30.8	20.3	7.4			30.8	20.3	30.8	20.3
							max	97.1	21.2	12			82.3	21.6	100	20.3
								+66.3	+0.9	+4.6			+51.	+1.3	+69.2	0
4	I	9.4.	0.53	616	09:25	5.8	initial	34	20.2	7.4	27.1	20.5	34	20.2	27.1	20.5
							max	74	20.4	8.8	100	20.5	72.4	20.3	100	20.5
								+40	+0.2	1.4	+72.9	0	+38.	+0.9	+72.9	0
								RH	Temp.	WMC	RH	Temp.	RH	Temp	RH	Temp

5 CONCLUSIONS

The results from this paper show that the buffering effect from large areas of exposed wood surfaces helps keep the RH within a closer interval, with slower alteration upon moisture load being applied/removed compared to impermeable surfaces. The latent heat exchange gives rise to the indoor temperature. There is a significant potential regarding exposed wood and indoor climate, especially in combination with a well-controlled HVAC system. For this to become practically applicable there is however still need for research and engineering.

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