Moisture buffering, energy potential and VOC emissions of wood exposed to indoor environments

The use of wood in built environment has been increased during the last decades and more focus has been set on the influence of wood surfaces on indoor environments on objective and subjective measures of human well-being. In addition, moisture buffer capacity of hygroscopic materials, as wood, has been under investigation in order to quantify the impact of wooden surfaces on energy savings in buildings. This study presents results of wood surface and indoor air temperature as well as indoor air relative humidity measured in two solid timber test houses. The findings reveals a substantial effect on wood surface temperature under fluctuating indoor relative humidity, due to the latent heat of sorption of water vapours. The results were compared with hygrothermal numerical simulations, showing good agreement and the validated numerical model was used in order to quantify the energy performance in a bathroom when latent heat of sorption is exploited. The combination of wood with a well-controlled HVAC system in rooms with moisture production shows a significant potential for indirect energy savings by adjusting the indoor temperature and exploit the increase of surface temperature in the hygroscopic structure. Furthermore, the emissions of volatile organic compounds (VOCs) from pinewood were studied in laboratory facilities, with focusOn the variations of emissions due to diurnal fluctuations in air humidity. Human participants were exposed in a large test chamber to a concealed source of VOC emissions in the form of fresh pinewood, while the actual exposure reached air levels of monoterpenes up to 18 mg/m3 during the intervention situation. Perceptions of air quality and mucosal irritation effects were reported in a standard questionnaire during this double blind test withno irritation effects reported.

Introduction

In the last decade, studies on the moisture buffer capacity of hygroscopic materials have shown that they have a great ability in terms of moderating the indoor RH levels and thus reducing the energy consumption for ventilation (Rode and Grau, 2008). Moisture buffering is described as the ability of porous materials to buffer changes in the RH by absorbing and desorbing water vapor 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.

Osanyintola and Simonson (2006) showed that when a hygroscopic material, as wood, is combined with a well-controlled heating, ventilation and air conditioning (HVAC) system, the potential for direct energy savings -through latent heat- is relatively small for heating, i.e. 2% to 3% of the total heating energy, but significant for cooling, i.e. 5% to 30% of the total cooling energy. The potential indirect savings from adjusting the ventilation rate and indoor temperature, while maintaining adequate indoor air quality and comfort, are in the order of 5% for heating while they range from 5% to 20% for cooling.

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 (Hameury, 2006). These phenomena can be utilized for improved thermal comfort and reduced energy consumption. Previous experimental studies showed that the surface temperature of wooden building elements increase when moisture is absorbed in their hygroscopic structure (Nore et al., 2015; Kraniotis et al., 2016a; 2016b).

Emissions from untreated wood icludes so called Volatile Organic Compounds, i.e. VOCs, VOCs are organic compounds eluting between and including n-hexane and n-hexadecane on the gas chromatographic column specified as a 5 % phenyl/95 % methyl polysiloxane capillary column, including all compounds which are considered to be VOCs even if they elute after n-hexadecane or before n-hexane under the specific test conditions (ISO 2006). The sum of the concentrations of the identified and unidentified volatile organic compounds is referred to as TVOC (ISO 2006).

Spruce and pine are both softwood species that have high emissions of terpenes and some organic acids while the emissions from hardwood species generally are dominated by organic acids and aldehydes. Emissions from wood based panels will reflect both the compounds typical for the wood species used and from non-wood additives (cf. Risholm-Sundman et al, 1998; Baumann et al., 1999 and 2000; Englund, 1999; Gminski et al., 2011). Pine delivers the highest levels of volatile compounds, mainly terpenes which are chiefly responsible for the characteristic smell of wood from pine. The health effect of exposure to terpenes in the built environment is not studied extensively. Two German experimental studies did not identify adverse health effects from exposure to emissions from pine (Gminski et al., 2010; Gminski et al., 2011), but previous laboratory experiments have shown that terpenes may cause irritation effects to the eyes (Wolkoff et al, 2000; Nøjgaard et al., 2005). Furthermore, exposure to chemical fumes from cleaning agents, e.g. formaldehyde and terpenes, were associated with an increased risk of developing asthma (Zock et al, 2001; Wolkoff et al., 2003; Le Moual et al, 2012).

Current European regulations in Belgium maintain 1000 $\mu g/m^3$ as a limit value of TVOC emissions from various construction products, mainly flooring materials, where the limit is defined as the chamber concentration when tested according to ISO 16000 and CEN/TS 16516, and in France the same applies for a product classification in the highest class (cf. AFFSET. 2009; FPS Health, 2015). In the German AgBB scheme (AgBB, 2015) corresponding limit values (LCI, Lowest Concentration of Interest) for terpenes fall in the range of 1400-5000 $\mu g/m^3$. These regulations of the emissions from the indoor materials have been calculated after 28 days storage of the material in a ventilated test chamber. As a further point of reference, occupational environmental regulations in *e.g.* Sweden, give a level threshold for terpenes of 150,000 $\mu g/m^3$ (AFS 2015).

A study of possible health effects will provide better documentation of the consequences of use of wooden materials in buildings. This paper aims to quantify the significance of the moisture buffering capacity and latent heat of sorption of exposed spruce CLT (cross-laminated timber) in full-scale experimental facilities as well as using numerical methods and comparing the results with the scenario of non-hygroscopic surfaces. Furthermore, the potential of direct energy savings is highlighted when the two scenarios (hygroscopic and non-hygroscopic) are compared. In addition, the project included VOC emissions from spruce and pine and in this context participants have been subject to a controlled and stable exposure to VOCs from materials of these wood species in order to evaluate possible influence on health and well-being from exposure to VOCs from pine, i.e. (i) symptoms of irritation of eyes and mucosal irritation symptoms from the respiratory system and (ii) subjective experience of indoor environment and odour.

Methods

Moisture buffering effect and latent heat; full-scale experiment and simulations

The first case study refers to full-scale experiments conducted at two identical test houses, module A and module B, located in a meteorological field, affiliated to the Norwegian University of Life Sciences (NMBU), Ås, Norway (Fig. 1). The test houses are constructed of CLT made of spruce and the internal volume is 7 x 3.6 x 2.26 [m] = 57 m^3 (Fig. 2). The thickness of CLT elements is 100mm in the walls and 140mm in the ceiling. The module A has exposed spruce as interior surface, while the interior surfaces of the control module B is covered by non-hygroscopic material (PE-foil). Both the modules are insulated externally.

Figure 1: Plan view of the modules and schematic overview of the instrumentation used.

Figure 2: Cross section of the test houses' wall.

Surface temperatures at the ceiling and at the north and south walls were monitored during 30 hour interval periods. In parallel, the relative humidity (RH) of indoor air was monitored as well as the wood moisture content (WMC) at a depth of 9 mm at predefined sampling points in the walls (Table 1). Pre-weighed amounts of water were used in a humidifier in order to add moisture in both modules for a period of 9.5 hours. Different moisture protocols are studied (Table 2) and the responses of the test houses are compared to each other. In addition, the results from the measurements in both modules are shown against the respective ones obtained using a commercial hygrothermal software, i.e. WUFI®Plus.

Table 1. Specifications of the equipment used and measurement errors of devices.

Table 2. Presentation of test scenarios for the first case study, i.e. full-scale experiment in the modules at Ås)

In addition, a second case study that refers to a numerical investigation of the phenomena is studied and presented. In the second case study the validated numerical model is used to study the potential of exploiting latent heat, which is released when moisture generated, e.g. during a shower, and consequently absorbed in the wooden surfaces (Table 3). The simulated room was a bathroom and two scenarios were studied; in the first all interior surfaces of walls and ceiling are assumed to be covered by wood panels, i.e. spruce, (hygroscopic scenario) while in the second scenario all interior surfaces are assumed to covered by tiles (non-hygroscopic scenario). The results from the two scenarios are in comparison for two different climates; Oslo's (continental climate) and Tromsø's (arctic climate) (Lisø and Kvande, 2007). A typical year in Oslo is characterized by RH = 45% - 90% and T= -5°C - +22°C, while in Tromsø RH varies from 70% to 90% and T from -5°C to +12°C.

Evaluation of health outcomes for subjects exposed to VOC emissions from spruce and pine in a climate chamber

The experiment was a cross-over experiment on humans; the intervention treatment was an exposure to VOCs from pine wood while the control treatment was an exposure to VOCs from spruce wood. The experiment was conducted in a double-blind way. Neither participants nor researchers were informed whether exposure was an intervention treatment or a control treatment. The experiment was carried out with an exposure time for two hours in a test chamber (7.2 m^3). Figure 3 a-b shows the system on how pine plank were placed in the chamber behind a spruce wall. The area of pine plank surfaces was about 39 m^2.

The chamber was ventilated by filtered outdoor air from the lowest rear part of the chamber, then rose up between the pine planks and got out at the top end of the loose wall and into the part of the chamber where the participants were located. The ventilation system contained an air-conditioner to stabilize the temperature and a dehumidifier to prevent high humidity from outdoor air. The air qualities were continually measured by a Q-track. Table 3 shows that the indoor climate was relatively stable in the two groups, however the %RH was higher in the intervention treatment compared to control treatment. A possible explanation may be that humidity was evaporated from the pine planks.

Figure 3: Pine planks against back wall (a) and partition wall placed in front of the pine planks (b).

Table 3. Presentation of test scenarios for the second case study, i.e. numerical simulation of bathroom

The experiment was designed in the randomly way that some participants were exposed to spruce first, and secondly to pine while others were exposed to pine first and spruce secondly. Participants and researchers were both unaware of the exposure test situations.

The participants were healthy, non- or slightly- allergic and non-smoking subjects aged 20-40 years. 17 men and 13 women participated. All participants were informed about the study and each signed a written consent form of voluntary participation.

The VOCs were continuously measured by a PTR-TOF-MS (Proton transfer reaction time of flight mass spectrometer) (Wisthaler, 2002). The subjective health variables were recorded by a modified version of the Swedish Indoor Air Questionnaire (Stenberg, 1993; Skyberg et al, 2003). The modification was a change of the recall time, this modification has been used in earlier intervention studies (Skulberg et al, 2001; Skulberg et al, 2004). The lung functions, forced vital capacity (FVC), forced exhaled volume after 1 sec (FEV1) and Pulmonary peak expiratory flow (PEF) was measured by a Micro medical spiro usb with Spida5 software. Exhaled nitric oxide from the airways (NO) was measured by a small handheld unit (NIOX MINO® from Aerocrine, Sweden). The measurements were performed according to the recommendations by European Respiratory Society (Dweik et al, 2011). The blinking frequencies were counted for five minutes 10 minutes after start of the exposure and recounted for five minutes 20 minutes before the end of the stay. When blinking frequencies were registered the participants performed work at the computer.

The analyses were performed with a student's T-test of the change in the intervention group compared with the change in the control group.

Variations of VOC emissions from wood due to air humidity fluctuations

Smaller test specimens were taken from a subset of the same pine material used in the chamber studies. 0.5 m long samples were cut from two randomly chosen planks, wrapped in aluminium foil and plastic bags, and transported to the emission laboratory. Upon arrival, the samples were unwrapped, and circular discs with a diameter of 150 mm were cut out to fit in the FLEC® sub-unit. These were then conditioned at 20 °C / 65 % RH for 3 months in a dedicated storage chamber supplied with a slow (0.1 ach) stream of air, purified by an active carbon filter. They were subsequently transferred to a FLEC® (Field and Laboratory

Emission Cell, Chematec, Denmark) emission cell, where their emissions were monitored during a short series of variations in air humidity. . The wood surfaces were thus not freshly cut, but aged for a short time, which gives a better representation of wood in actual indoor environments.

The test series was run at a constant temperature of 23 °C and a flow rate of 100 ml/min, while the RH was held at 30 % RH, then 80, 30 and finally 80 % again, all during 24 hour periods. At the end of each setting, the area specific emission rate SER_a was measured through sampling on 60-80 mesh Tenax® TA tubes, thermal desorption in a Perkin-Elmer ATD-400, and separation by capillary GC (P-E Autosystem XL, DB-Wax 30m x 0.32 mm, phase 0.5 μm, programme 50 °C, 5 min, 8 °C/min to 240 °C, 2 min). The mass spectrometry detection and quantification was afforded by P-E TurboMass in full-scan mode 45-300 m/e. Quantifications were made with an external reference mixture, expressing all peaks as α-pinene equivalents.

Results and discussion

Moisture buffering effect and latent heat; full-scale experiment and simulations

The results from the three scenarios (case I, II and III) from the full-scale experiment are presented in Fig.4 and shown in comparison to the numerical simulations. The experimental data are depicted with full line and the simulated results with dotted. The RH curve starts rising as soon as the moisture is applied. The RH in the non-hygroscopic case (module A) reaches 100 % in a short amount of time. The curves are steep, both increasing and decreasing. In the hygroscopic case (module B), the RH has a lower interval, a gentler slope and delayed peak. 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 III (last experiment) 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.

Figure 4 a-c: Results from case I-III 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. (Note: in the Case III (Fig. 3c), only the module A was used, thus experimental data don't exist for the module B).

The agreement between the experiments and the simulations is rather good for the module with the non-hygroscopic surfaces, i.e. module B). Howevere, for the module with hygroscopic surfaces, i.e. module A, there is more discrepancy. The heat and moisture surface transfer coefficients used by the simulation software as well as the thermal mass of solid timber, i.e. CLT, might have caused the offset shown among the surface temperatures measured in the module A.

In Fig. 5 the results from the second case study (simulations of bathroom) are shown. The resulting heat savings from using wood surfaces in the bathroom was 296 kWh in Oslo and 320 kWh in Tromsø (Fig. 5a). The heat savings are based on simulations for the standard MDRY years (Geving and Torgersen 1997) and they correspond to energy savings of 36.5% and 45% for a bathroom in Oslo and Tromsø respectively. The decreased heat demand with wood surfaces in the bathroom is enabled by a lower set temperature, i.e. 20 °C instead of 23 °C. When the bathroom is to be used (during a shower) then rapid reaction of between the moisture generated in the air and the wood surfaces results in the increase of the temperature by approximately 3 °C, heating the bathroom air to a desired comfortable temperature "on demand" (Fig. 5b). In this way, energy is saved when the bathroom is not used by the residents, which happens during the longest period of a day.

Figure 5: Results from the second case study (bathroom). (a) Heat demand for bathroom with tiles and with wood panels in Oslo and Tromsø. (b) The increase of the surface temperature in the two cases studied. (c) The variation of indoor RH in an overview of two days.

In reality, the potential savings may exceed the estimates, due to reduced ventilation rates and less energy and investment in fan capacity. Potential heat recovery is not regarded, but this will never exceed the use of latent heat in situ. The risk of mold growth is not present due to the low equilibrium moisture balance when the moisture dries out in the hours after the shower. The resulting relative humidity in the bathroom is shown in Fig. 5b. As expected, the wood bathroom have a less varying relative humidity because of the buffering function of the wood surfaces. The resulting effect is that the experienced comfort is higher in the bathroom with wood (Fig. 6a,b).

Figure 6: Visualisation of the comfort zone experienced by persons in a room. (a) Bathroom with wooden surfaces. (b) Bathroom with tiles (the resulting conditions in the simulations are marked by blue circles, while the green area marks the desired comfort zone).

VOC emissions from spruce and pine in the human exposure study

The VOCs were measured as total amount of volatile organic compounds (TVOC) and as single VOCs. Figure 7 shows a boxplot of the TVOCs during the control and intervention treatments.

Figure 7: Boxplot of TVOC exposure during control and intervention treatments.

The resulting room concentrations of TVOCs were all between 985 and 1580 µg/m^3 when the exposure consisted of pine wood and in the range of 50-120 µg/m^3 in the spruce case. An aggravating circumstance in the comparisons of concentrations is the output of the PTR-TOF-MS instrument, which delivers concentrations in ppb. In order to apply the conversion formula (1) to mixed gases it is thus necessary to calculate a weighted mean molar mass $M_{w,}$ using the known proportions of six major identified compounds and then assuming the same M_w also for TVOC. As a consequence, such TVOC data are not directly comparable to analysis results given directly in mass/volume.

$$\mu g/m^3 = M_w \times ppb /24.1 \quad \text{(at 20 °C and 101.3 kPa)} \ldots\ldots(1)$$

An ANOVA test showed a statistical significant difference between the two different exposures (F = 561.21, p-value = 1.427*E-13 ***), thus an experimental research design with different exposure during intervention treatment and control treatment was established. It should be noted that these room concentrations cannot readily be compared with test results under strictly defined conditions of air flow, humidity, temperature etc. in laboratory test schemes mentioned earlier.

For the intervention setting (i.e. exposure to emissions from pine) the six most important single VOCs or subgroups were monoterpenes, methanol, acetone/propanol, acetaldehyde, formic acid and acetic acid. The emissions of monoterpenes consisted predominantly of α-pinene and Δ^3-carene. The mean of the median exposure concentrations from these six subgroups was 1287 µg/m^3. The relative percentage of the six largest subgroups of VOCs compared with the TVOC was 87.6 % in the intervention setting. The TVOC concentration of the intervention setting was higher than the limit values of 1000 µg/m^3 in some European national guidelines or regulations. The mean of the median VOC concentration in the control setting was 43 µg/m^3, in this case the relative percentage of the six largest subgroups of VOCs compared with the TVOC was and 57.3 %.

Table 4. Relative humidity and measured TVOC from pine in the timespan February 13th to February 28th.

Table 4 shows that the relative humidities were relative stable, but the concentrations of TVOCs decreased over the timespan. The evaporation of VOCs was more concentrated from the fresh pine planks.

Influence of fluctuating air moisture contents on the VOC emissions from pine Large inherent variations of the contents of extractives are typical of pine wood, ranging over one order of magnitude or more (Englund 1999, Levin 1992, ECA-IAQ 1997). This is reflected in large differences in emission fluxes, and a few samples can never be relied on as giving typical values. However, the response of pine wood in general to the moisture content in the surrounding air, i.e. the rate and extent of moisture transported over the interface, is not subject to large variations at all (Kollman, Côté 1968). A given change in wood moisture content is expected to result in similar proportional changes in the emission rates, regardless of the initial source strength. It is therefore justified to draw some conclusions even from a very small set of test specimens without replicates, since the experiment consists of an intervention where the specimens form their own reference.

This very limited sub-study aimed at giving some indication concerning the emission behaviour in a climate fluctuating rapidly enough to never reach equilibrium conditions. Since the main theme of the study was to investigate moisture buffering capacities and ensuing energy aspects, the rationale behind checking the moisture-induced emission dependence was chiefly to learn whether such variations were large enough to consider. The laboratory trials with pine samples in a fluctuating moisture climate showed a moderate but significant influence on the VOC emissions (Fig. 8).

Figure 8: Total VOC emissions from two different pine samples, area specific emission rates SER_a, after 24 h periods of dry and moist air exposure.

The two specimens labelled 11 and 22 exhibited clearly different emission levels, which is consistent with expected natural variations. In short, the results show increased emissions after a period of flushing with a dry air stream (evaporation phase) and decreased emissions after the surface has been subjected to more moist air(phase of adsorption). This behavior is consistent with the expected partition coefficients of hydrophobic compounds in a matrix with a varying moisture content. The most important conclusion is that the observed variations still are so small that they have no practical implications.

Mucosal irritation effects from exposure of VOCs from pine and spruce in the human exposure study

The room was perceived as closed but safe, non-modern and non-stimulating. The smell was not perceived as very intense, either for the spruce or the pine exposure.

The results of the questionnaires, exhaled NO, blinking frequencies and lung function are shown in Table 5. Participants exposed to pine reported more general symptoms before the treatment and improved their symptoms more than participants did through the control treatment. The changes were statistical significant regarding the symptoms heavy-headed and concentration problems. There were no statistical differences regarding the mucosal irritation symptoms. One can note that both the subjective symptom eye itching and the frequency of blinking were improved during the intervention treatment compared to the control treatment.

Table 5. Results of questionaires and measurements – Average and changes

No statistical significant difference regarding exhaled NO measurements and number of blinking were revealed. The spirometry analyses included several variables, three of which showed no statistically significant changes. The fourth variable (FEV1: what you exhale in the first second) showed a statistical significant difference between the exposure of spruce and pine. Upon exposure to spruce a positive change was detected, while the exposure of pine did not lead to any change. This shows that there is no increasing "irritation" in the upper respiratory tract.

Further analysis may be performed to explore the irritation effects of the different exposure concentrations of VOCs. The severity of symptoms before the experiment is of great significance for the change of the symptoms (Skulberg et al, 2004).

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 non-hygroscopic surfaces. Moisture absorption results in increase of surface temperature of the hygroscopic surfaces and thus in energy savings by regulating the temperature in a HVAC system in lower levels (20 °C instead of 23 °C in the non-hygroscopic scenario), while the resulting indoor temperature is at same level.. The results from the simulations show potential heat savings of 296–320 kWh/year (Oslo and Tromsø) when using hygroscopic surfaces, i.e. wood, instead of tiles in bathrooms, due to a lower overall temperature setting. In Norway, with 5 million people, 2.5 million residences and 3.3 bathrooms, this means energy savings almost reaching 1 TWh, or in total summing up 4 TWh in the Nordic countries using relevant metrics.

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. New wood coating techniques that protect the hygroscopic surface from water while allowing the vapor exchange between hygroscopic surfaces and indoor environment will contribute to realize the exploitation of latent heat of sorption in rooms with significant moisture generation. The substantial share of energy savings possible by using latent heat from wooden surfaces should be part of the total energy balance. Thus, calculations must take hygroscopic materials and small steps into consideration when defining expected energy use in buildings.

In an experimental study health effects due to VOCs emissions from pine and spruce, two different settings with respect to the emissions were achieved. The results of the questionnaires, spirometry measurements and NO measurements showed no significant differences from the exposure of pine compared to exposure from spruce. Seasonal or short-term changes in the air humidity will affect the emissions of terpenes and other VOCs, but this has no practical importance.

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Table 1

	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		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

Table 2

	Moisture load		**Initial conditions**				**Measurements**		**Simulations**	
Protocol	Moisture load rate [g/h]	Total load [kg]	Operative temperature [°C]	RH_{in} [%]	Equilibrium moisture content [%]	Air change rate [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

Table 3

Scenarios	**Walls**	**Ceiling**	**Door**	**Floor**	**Min T_{in}**	**Mech. ventilation**	**infiltration**	**Total air exchange**
Spruce	spruce	spruce	spruce	tiles	20°C	0.4 h^{-1}	0.1 h^{-1}	0.5 h^{-1}
Tiles	tiles	coating	coating	tiles	23 °C	0.4 h^{-1}	0.1 h^{-1}	0.5 h^{-1}

Table 4

Date	**RH** (%)	**TVOC** (ppb)
13.feb	20,1	181.8
14.feb	20,3	197.6
18.feb	23,8	155.0
19.feb	16,9	149.8
28.feb	20,0	133.0

Table 5

	Spruce		**Pine**		**P-value ****
	Before	**Change**	**Before**	**Change**	
Mucosal irritation symptoms*					
Eye itching	2.9	-0.33	2.8	-0.27	0.69
Nose irritation	2.8	-0.03	2.7	0.10	0.29
Hoarse, dry throat	2.8	0	2.8	-0.03	0.75
Cough	2.8	0.03	2.9	0	0.66
General symptoms*					
Fatigue	2.4	-0.10	2.5	-0.27	0.39
Heavy-headed	2.7	0.07	2.9	-0.27	**0.05**
Headache	2.6	0.03	2.7	-0.20	0.13
Nausea/dizziness	2.9	0.03	3.0	-0.13	**0.02**
Concentration problem	2.7	0.03	2.8	-0.08	0.80
Objective irritation measurement					
Exhaled NO	22.27	-0.12	22.48	-0.97	0.17
Frequency of blinking	63.9	13.8	57.6	4.4	0.22
Lung function					
FEV1	366	12	372	-1	**0.04**
PEF	773	15	786	9	0.66
MEF50	469	-1	461	-2	0.90
FVC	428	6	437	3	0.54

* The changes are presented as negative numerical value by deterioration, and positive numeric value by improvement of symptoms.

** The statistical analyses were performed with a student's T-test of the change in the intervention group compared with the change in the control group. Statistical significant values in bald

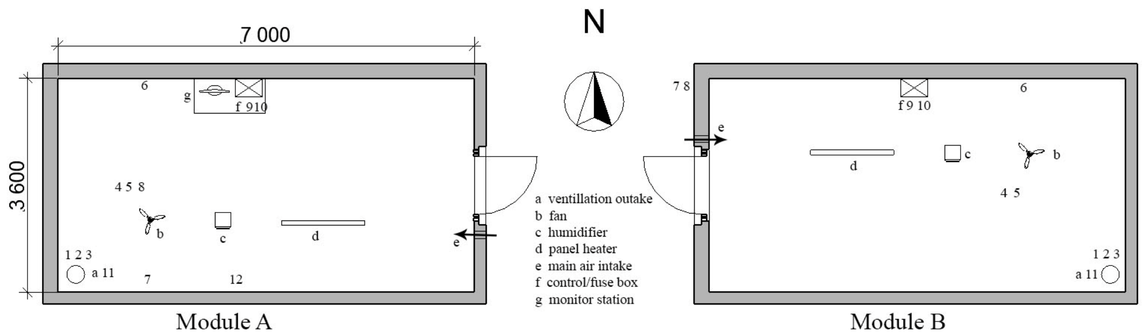

Figure 1

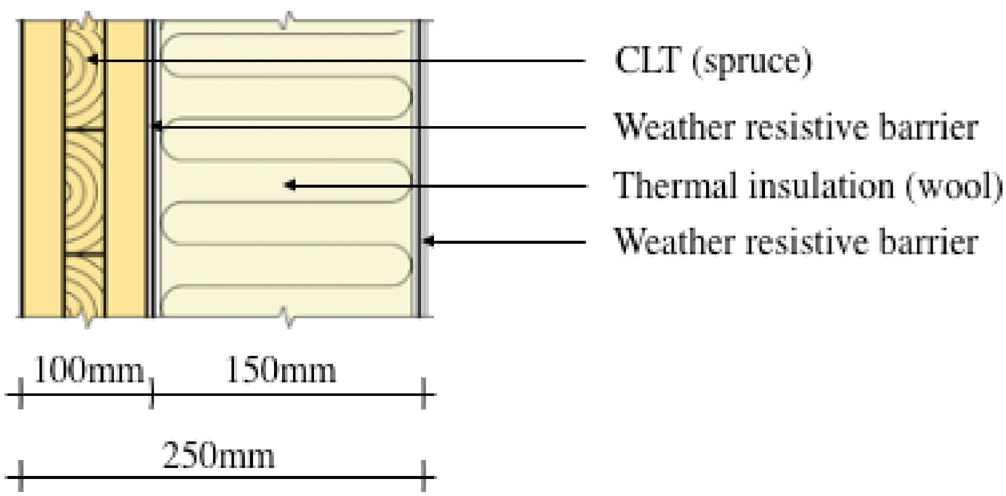

Figure 2

Figure 3a and 3b

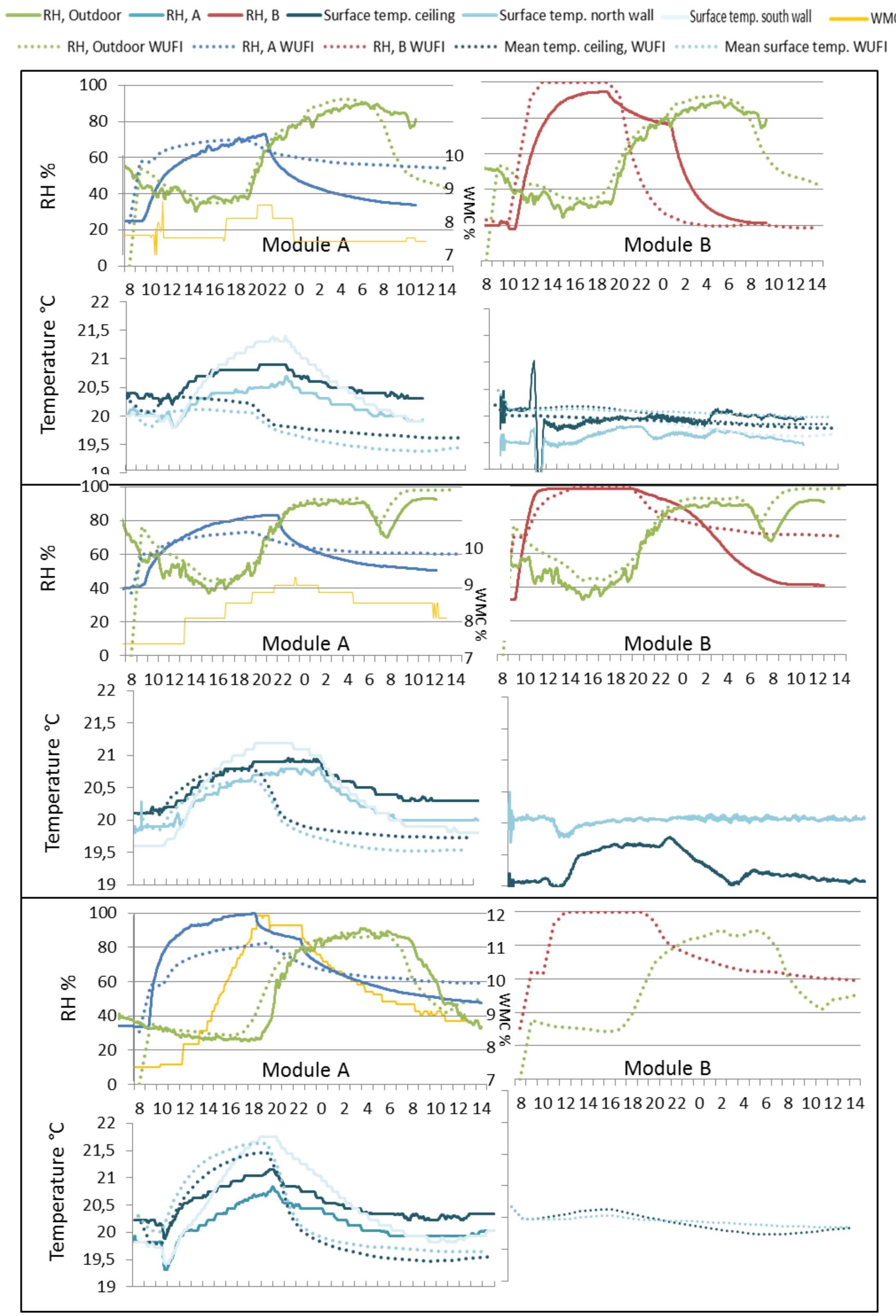
RH, Outdoor
RH, A
RH, B
Surface temp. ceiling
Surface temp. north wall
Surface temp. south wall
WMC
RH, Outdoor WUFI
RH, A WUFI
RH, B WUFI
Mean temp. ceiling, WUFI
Mean surface temp. WUFI
RH %
WMC %
Temperature °C
Module A
Module B

Figure 4a-c

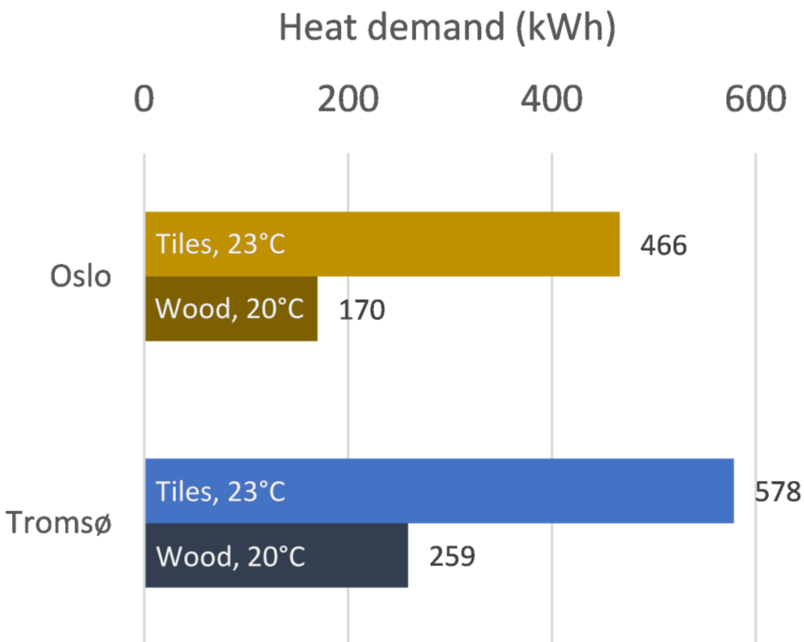

Figure 5a

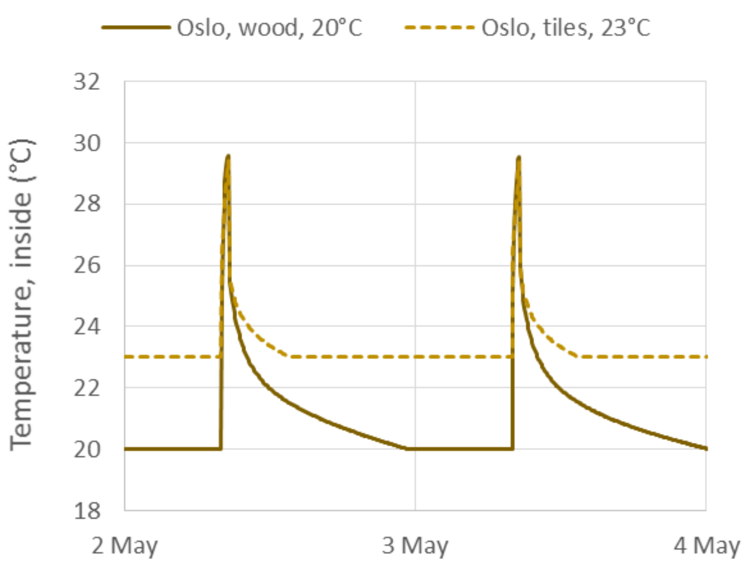

Figure 5b

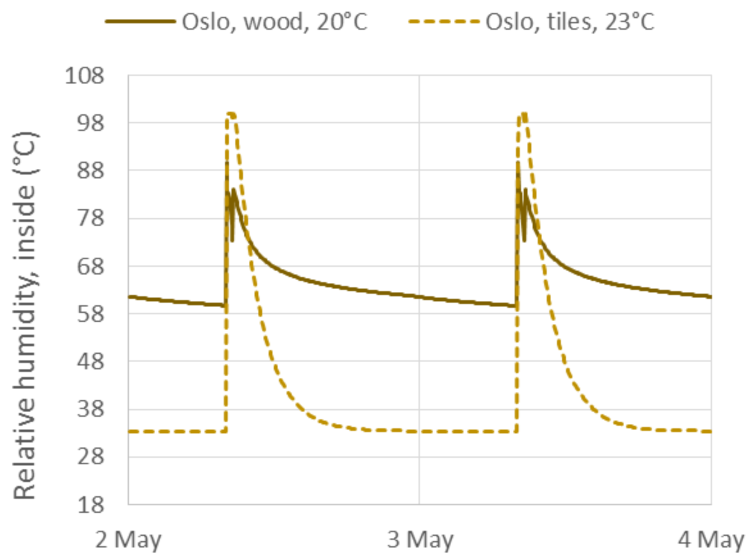

Figure 5c

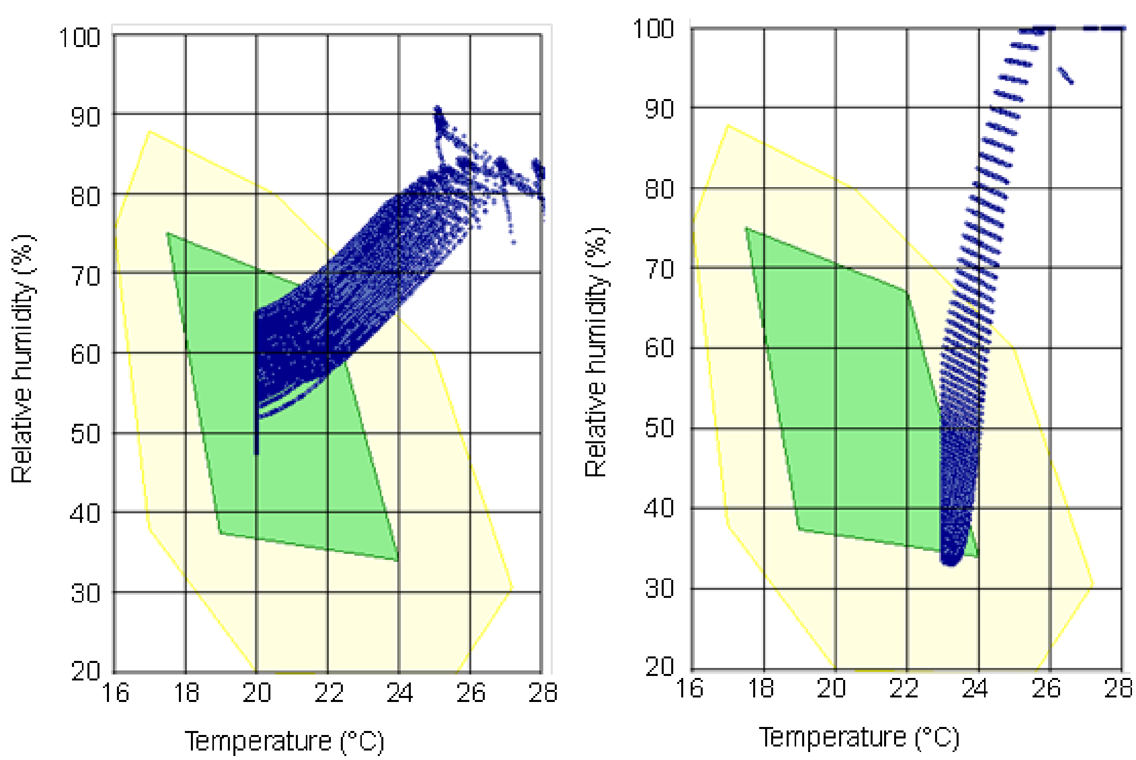

Figure 6a and 6b

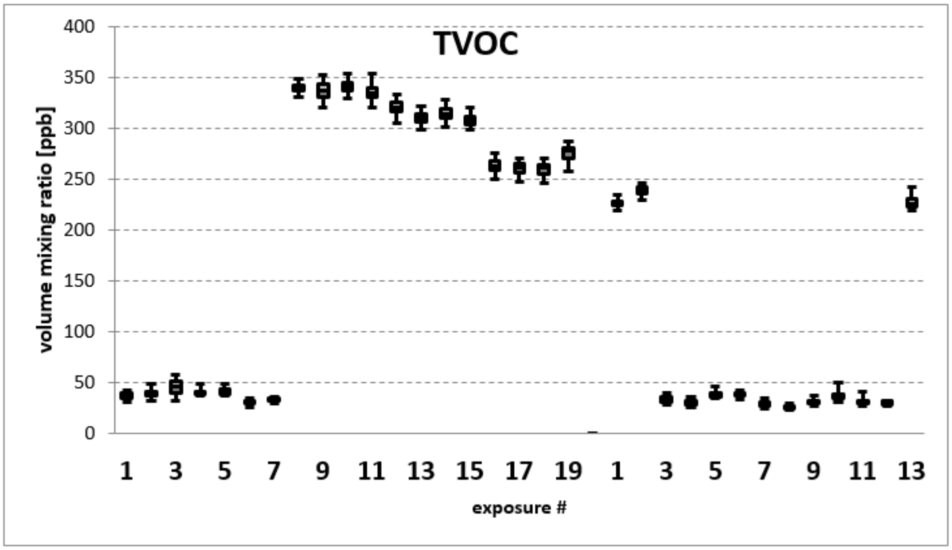

Figure 7

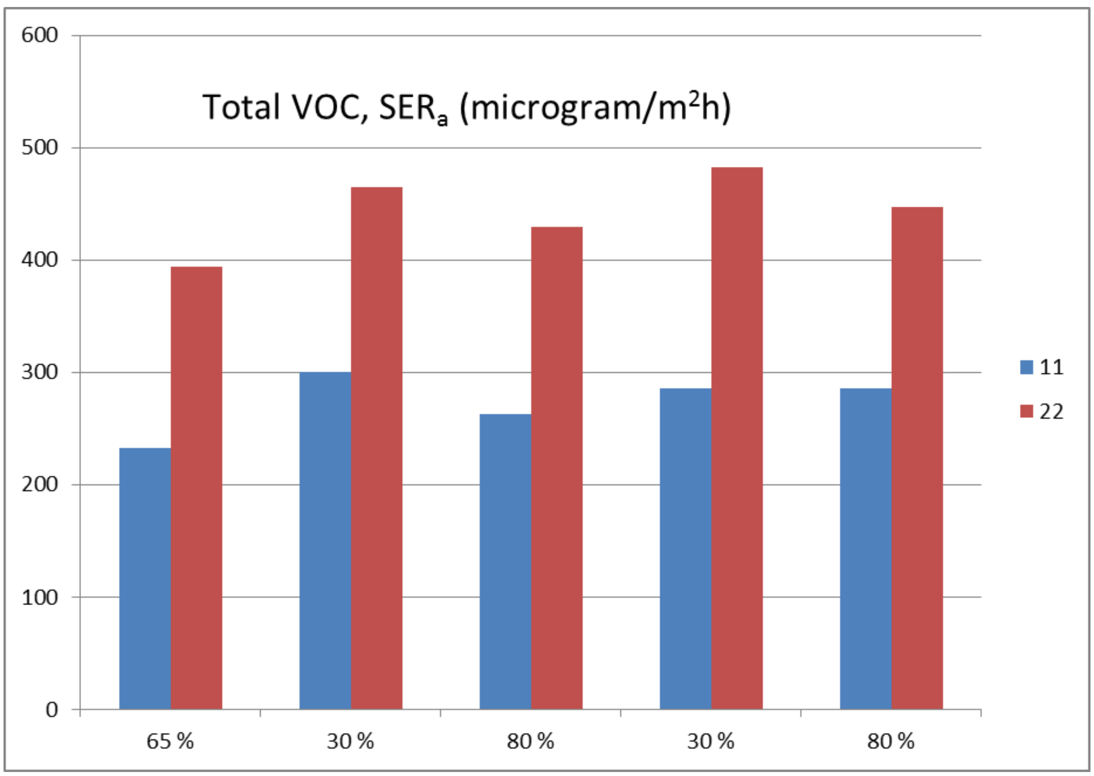

Figure 8