WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

MOISTURE BUFFERING AND LATENT HEAT SORPTION PHENOMENA OF A WOOD-BASED INSULATING SANDWICH PANEL

Dimitrios Kraniotis[1], Nathan Langouet[2], Thomas Orskaug[3], Kristine Nore[4], Geir Glasø[5]

ABSTRACT: The capacity of hygrothermal materials to buffer the maxima and minima of relative humidity indoors has been discussed and presented during the last years. In particular, the wooden surfaces have the potential to contribute to the reduction of the mechanical ventilation loads and consequently to the energy demand and consumption. In this paper, the hygrothermal performance of a wood-based prefabricated insulating sandwich panel is under investigation. Thermography techniques are employed to monitor the increase of interior surface temperature (3 °C) of the panel when water vapour migrate to the wooden structure. A hygrothermal simulation tool is used and the results are compared with the experimental data. The results show that the temperature increases in the whole inner solid wood component, contributing to reducing the conductive heat losses. Furthermore, state-of-the-art equations are used to quantify the latent heat of sorption in the solid wood. The mathematical calculations show that heat of sorption can counterbalance up to 37.1% of the conductive heat losses through opaque elements during a winter day. Finally, the potential of using the sandwich panel for rehabilitation purposes is presented.

KEYWORDS: moisture buffering, hygrothermal performance, latent heat of sorption, thermography, wood-based insulating panel

1 INTRODUCTION

The property of hygroscopic structures to damp the maxima and minima of indoor relative humidity (RH_i) has been presented and discussed in many studies during the last decade [e.g. 1, 2]. A new material property, the so-called 'moisture buffer value' (MBV) describes the ability of building materials and systems of materials to exchange moisture with the indoor environment [3]. The *MBV* of wood is thrice as *MBV* of concrete and brick, twice as of gypsum and about 20% higher than cellular concrete. Hygroscopic wall surfaces provide a noticeable effect on damping of indoor humidity variations; damping effect is analogous to the *MBV* of a material [4]. Simonson *et al.* showed that when the internal surfaces of a wooden apartment building were permeable, the maximum indoor RH_i was lower compared to the impermeable case assumed (impermeable paint) [5]. In addition, RH_i dropped below 20 % for less period of time compared to the impermeable case. The results showed that hygroscopic materials, as wood, hold the potential for energy savings through reduction of ventilation rates.

Moisture buffering is closely related to an area of the building physics that has been so far limited exploited: the latent heat of sorption. Latent heat is the amount of heat required for the phase change of substance without any temperature change in the substance. When condensation occurs from a vapour phase to a liquid phase heat is released is at a rate of 2501 J/kg of vapour condensing at 0°C [6]. This is the latent heat of vaporization of water H_v. In typical indoor temperatures, i.e. 10 – 30°C, it varies from 2477.7 to 2430.5 J/kg. The enthalpy of sorbed water is less than the one of liquid water and the differential heat of sorption ΔH_s has to be added at the latent heat of vaporization of water in order to equal the total latent heat of sorption H_m of bounded water in the cell walls of a wood structure. Thus, the latent heat of moisture H_m is the

[1] Dimitrios Kraniotis (corresponding author), Norwegian Institute of Wood Technology, Postboks 113 Blindern, 0314 Oslo, Norway, dimitrios.kraniotis@treteknisk.no
[2] Nathan Langouet, Polytech Nantes, France, nathan.langouet@etu.univ-nantes.fr
[3] Thomas Orskaug, Norwegian Institute of Wood Technology, Norway, thomas.orskaug@treteknisk.no
[4] Kristine Nore, Norwegian Institute of Wood Technology, Norway, kristine.nore@treteknisk.no
[5] Geir Glasø, Norwegian Institute of Wood Technology, Norway, geir.glaso@treteknisk.no

sum of the latent heat of vaporization of water H_v and the differential heat of sorption ΔH_s, described by the following equation [6]:

$$H_m = H_v + \Delta H_s \quad (1)$$

Osanyintola and Simonson 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 [1]. 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. Woloszyn *et al.* [7] confirmed that the use of gypsum-based moisture-buffering materials, combined with a relative humidity sensitive (RHS) ventilation system, could reduce the mean ventilation rate by 30% to 40% and generate 12% to 17% energy savings while during the heating period. The combined effect of ventilation and wood, as buffering material, make it possible to maintain a stable indoor RH_i between 43% and 59%. In particular in rooms with high moisture generation and consequently significant potential of heat of sorption, as bathrooms, hygroscopic surfaces can save up to 320 kWh/year from the energy demand of such spaces compared to a bathroom with non-permeable surfaces, by adjusting the heating system 3°C lower [8].
Excluding moisture transport in the building envelope from the whole-building energy simulation models potentially results in overestimation of conduction peak loads, but also in underestimation of the yearly integrated heat fluxes [9]. The latter may lead to over dimensioning the HVAC systems, especially in dry climates, as well as to underestimate energy consumption, primarily in humid climates.
In this paper, the hygrothermal performance of a recently certified insulating wood-based sandwich panel system, called TermoElement [10], is under investigation and the latent heat phenomena are studied. A testhouse is entirely constructed of this element. Thermography techniques are employed in order to monitor the surface temperature T_s variations of the interior wooden panel when moisture is adsorbed. Previous studies has shown that thermography can be a useful tool for detecting latent heat of sorption, by means of surface temperature increase [11, 12]. The results from thermography are used to validate a hygrothermal simulation model. The findings of the simulations show that the temperature increases in the whole interior wooden panel of the element. Finally, the theoretical latent heat of sorption in the testhouse are calculated based on state-of-the-art equations and the role of wood as thermal energy reservoir is discussed. The possibilities of using the sandwich panel for rehabilitation purposes is also presented.

2 METHODOLOGY

A series of experiments were conducted in a testhouse built using the sandwich element. The experiments were consisted of two phases: humidification and drying. The indoor parameters, i.e. temperature T_i and RH_i were monitored as well as the moisture content w in the wooden structure, at different heights and depths. A thermography camera, placed on the floor, is used to record the surface temperature variations in the ceiling of the house.
The findings of the experiments are used to validate a hygrothermal simulation model. The findings of the latter are used to provide further information regarding the temperature profile in the interior wooden panel.
Furthermore, the latent heat of sorption is calculated based on the experimental findings and state-of-the-art equations.

2.1 EXPERIMENTAL SETUP

The sandwich panel consists of three components: 3 ply layer solid wood (spruce), insulation, 3 ply layer solid wood (spruce). The total thickness of each of the wooden component is 40 mm, while the insulation is 200 mm. The total thickness of the sandwich panel is 280 mm, while the thermal transmittance is U = 0.16 W/m^2K.
In order to study the hygrothermal performance of the element, a test house was constructed (Fig 1, 2). Its internal volume is approximately 8.7 m^3, i.e. 2.44 m × 1.44 m × 2.5 m (Fig 3, 4). The testhouse has two openings, a door (SE) and a window (NE). The total surface area of the wooden panels (walls and roof) is 16.5 m^2, while the two openings cover an area of 2.9 m^2.
A mechanical extract ventilation with a flow rate Q_v = 84 m^3/h of is installed on the top area of the SW wall, contributing to the drying of the structure (drying phase). In addition, a simple remote heating device was used in order to secure that the levels of moisture content will drop down after the drying phase, at the levels of the beginning of the previous humidification circle.

Figure 1: *Exterior view of the testhouse built of the wood-based insulating sandwich panel*

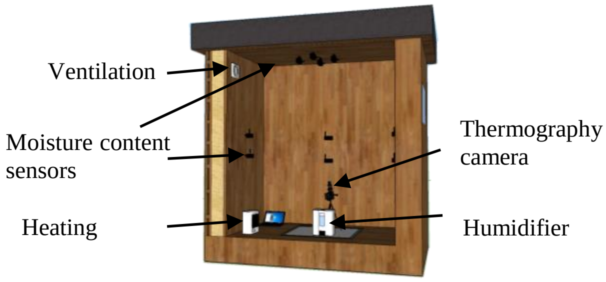


Figure 2: *3D sketch of the testhouse with the instruments and the sensors used*

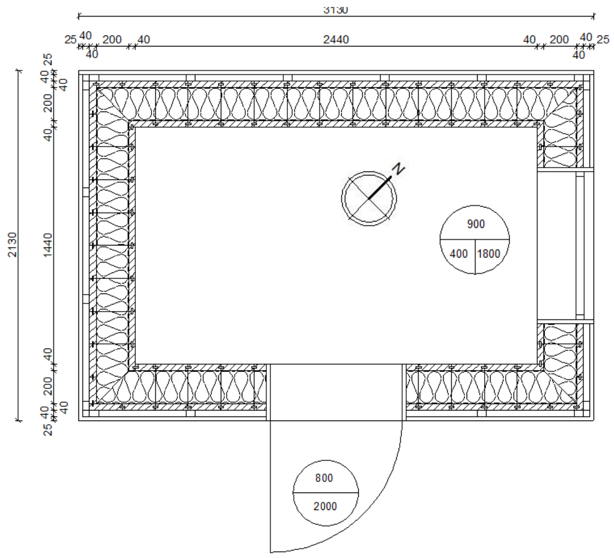


Figure 3*: Plan view of the testhouse used in this study*

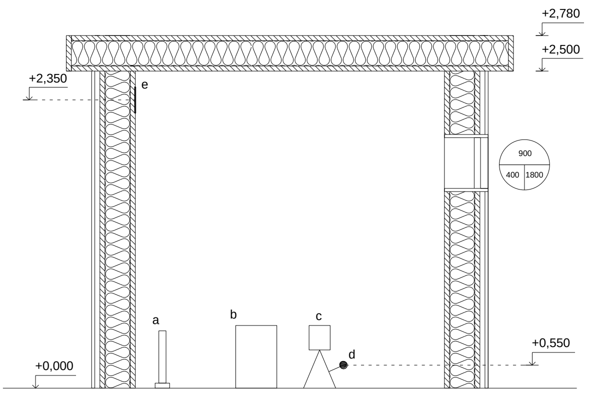


Figure 4*: Section of the testhouse showing the position of the heating device (a), the humidifier (b), the thermography camera (c) and the logger used for recording T_i and RH_i (d)*

2.2 EXPERIMENTAL PROCEDURE

Each experiment has a duration of 24 h and it consisted of a humidification phase and a drying phase (Fig. 5). During the humidification, which lasted for 8 h and the RH was rising up to 75%, the vent remained sealed and the heating was turned off.
The drying phase lasted for 16 h and the moisture release was stopped, while the ventilation was turned on. For only the first 8 h of this phase, the heating was activated to 30°C so that the wood structure could dry out and then deactivated to let the room reach an equilibrium.

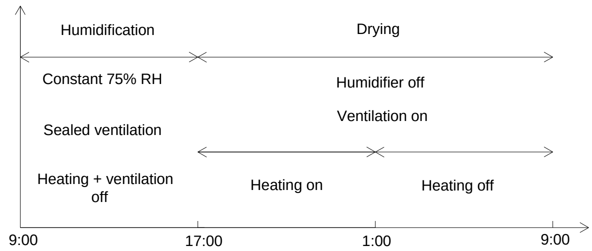


Figure 5: *Schematic representation of one experimental cycle*

2.3 NUMERICAL SIMULATIONS

A 1D hygrothermal numerical tool (WUFI® Pro 5.3) is employed to calculate the temperature profile in the interior wooden panel in the walls and the roof. The model uses Künzel code [13] and employs two fundamental equations, for moisture and energy transfer respectively:

$$\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla(D_{\varphi}\nabla\varphi + \delta_p \nabla(\varphi p_{sat})) \qquad (2)$$

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial t} = \nabla(k\nabla T) + H_v \nabla(\delta_p \nabla(\varphi p_{sat})) \qquad (3)$$

where
c: specific heat [J/kgK]
D_{φ}: the liquid conduction coefficient [kg/ms]
H: total enthalpy [J/m^3]
H_v: latent heat of phase change [J/kg]
k: thermal conductivity [W/mK]
p_{sat}: saturation vapour pressure [Pa]
t: time [s]
T: temperature [K]
w: moisture content [kg/m^3]
δ_p: vapor permeability [kg/msPa]
φ: relative humidity

Outdoor weather data collected locally in a short distance from the testhouse were used as inputs while recorded experimental values of indoor conditions were used an interior climate in the model. The 1D simulation employed take into consideration the exposure of the walls by means of orientation.
The model neglects airflow assessment through the building elements. Despite the fact that the testhouse fulfils the requirements of the Norwegian building Regulations regarding airtightness, infiltration and especially locally concentrated leakages can influence the variation of moisture content in the structure [14].

2.4 CALCULATION OH HEAT OF SORPTION

The total heat of sorption H_s released during the humidification process, when water vapours are migrating into the interior wooden panel is given by the followed equation:

$$H_s = \frac{S \cdot \rho_m \cdot d_m \cdot \Delta MC \cdot H_v}{t} \qquad (4)$$

where

H_s: the heat of sorption [kWh] released or absorbed within a time interval t [s]

S: the surface area of the hygroscopic structure [m^2],

ρ_m: the density of the hygroscopic material [kg/m^3]

Δw: the increase/decrease of the moisture content in the material in the volume of interest [%]

d_m: penetration depth [m]

3 RESULTS

3.1 INDOOR CONDITIONS

A typical time series of indoor and outdoor air temperature and air relative humidity is shown in Fig. 6. The different phases of the experimental procedure can be depicted: the humidification phase is characterized by an increase of RH_i, while during the drying phase decreases. The fluctuations of RH_i occur due to the instability of the humidifier to keep the relative humidity constantly at 75%. Similarly, during the drying phase RH_i fluctuates as well as T_i due to instability of the heating device to maintain a completely constant temperature.

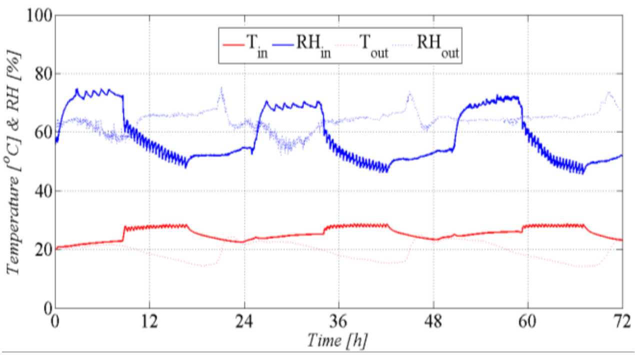


Figure 6: *Time series of three experimental cycles*

3.2 VALIDATION OF THE MODEL

The results from the thermography camera were used to validate the hygrothermal model. In particular the surface temperature of the ceiling is used (Fig. 7). The agreement between measurements and simulations is good, especially during the humidification phase. During the drying phase and when the heating is activated, significant fluctuations as observed in the surface temperature T_s of the ceiling. The fluctuations can be depicted both in the experimental data and the simulations results. The reason for the latter is that the indoor T_i and RH_i that were used as interior climate fluctuate as well, as explained before in Fig. 5.

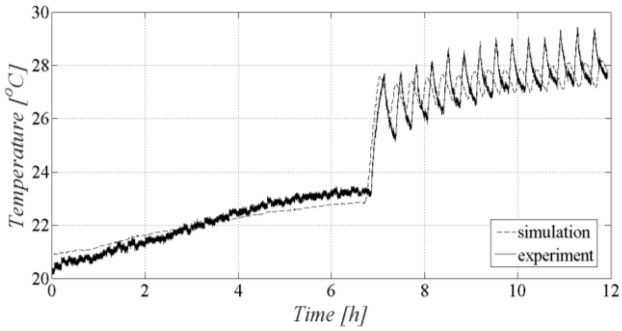


Figure 7: *Comparison between measurements of the surface temperature and simulations*

3.3 MOISTURE CONTENT AND WOOD TEMPERATURE

The variation of moisture content w in the inner 10mm of the interior solid wood panel during three experimental cycles is shown in Figure 8. The moisture content in this area of interest varies ±0.6% or 2.7 kg/m^3 given that the density of the hygroscopic structure is ρ_m = 450 kg/m^3. However, the numerical simulations show that penetration depth exceeds the 10 mm. Based on the hygrothermal model and considering the whole interior solid wood panel, the fluctuations of moisture content w are larger (Figure 9).

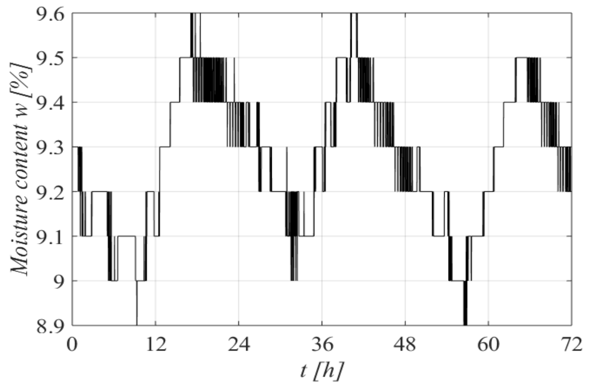


Figure 8: *Variation of moisture content in the inner 10 mm of wooden panel (ceiling) during three experimental cycles (experimental data)*

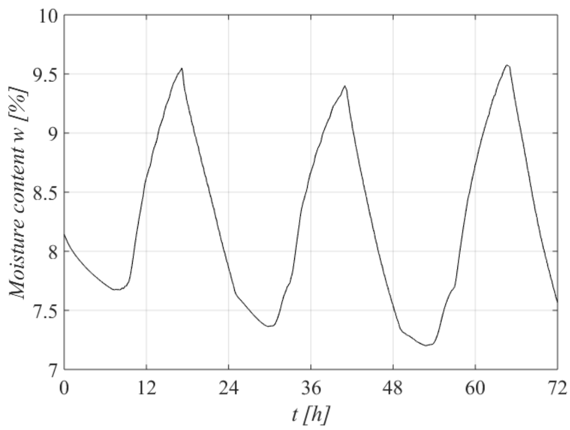


Figure 9: *Variation of moisture content in the whole interior solid wood panel during three experimental cycles (simulation data)*

In Figure 7 it was shown that the interior surface temperature T_s of the wooden panel increases when moisture migrates in its structure. This is consistent with findings of a previous study that employed thermography techniques to highlight the potential of wood as hygroscopic material to increase its temperature due to moisture adsorption [11]. Furthermore, another study employed a validated hygrothermal model to show that the temperature increases in the wooden structure as well and not only on the interior surface [15].

Figure 10 depicts the variation of the temperature at various positions/depths within the interior solid wood component. The results are consistent with the findings of the study mentioned above, showing that the temperature increases within the wooden structure and not only on the surface, as the thermography camera can monitor. Moreover, given the small area of the window and the fact that the testhouse is well-insulated, it would be reasonable to claim that the direct solar gains and the heat transfer from the surroundings are not very strong. Therefore, it can be assumed that the temperature increase, i.e. 3 °C, occur because of the moisture absorption in the wooden structure (latent heat of sorption).

The latter can be also justified by the fact during the heating period (high values of temperature), there is a noticeable difference between the temperature variation within the wooden panel.

It seems that the mass of wood as hygroscopic structure and not only the surface has the capacity to get active during moisture migration and because of its favourable hygrothermal properties. The temperature increase during humidification is also consistent with the increase of the indoor temperature T_i, revealing that there is an impact on the indoor climate from the heat released by the wooden structure.

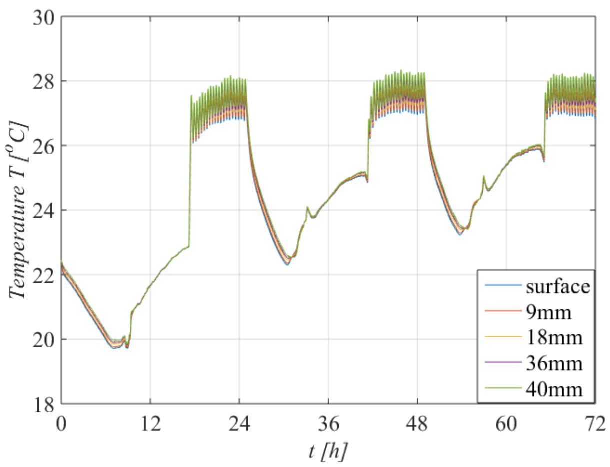


Figure 10: *Variation of temperatures at various depths within the interior solid wood component (simulation data)*

3.4 HEAT OF SORPTION

Based on Eq. 4, the heat of sorption can be calculated. The measurements of moisture content showed that during humidification the moisture content increases by 0.6% within 10 mm. The latter is considered as penetration depth d_m. The density of the solid wood is ρ_m = 450 kg/m^3. The surfaces that absorb moisture are assumed to be the walls and the ceiling. Thus, the total surface area to be consider in Eq. 2 is 16.5 m^2. Therefore, the heat of sorption during the whole humidification phase (8h) is H_s = 0.3 kWh. If the simulation findings are used, i.e. moisture variation Δw = 2% and penetration depth d_m = 40 mm, the heat of sorption is calculated as H_s = 4 kWh.

Despite the fact that the heat of sorption is a small absolute magnitude, it can be comparable to the conductive heat losses through the opaque components of the testhouse. In particular, during a spring or autumn day with an outdoors temperature T_o = 5 °C, the temperature gradient between indoors and outdoors is ΔT = 15 °C. Given that the –value of the 280 mm thick TermoElement is U = 0.16 W/m^{2}K, the total conductive heat losses during a day through the walls and the roof are 0.95 kWh. Thus, the heat of sorption can counterbalance more than 30% of the heat losses.

A hypothetical scenario of a building built of this sandwich panel is employed. It is assumed that the building has a floor area of 100 m^2, i.e. 10 m × 10 m, while the net height indoors is h = 2.7 m. The non-opaque elements of the building are considered as covering the 25% of the floor area, i.e. 25 m^2. The total surface area of the walls and the ceiling in this case would be (108 – 25) + 100 = 183 m^2.

Using the validated hygrothermal model, the heat of sorption is calculated for a typical spring/autumn day in Oslo, i.e. T_o = 5°C, as well for a typical winter day, i.e. T_o = -15°C. A MDRY year of Oslo is used as exterior climate in the model. The indoor conditions are assumed as constant T_i = 20°C and RH_i that fluctuates between 40% - 50%. The latter represents usual fluctuations in a residential building and in particular a humidification phase 16 h (occupancy) and a drying phase of 8h during the daytime. In addition, a hypothetical case with diurnal variations of RH_i = 30% - 60% is also employed.

The diurnal moisture content *w* variation in the ceiling is in this case Δw = ±0.25% for the milder RH_i and Δw = ±0.7% for the moister case (Fig 11).

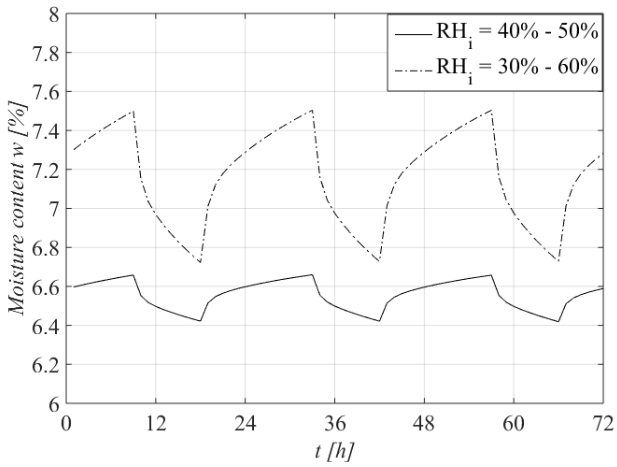


Figure 11: Variation of moisture content w within the inner 10 mm of the solid wood component (T_o = -15 °C)

Using the new data and inputs, the heat of sorption can be calculated based on Eq. 2 for a realistic residential building with solid wood as interior surfaces. Table 1 summarizes the latent heat released during humidification over one day. Table 2 and 3 show the conductive heat losses through the walls and roofs during a typical day with T_o = 5 °C and T_o = -15 °C respectively. Furthermore, the heat of sorption as a fraction of these losses is depicted in parenthesis.

***Table 1:** Latent heat of sorption, H [kWh], released during one-day time interval during water vapor migration in the inner solid wood of the sandwich panel*

Surfaces	RH_i = 40% - 50%	RH_i = 30% - 60%
Walls and roof	1.4	3.9

***Table 2:** Conductive heat losses per opaque element [kWh] and the latent heat of sorption as fraction of it [%] during an one-day time interval (T_o = 5 °C)*

Surfaces	RH_i = 40% - 50%	RH_i = 30% - 60%
Walls and roof	10.5 (13.3%)	10.5 (37.1%)

***Table 3:** Conductive heat losses per opaque element [kWh] and the latent heat of sorption as fraction of it [%] during an one-day time interval (T_o = -15 °C)*

Surfaces	RH_i = 40% - 50%	RH_i = 30% - 60%
Walls and roof	24.6 (5.7%)	24.6 (15.9)

The results show that heat of sorption can counterbalance from 5.7% up to 37.1% based on the temperature gradient between indoors and outdoors as well as the moisture generation indoors. Potentially, this means that the latent heat can function as a 'dynamic insulation' for the elements that have hygroscopic surfaces.

However, the biggest challenge in order to exploit the heat sorption is the fact that after the humidification phase (increase of RH_i) the solid wood will need to absorb energy to dry out. This is fundamental requirement in order the Δw to occur. In this way the interior solid wood will regain its capacity to absorb water vapour in the next humidification period.

If the drying process is controlled by the HVAC system, the energy spent will tend to cancel the benefits of heat sorption gained during the wetting phase. The exploitation of solar gains during daytime through a strategically chosen windows size and orientation would drastically contribute as a free energy source for the necessary drying process.

One of the 'non-material' parameters that affect the moisture buffer capacity of surfaces is ventilation both mechanical and natural [16]. Higher ventilation rates result in reduced buffering effect [17]. An HVAC system that regulates constantly the RH_i will buffer the peak and valleys of RH_i, eliminating the potential vapour migration in the solid wood. Similarly, infiltration can also reduce the efficiency of the phenomena discussed. Infiltration contributes to extract the moisture outside the building and thus the potential increase of MC decreases, in particularly locally where leakages are located [15].

4 THE POTENTIAL USE OF THE PANEL FOR REHABILITION

Mounted as either single wall segments or small elements or large elements or even as a mixture of all three, makes the system very flexible and efficient in terms of adjusting it to the geometry and tolerances of an existing building. The outer layers of the modular wall system consists of a multiply solid wood panel which facilitates the mounting of the system on timber as easily as on either concrete or brick surfaces. For light-frame structures self-tapping screws or special timber connectors are used to attach the modular wall system. The length of the connecting rods between the multiply solid wood panels can be adjusted in order to serve a specific U-value requirement for external walls. Moreover, the modular wall system can be prefabricated with in-blown insulation, insulation mats or both, depending on what is more rational and economical for the individual project.

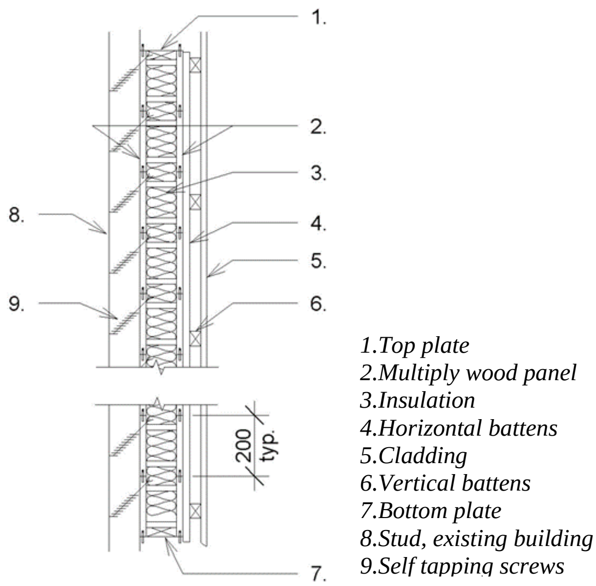
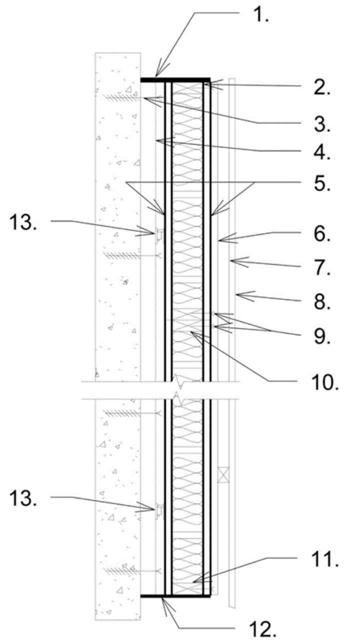


***Figure 12:** Vertical cross section, rehabilitation of light frame wall with the patented modular wall system*

For rehabilitation of brick and concrete walls, special timber connectors or wooden battens are fixed to the load carrying structure by using concrete anchor bolts or screws. The modular wall system is attached to the timber connectors or screwed onto the battens with self-tapping screws.



1.Airtight membrane
2.Top plate
3.Concrete anchor or screw
4.Vertical battens
5.Multiply solid wood panel
6.Vertical battens
7.Cavity layer
8.Cladding
9.Self tapping screws
10.Top plate
11.Bottom plate
12.Airtight membrane
13.Special timber connector

Figure 13: *Vertical cross section, rehabilitation of concrete wall with the patended modular wall system*

5 CONCLUSIONS

This paper discussed the hygrothermal performance of a recently certified wood-based prefabricated insulating sandwich panel, called TermoElement. The experimental findings using thermography techniques in a testhouse built entirely of this element showed that when indoor RH_i increased (from 50% to 75%), the surface temperature of the interior solid wood component increased as well, approximately 3°C. The corresponding increase of moisture content w was Δw = 0.5% in the inner 10 mm of solid wood.

A validated 1D hygrothermal model showed that the temperature increases in the whole 40 mm of the inner solid wood component and not only on the surface. This fact can drastically contribute to reduce the temperature gradients between indoors and outdoors and thus the conductive heat losses through the opaque elements. In addition, the results from the simulation showed that the penetration depth exceeds 10 mm allowing the whole mass of solid wood to contribute to moisture buffering.

Furthermore, the latent heat of sorption was calculated based on state-of-the-art equations. When the results are compared to the conductive heat losses of the testhouse during a typical mild spring/autumn day in Oslo (T_o = 5 °C), it is clear that heat of sorption can counterbalance more than 30% of them.

To highlight the potential of heat of sorption to function as dynamic insulation in building elements, a hypothetical case of a building constructed of the same sandwich panel was employed. Typical values of indoor and outdoor conditions were taken into consideration. The mathematical calculation showed that when the diurnal variations of relative humidity indoors are RH_i = 40% - 50%, the latent heat can counterbalance 5.7% of the conductive losses through the walls and the roofs during a typical spring/autumn day (T_o = 5 °C) and 13.3% during a typical winter day (T_o = -15 °C). In case the levels of the relative humidity indoors are higher, i.e. RH_i = 30% - 60%, the gains due to latent heat are multiplied and can be 15.9% and 37.1% respectively, by means of fraction to the conductive heat losses.

During evenings and nights when the moisture generation increases due to occupancy, a ‘humidification phase’ for the wooden structure can be assumed. The increase of the latent heat of sorption during this period can reduce the heating demand in a building and can lead to energy savings by adjusting the operative temperature to a lower level. The exploitation of the solar gains during daytime will contribute to dry out the wooden structure in order to secure the diurnal dynamic circle of RH_i which is necessary for the latent heat phenomena to get activated. In addition, the mechanical ventilation ought to be regulated in such way that allows the moisture to migrate into the hygroscopic structure before it is extracted outwards.

In a dynamic estimation of thermal insulation in building components, the exploitation of latent heat would significantly reduce the required thickness of this layer. The authors believe that taking into account the building materials properties hold a key for energy savings by including in the energy balance equations the thermal energy stored in heavy materials by means of thermal mass and in hygroscopic materials in a form of ‘hygrothermal mass’. A more detailed approach to the dynamic phenomena, as mass transfer, that occur in a building ought to lead towards a more accurate calculation of the actual energy demand and heat losses, while it will also fortify the position of natural materials and ‘low-tech’ technology as an effective solution implemented future buildings design.

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