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MEASUREMENT OF SORPTION HEAT IN LABORATORY AND FIELD TESTS IN COMPARISON WITH HYGROTHERMAL SIMULATIONS

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Abstract

The temperature changes after moisture jumps on different material surfaces were demonstrated in laboratory tests. These phenomena (latent heat effects) also occur with gradual moisture changes but less pronounced amplitudes. Especially measurements in field tests, therefore, require methods that can record very small temperature differences without environmental influences. The measuring technique developed for this purpose shows promising results for measurements on different wood surfaces and might allow conclusions about the transient hygroscopic behavior. Although, we found limitations in the measurement method in the case of increased air velocities on the component surface.

Introduction

Hygroscopically active building materials are in constant exchange with the surrounding climate. If the ambient relative humidity changes, the material adapts to it by sorption, and enthalpy is either released or bound. This process always occurs as a function of time and the specific material parameters of the surfaces. If a component absorbs moisture, the water vapor condenses in the pores of the building material and it heats up as a result of the phase change. If the room air humidity is drier than the building component, then water stored in the pores evaporates back into the room air. Enthalpy is required for this phase change from liquid to gaseous to cool down the building component. We can calculate these transient phenomena through hygrothermal simulation tools. To what extent can measurements validate these results?

In the context of room cladding materials, latent heat is prospected to have a positive potential. With materials such as wood, the latent heat effect is assumed to have a thermoregulating impact in addition to their purely hygroscopic moisture buffering properties. Conversely, these thermal effects could potentially be used for developing a measurement technique to detect moisture buffering in the layers close to the surface. Could we use simple temperature measurements to detect moisture transfer on the surface of building elements? When moisture is transported into or through a material layer, enthalpy changes occur, which can be experienced or measured by the release of sensible heat. In (Winkler et al., 2014) both the buffering of relative humidity and the heat transport due to sorption are investigated using hygrothermal simulation. In (Dupleix et al., 2018; Kraniotis et al., 2015) laboratory experiments have already been carried out in which the increase in mass and heating of small wooden test specimens after abrupt humidification are documented. In (Nore et al., 2017) hygrothermal simulations of this phenomenon are validated using experiments in two test rooms made of solid wood. Similar room-scale numerical simulations in (Legros et al., 2020) show, that a spruce surface has a lower surface temperature and air temperature during the summer period when compared to painted plasterboards. They attribute these findings to the higher hygroscopicity of the spruce. Laboratory studies on the moisture buffering behavior of various building materials have shown that a glaze alone can significantly reduce the moisture buffering value (MBV) of wooden surfaces. For example, an MBV of 0.70 kg/m²-%RH has been determined for cross-laminated timber without any further coating, whereas a reduced MBV of 0.61 kg/m²-%RH has been measured for cross-laminated timber with a glaze (Ineichen, 2020; Flexeder et al., 2022 - in press).

(Skulberg et al., 2022) conduct an experiment, where two classrooms with differently treated wooden claddings are compared. Using electrical resistance measurements they can detect differences between the moisture content of building elements having spruce surfaces sealed with transparent varnish and similar ones which stayed untreated. Even though they attribute the higher hygroscopicity of the untreated surface to a higher hygrothermal mass, they don´t measure these effects. They note that the moisture buffering effects seem to be lower when the rooms are more ventilated.

In (Winkler et al., 2014) as well as (Nore et al., 2017), only constant air changes were assumed. On the contrary, natural concepts result in different air velocities in the room as well as along the surface of the enclosing surfaces, strongly dependent on the pressure difference between inside and outside.

So far, it remains unclear to what extent the measurement of surface temperature changes after artificially generated moisture jumps can be transferred to realistic indoor climates in the course of the day or season. How does an inside glaze affect the hygrothermal behavior of a cross-laminated timber surface under realistic climatic conditions? Can differences between the non-stationary sorptivity of untreated, glazed cross-laminated timber surfaces and those covered with vapor-retardant foil be measured in the field test in passive behavior without air conditioning? To what extent do these differences in thermal behavior show up?

Methods

Description of the field test set-up

The test setup was built to perform a wide range of experiments on hygroscopic materials. The interior dimensions of the test chambers are approximately 1.30 m x 1.30 m x 1.10 m (length x width x height) and can be accessed through a window, see Figure 1.

Figure 1: Measurement setup for the experiments in the test cube with two facade test elements: untreated (left) and glazed cross-laminated timber surface (right). The humidifier shown was not used for the analyzed period.

The chamber environment can be regulated through heating, humidification, ventilation, and orientation along two axes. In addition to the technology for supply and data processing, the test chamber contains the following measurement equipment: fifteen temperature PT1000-sensors, twenty-three hygro-thermometers, one black-globe thermometer, three barometers, two luminance meters, one heat flux plate with a built-in surface thermometer, three energy monitoring drivers with three Current Transformer (CT) clamps.

Description of the measurement technique to detect minute temperature changes

The more pronounced the change in humidity, the more distinctive the temperature change at the surface under otherwise constant conditions. The enthalpy release/binding due to successive changes in relative humidity can therefore only be observed by very small temperature changes over a longer period. In addition, the measurement of surface temperature changes due to humidity sorption results in a conflict: at the very location covered by a sensor itself, the surface will not be able to sorbe water vapor. This means that all measured surface heating can only stem from the surrounding areas.

To evaluate the minute temperature deviations on several points of the test elements, 4-wire cables were soldered to platinum RTDs (M 222, type: pt1000, accuracy: ≅ ±0.1°C, class: 1/3 B, DIN EN 60751) [x]. These tiny temperature chips (2.3 mm x 2.1 mm x 0.9 mm) were attached to specially designed 3D-printed casings to mount them on the surfaces of test elements (Flexeder, 2022). Individual wires were passed through the perforations of each pyramid and joined to the pins of the temperature sensors on one end, and on the other end to the RTD-to-digital converter to transfer a compatible signal to the microprocessors (Maxim Integrated Products Inc., 2012). The data was then logged on the computer through the microprocessor unit. For the sensor mount, we used rapid prototyping as a design method, see Figure 2. The final geometry allows for the optimum ratio of curvature and insertion angle to be determined to ensure stable solder joints while protecting against condensation and possibly short circuits.

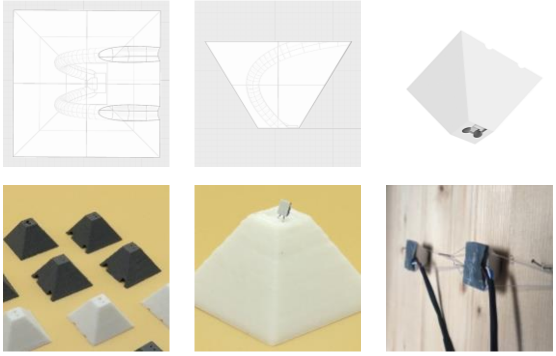

Figure 2: Design of the sensor mount (Flexeder, 2022)

In the measurement method used, interferences are factored out by measuring a "twin" in parallel. Here, two identical temperature sensors are mounted on the component, with a vapor-barrier film previously applied under one of them. This procedure makes it possible to isolate a single effect (the change in surface temperature due to water vapor sorption) from temperature fluctuations, which are often inevitable even in laboratory operations. The cover used has a minimum s_d-value of 5 m. An s_d-value of 0.1 m is assumed for the wood glaze investigated based on the moisture buffering values (MBV) previously determined (Ineichen, 2020; Flexeder et al., 2022 - in press).

Description of lab set-up for experiments on air velocity

In order to measure the influence of the air velocity on the sorption process and thus on the measured heating at the surface, a moisture jump test is undertaken in the laboratory in a conditioning chamber. In addition to two fans and two scales, the chamber has numerous sensors for measuring relative humidity and temperature. For the experiment, two test specimens (spruce) with the same dimensions and the same preconditioning are each covered with vapor-barrier adhesive tape: test specimen a is sealed on five sides, reference specimen b is sealed on six sides. Both specimens are weighed with a precision balance before and after the test and each is fitted with a temperature sensor. After sufficient preconditioning, the actual main test is carried out with an isothermal moisture jump. For this purpose, the conditioning chamber is opened and the specimens are quickly placed each in front of a fan. When positioning them in the conditioning chamber, care is taken to ensure exactly similar alignment. This is followed by several hours of isothermal conditioning at a humidity of 99 % and a constant air temperature of 20 °C. Depending on the test series, circulated air is blown past both test specimens with a fan at around 1.5 m/s. The surface temperature is logged every 30 seconds on both specimens a and b and used to derive the temperature difference caused by the adsorption on test specimen a.

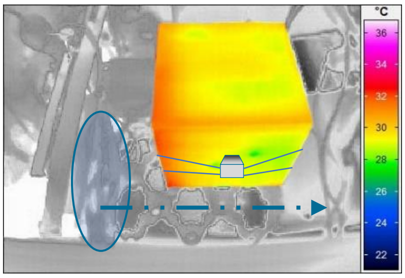

Figure 3: Thermography of the experiment setup with heating (only used to illustrate air flow). The position of the temperature sensor and the fan is marked schematically.

Our method has a disadvantage due to the spatial proximity of the test specimen and the fan: turbulence does not produce a uniform air velocity on the tested wood surface. Rather, this must be measured at several points with an anemometer and then averaged. To illustrate this, we performed another test with heated air, the result is shown in Figure 3. In our main experiments, however, isothermal ventilation was used exclusively.

Description of the simulation model

Various simulation models to calculate moisture transport in hygroscopic materials use the Fourier-Fick-analogy and can be found in numerous publications using the thermal modules in software like ANSYS or Abaqus. These approaches offer the possibility to work with varying surface resistances. The surface-emission coefficients (herein often described by the formula symbol S [m/s]), are the important material parameters in this simulation method. (Schaffrath, 2015) provides a detailed description of this method as well as a discussion of the coefficient specifically concerning wood moisture content. However, due to their analytics, these simulation models are not suitable to calculate any coupled enthalpy effects.

With hygrothermal software like WUFI, DELPHIN or TRNSYS (with an adapted new plug-in, not officially released yet) the enthalpy effect can be simulated. For our work we used WUFI Pro, which is often used in engineering practice. It too can be used to model the effects of enthalpy of sorption under different air velocities, although with some constraints. It offers the possibility to modify the surface conditions by an additional thermal transfer resistance [(m²K)/W], but these are then fixed for the entire duration of the simulation. The adjustment of the vapor transfer resistance at the surface could be done by the conversion to an equivalent s_d-value. (Worch, 2002) provides comparative measured values on the relationship between air movement, the water vapor transfer coefficients β and β´, and the s_d-value for numerous building materials and conditions. Consecutively, they show the analogy between the thermal resistance at the surface and an additional vapor transfer resistance in (Worch, 2004). Their experimental set-up including wind tunnels enables the measurement of air-velocity-dependent diffusion parameters. They test their hypothesis using two building materials (foam concrete and plaster), unfortunately, no type of wood species was examined. Table 1 shows the relationships, which we adapted and used in our WUFI simulations. In order to reproduce the behavior of the facade test elements, the following

Table 1: Values for heat and moisture resistance at the surface under different air velocities by (Worch, 2004), adapted to be used in a hygrothermal simulation with WUFI Pro

AIR VELOCITY	0 m/s	1 m/s	2 m/s
HEAT TRANSFER RESISTANCE [(m²K)/W]	0.25	0.125	0.08
SD-VALUE [m]	0.015	0.00625	0.004

material parameters were measured with the same materials (cross-laminated timber, glaze) in laboratory tests: water absorption coefficients, density, sorption isotherms (averaged, since no distinction between adsorption and desorption in the WUFI simulation), transient sorption behavior. Suitable sd-values to model moisture dependency were then derived from fitting simulation results to the measured curves from the lab experiments. (Ineichen, 2020)

Results and analysis

Comparison of laboratory measurements and adapted hygrothermal simulations

As a preliminary test of the thermal response to a simple isothermal humidity change, the values from Table 1 are used to simulate the effect of air velocity according to (Worch, 2004). Figure 4 shows the difference in surface temperatures that would occur according to the simulation on a spruce surface with a sudden climate change from 20 °C / 50 % RH to 20 °C / 99 % RH. The measurement results shown in Figure 5 were measured several times using the difference method with a taped twin. Since we did not use a wind tunnel in our experiments, the results from the laboratory test with different air speeds show some irregularities (turbulence). The specified air velocity value of 1.5 m/s was, therefore, averaged from repeated measurements at various points on the test body using a hand-held anemometer. The comparison with the expected values from the simulation shows similar tendencies in the curve progression and thus a satisfactory qualitative agreement.

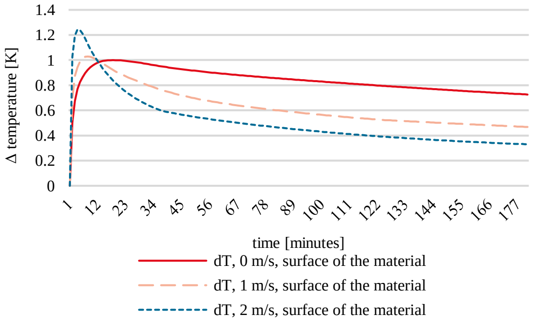

Figure 4: Comparison of the different air velocities, simulated material temperatures after an isothermal change of RH from 50 % to 99 % at 20 °C

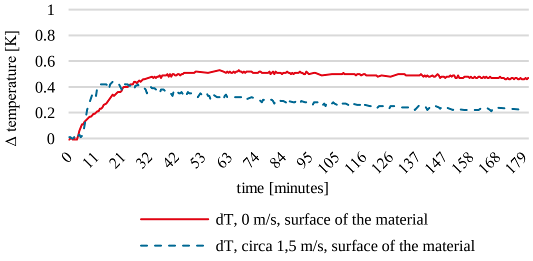

Figure 5: Measurement results of two experiments with different air velocities at the surface

Measurement results for hygrothermal behavior of untreated and glazed cross-laminated timber surfaces in field tests

The measurements in the test cube were carried out over several years with different facade test parts and room climate concepts. In the following, the measured values of 72 hours with a typical transition climate are analyzed. Figure 6 shows the variations in indoor humidity and temperature due to day-night fluctuations. The fluctuations in relative humidity automatically result in latent heat effects on the sorptive interior surface of the facade test parts. Depending on whether they consist of untreated, glazed, or covered wood, corresponding temperature fluctuations occur. Figure 7 shows the resulting temperature curves for the selected section (72 hours with the measured values typical for October), which vary depending on the position on the facade test part. After filtering the data from environmental effects and short-term fluctuations, surface temperature differen-

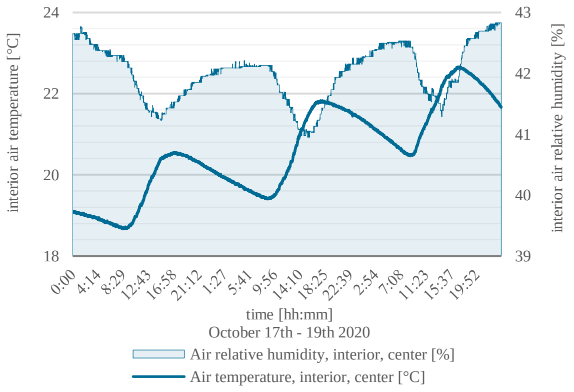

Figure 6: Air temperature and relative humidity measured in the center of the test cube

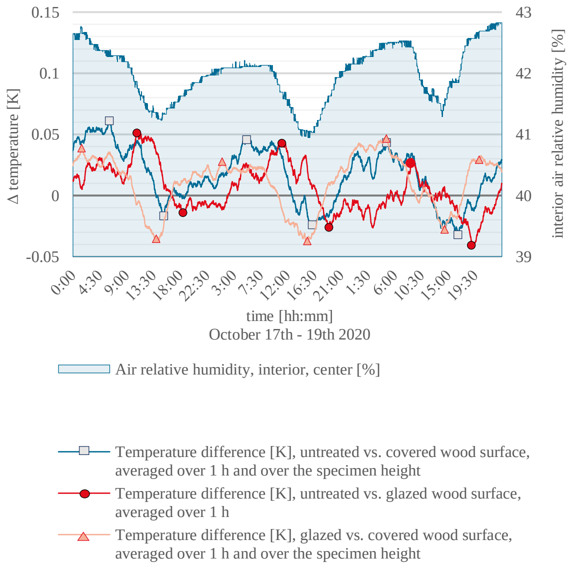

Figure 7: Differences between the different surface temperatures, measured in the test cube. The shown data is already cleaned from other influences

ces can be identified as a function of the daily indoor climate. The glazed cross-laminated timber surface is around 0.15 K warmer in the early hours of the morning (around 1 a.m. to 6 a.m.) than later in the day and in the early afternoon (around 12 a.m. to 3 p.m.) comparatively cooler than the reference surface sealed with foil. In addition, the curve for the untreated cross-laminated timber shows a slightly higher temperature in the morning (approx. 9 a.m. to 12 p.m.) compared to the glazed surface. Certain buffering effects can therefore be detected for the measurement period under investigation, with the temperature sub-fluctuations of the air being around 20 times greater than the determined surface temperature differences due to sorption heat. The influence of the thermal buffering effects would therefore only have a very minor influence on the total thermal balance in the room.

Simulation approaches to replicate the results from the field tests on the hygrothermal behavior of differently treated wooden surfaces

The climate file to be used in WUFI was created with input conditions based on the measured relative humidity. The hourly values were taken from exact measurement in time, as this provided a better representation of the data than simple averaging. The expected surface heatings are first simulated purely by sorption (with starting conditions of 20.56 °C / 42.65 %). For better clarity, the simultaneous fluctuations of the air temperature are neglected in the following two illustrations. Figure 8 shows the influence of the different surface treatments on both, the temperature on the surface as well as 6 mm inside the timber element. For the results in Figure 9, the values from Table 1 were assumed.

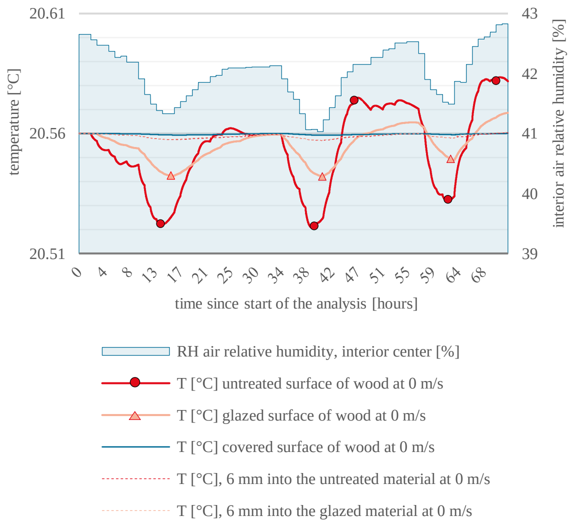

Figure 8: Simulation results for differently treated wooden surfaces based on the interior climate measured in the test cube

Further, Figure 10 depicts the resulting temperature differences considering the prevailing air temperature as well as with sufficient settling time in the simulation. Finally, the exemplary comparison of the temperature differences determined from measured data and simulation values shows that the measurement method works in principle. The quantitative deviations and time delays in Figure 11 might be caused by measurement inaccuracies.

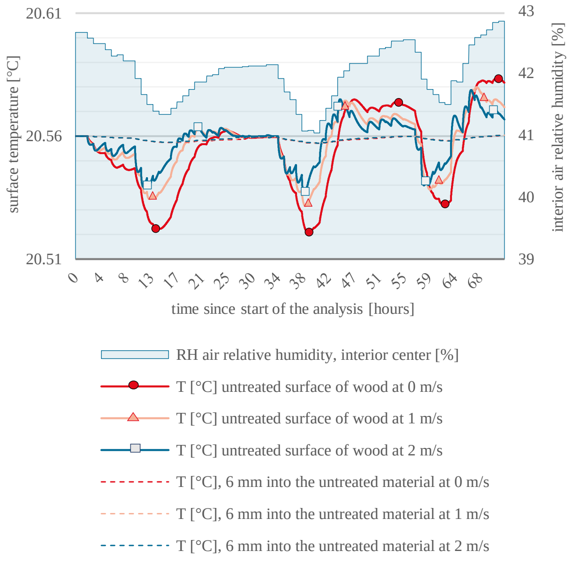

Figure 9: Simulation results for different air velocities on an untreated wooden surface, based on the interior climate measured in the test cube

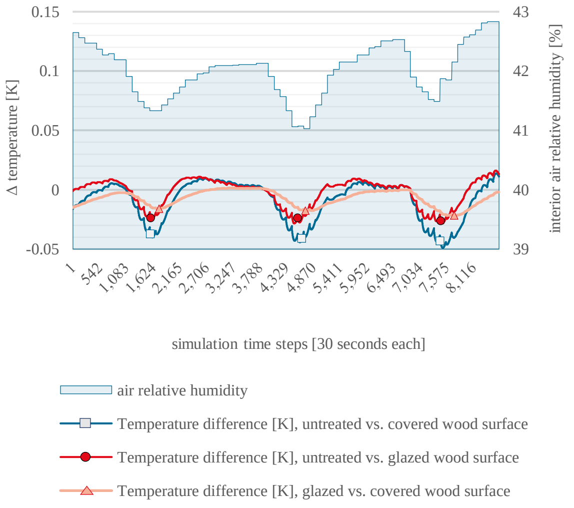

Figure 10: Differences between the different surface temperatures, simulated with WUFI and based on measured interior climate (see fig. 1).

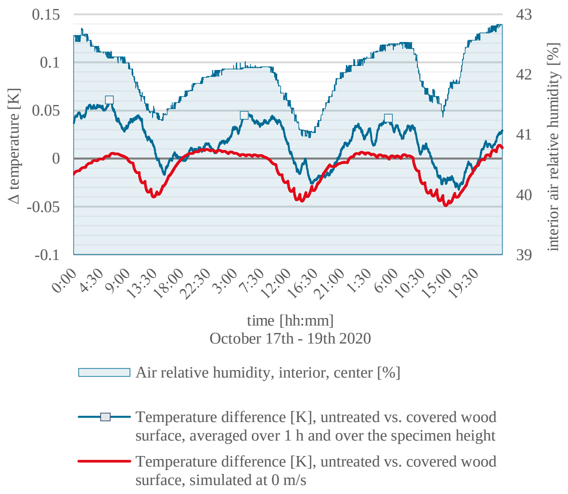

Figure 11: Comparison of measured and simulated temperature differences on the surface of untreated vs. covered CLT with no forced air movement.

Conclusion

We have developed a cost-effective method to monitor minute temperature changes caused by sorption on hygroscopic building components. According to the first field tests, the methodology is consistent with results from hygrothermal simulations based on individually determined material parameters and a simplified model for modeling surface resistances. However, there are still large deviations due to measurement errors with small amplitudes. The modeling also shows some inaccuracies, such as the neglect of the hysteresis between adsorption and desorption isotherms. For thorough investigations, elaborate test environments and a detailed simulation model would be necessary. Our approach intends to demonstrate a simple and efficient procedure. While room temperature regulation through the enthalpy effect plays a minor role in realistic scenarios, the measurement technique presented here could be a new and straightforward method for detecting adsorption and desorption on surfaces in-situ.

Acknowledgments

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