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MONITORING DYNAMIC MOISTURE GRADIENTS IN WOOD USING INSERTED RELATIVE HUMIDITY AND TEMPERATURE SENSORS

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FULL PAPER

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Abstract

To be able to combine the preservation of wooden objects of cultural significance with energy efficiency measures it is important to develop our knowledge of the relation between the rate of change of relative humidity and temperature, moisture content gradients and the resulting dimensional change of wood. The work presented here introduces and evaluates a method for monitoring dynamic moisture content gradients, mainly for research applications. Relative humidity and temperature were measured by miniature sensors, placed in drilled holes at different depths in wood samples to monitor the moisture transport. The data was used to calculate moisture content and the results could hence be compared with the results from a commercial resistance moisture meter, monitored at the same depths. The results of the two methods did not coincide. A Fickian model for moisture diffusion was chosen to verify the monitored results. It showed poor fit with the commercial resistance method and a reasonably good fit with the new method using relative humidity and temperature sensors. We concluded that the new method provides reliable and consistent data suitable for monitoring moisture content at different depths under unsteady state conditions, while the data generated by the resistance method in our set-up was inconsistent with the model and with our understanding of the moisture transport process.

1 Introduction

Two important tasks of museums are to exhibit and to maintain their collections. The latter includes preventive conservation. For instance, to avoid permanent damage to objects of organic, hygroscopic materials, one measure is to keep relative humidity (RH) and temperature (T) stable in galleries and storage. In this way, excessive adsorption and desorption of moisture, which may result in mechanical deformation, can be avoided. Recommendations for museums are often based on Thomson's climate specifications[1]. However, strict climate regulations have been questioned and substantial research has been performed to investigate to what extent the advised climate ranges can be widened due to energy efficiency demands, without putting the objects at risk[2, 3]. Some collections are housed in buildings without climate control favouring preservation of objects while other historic buildings are only occasionally heated[4]. The influence on hygroscopic objects due to dynamic environmental conditions found in such buildings is less investigated.

In order to widen the knowledge on the impact of indoor environment on hygroscopic objects, so as to be able to develop rational climate control criteria, further studies are needed. This includes determination of responses of objects in dynamic conditions over long periods of time in order to understand the impact of both daily and seasonal changes. Methods for monitoring strain are available, while methods for monitoring moisture transport are less used and evaluated. This paper presents a method which could be used for this purpose.

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moisture gradient, moisture transport monitoring, resistance moisture meter, wood.

In the cultural heritage sector, research in this area has focussed on wooden objects, such as furniture and panel paintings. Several methods have been used to measure and monitor the mechanical deformation of wood samples or authentic objects in laboratory and *in situ*[5, 6]. A less investigated area is moisture sorption as being the cause of mechanical deformation, such as studied by Senni et al.[7]. Modelling of the indoor climate and the influence on wood and numerous other materials was first introduced by Mecklenburg et al.[8] and has been performed and developed since, for instance by Jakieła et al.[9]. Data is available on the relationship between RH and equilibrium moisture contents (EMC) at constant temperatures, moisture adsorption or desorption isotherms, for various wood species found in heritage objects[10]. Moreover, modelling and simulation of the influence of outdoor climate and prediction of future global warming impact on the cultural heritage has also been performed[11].

Computer models for deformation in wood have to deal with the complexity of moisture transport in wood. Moisture is predominantly transported in wood by two mechanisms, water-vapour diffusion in the cell lumen and pit openings and bound water diffusion in the cell walls. The dynamic diffusion process can generally be described by Fick's second law which describes un-steady state (transient) conditions such as those found in an indoor environment of an historic building. Wadsö[12] observed that Fick's second law is essentially valid for low or moderate RH range approximately below 75 %. Above this range the transport processes are much more complex. Water vapour and bound water are not always in equilibrium because diffusion of vapour is almost instant compared to bound water diffusion. At high moisture content (MC) levels the resulting slow process is responsible for the so called non-Fickian behaviour[13]. To improve the models in the high RH range, coupled sub-models are suggested[14.]

Hysteresis, the different path of the adsorption and desorption isotherms due to the previous moisture history in wood, depends not only on RH but also T. At the full RH-range (0-100 % RH), EMC is higher at lower T and lower at higher T for the same RH. The dependence of sorption hysteresis on T is more pronounced in the lower T range. Above 75 °C, the T dependence disappears[15]. According to Hill et al.[16] the adsorption isotherms essentially remain unaffected, whilst the desorption isotherms are strongly affected by T, as the area bounded by the hysteresis loop decreases with T. The adsorption and desorption isotherms indicate the minimum and the maximum EMC values between 0 and 100 % RH respectively, and can be considered the boundary isotherms. Any smaller EMC fluctuations, so called scanning-curves, will stay within the area between the boundary curves[17]. One example is shown in Figure 1 in this article.

One area which needs to be further studied is how moisture moves in wood, since mechanical deformation is not only dependent on a mean MC value of wooden objects. By recording MC at different depths in wood the moisture transport can be monitored. Of interest are dynamic conditions and moisture gradients which will develop in historic building environments with limited climate control.

To be able to monitor moisture gradients with high accuracy the choice of method used is critical. The most common indirect method for MC measurements is based on electrical resistance[18]. However, a number of problems with the resistance moisture meters have been reported[19, 20, 21]. Moreover, the resistance meters do not monitor equally accurately in the entire RH-range. The most accurate readings by the resistance equipment used in this study are in the 10-25% MC range, according to the product information. Electrical resistance methods use various sensors applied inside the wood [21, 22]. Moisture profiles in wood have also been investigated using more accurate methods under laboratory conditions, for instance magnetic resonance imaging (MRI)[23, 24]. Because of the uncertainties with the electrical resistance methods the cultural heritage sector needs additional methods for monitoring moisture profiles in wood for extended periods of time, in laboratory and, equally importantly in field studies, in order to study the impact of both daily as well as seasonal RH and T variations. The sector requires non-invasive methods where original artefacts are involved. However, there is also a need to verify results by comparing different methods and for such purposes experimental wood samples are preferable.

The work presented here is introducing and evaluating a method for studying moisture transport in wood in order to estimate the moisture impact on wood during dynamic environmental conditions. It is based on measurements employing RH and T measuring sensors which are placed in drilled and sealed holes in wooden samples at different depths. In the present work the sensors were placed 1, 4 and 7 mm from the wood surface. The results were compared with results from the use of a commercial resistance moisture meter, monitoring MC at the same depths in wood samples. The measured data was validated by a Fickian moisture diffusion model.

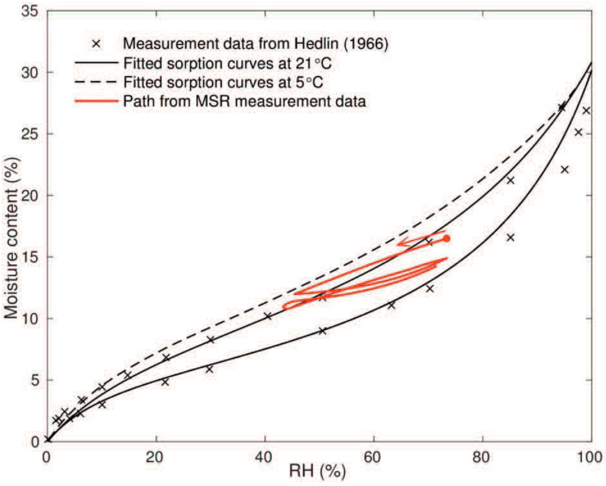

Figure 1: Sorption curves based on data from Hedlin[27].The red line shows the path in RH-MC-space for the experimental data at 1mm in wood for the data set shown in Figure 6. The arrow indicates the start of the RH step changes. The dashed curve shows the desorption isotherm at 5 °C, computed as described in section 2.4.1.

2 Materials and Methods

2.1 The Use of a Climate Chamber

All the experiments were performed in a Climatic Test Chamber (CTS Climatic Test Chamber, C-20/200, CTS

GmbH, Hechingen, Germany). In order to achieve an equal RH and T through the volume of the chamber, a built-in fan was constantly running during the experiments with an average wind speed of approximately 2 m/s. Hence the boundary layer, inducing resistance to the water vapour diffusion at the wood surface, was expected to be small. T and RH were monitored in different locations of the chamber during the experiment by external sensors of the Protimeter Hygrotracs (see section 2.3.1) as well as additional RH and T data loggers (Tiny Tag View 2, Gemini Data Loggers Ltd., West Sussex, UK).

2.2 Wood Sample Material and Preparation

The wood used for the experiment was Scots pine (*Pinus sylvestris* L.) from northern Sweden. The wood samples were chosen to be as homogenous as possible. The monitored front surface was planed and had a tangential cut with the bark side facing out. The monitoring surfaces of the wood pieces were positioned vertically during the experiments in the climate chamber. The five remaining surfaces, not monitored, were covered with aluminium foil and any small openings in the foil around the electrodes etc. were sealed with silicone (Sanitary Silicone, Casco Schönox Sweden AB, Stockholm, Sweden). Before monitoring started the samples had been kept at 70% RH in order to acclimatise to the initial conditions. Recordings were made once every hour.

In order to study the development of moisture gradients upon changes in the surrounding RH and T, monitoring of moisture content was done at 1, 4 and 7 mm from the surface using both methods. For each method and depth, three parallel recordings were made and hence the results are based on the value of triplet recordings.

2.3 Two Methods for Moisture Gradient Measurements

Two methods were chosen for monitoring moisture profiles in samples of wood. The first method using sensors for monitoring RH and T inside the wood (MSR logger), and the second method was a resistance moisture meter (Protimeter Hygrotrac).

2.3.1 The Resistance Meter

Protimeter Hygrotrac, (HygroTrac Kit, BLD9000-EU, OmniSense LCC, Ladys Island, SC, USA, distributed by GE Sensing at the time of purchasing the equipment) is a commercial pin-type resistance meter which consists of wireless sensors (Figure 2) and a Data Acquisition Gateway which collects the data and transfers it to the OmniSense LCC database server from which the data can be downloaded. It is intended for use in buildings and to monitor MC in building materials (mainly wood) as well as RH and T of the air (black antenna in Figure 2).

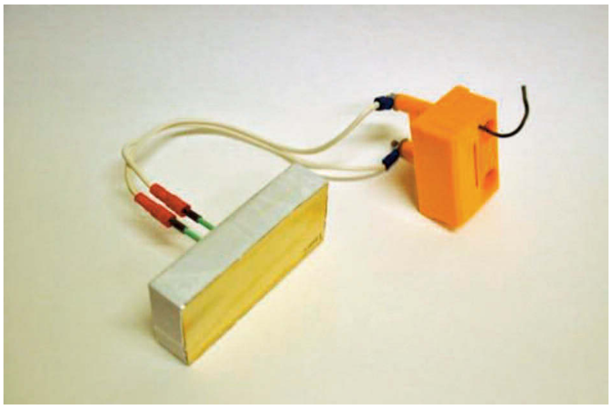

Figure 2: The resistance meter (Protimeter Hygrotrac) for monitoring MC at specific depths of the wood samples by means of electrodes inserted from the reverse side.

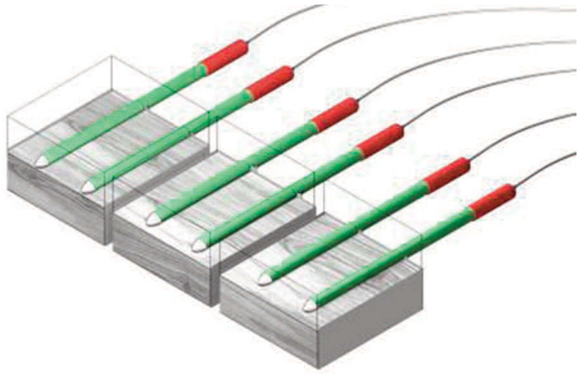

Figure 3: A schematic drawing of the experimental set up with the resistance meter's electrodes inserted to different depths of the wood. For this method only one resistance meter was used in one piece of wood (compare Figure 2).

In the original set-up, the sensors are mounted at the chosen location using stainless steel screws that function as the terminals for the moisture sensors which have a nominal transmission distance of 50 m. The RH range is 0-100% (non-condensing) with an accuracy of +/- 2.5% between 10 and 90%. The T range is -40 to 85°C with an accuracy of +/- 0.5°C at 25°C. The moisture sensor has a range of 0 to 40 % MC with an accuracy of +/- 1% in wood in the 10 to 25% MC range, subject to adjustments for species and T.

The accompanying screws were in this study substituted with electrodes (GE Sensing EMEA, Shannon, Ireland) that are insulated except for the 3 mm-long tip which makes them suitable for monitoring at different depths (Figure 3). Only one resistance meter was used in each wood sample in order not to disturb the measurements. The size of each sample was 45 x 100 x 20 mm. The electrodes were placed along the grain from the reverse side of the specimen and the distance between the electrodes was 10 mm. The effect of various distances (10 and 33 mm) used in this study did not show significant difference, and this corresponds with other studies[25]. Comparison of the results between the original set-up with the screws and the use of electrodes showed that the electrodes at four millimetres depth gave similar readings to the original screws.

2.3.2 The RH and T Measurement Method

The equipment for monitoring MC profiles in wood was a commercial data logger equipped with external, miniature T and RH sensors (MSR 145S, MSR Electronics GmbH, Henggart, Switzerland). It is developed to monitor RH and T in air. The working range and accuracy is for T-10°C to +58°C (accuracy: ± 0.1°C

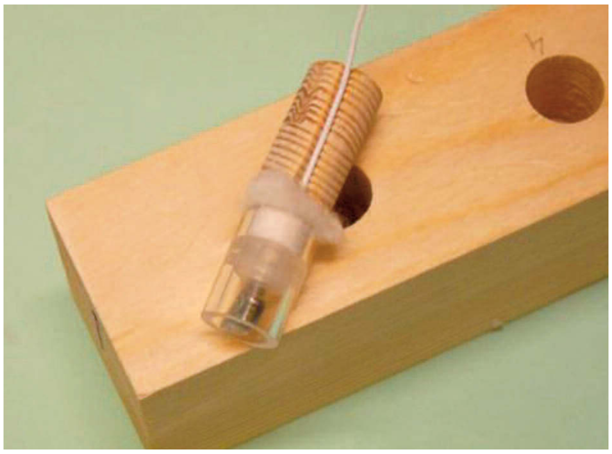

Figure 4: The small RH and T sensor can be seen in the bottom of the acrylic tube. Behind it are two silicon stopper discs, cotton wool and finally the wood plug. The setup was thereafter placed in the drilled hole of the wooden sample.

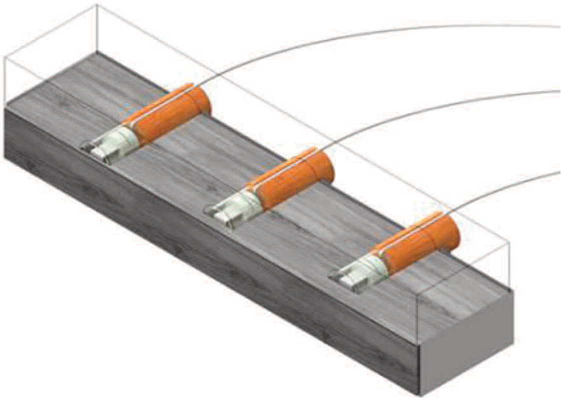

Figure 5: A schematic drawing of the experimental set up with the RH and T sensors inserted from behind in drilled holes to different depths from the wood surface.

in the range 5°C to 45°C) and for RH 0-100% RH (accuracy: $\pm$ 2% RH in the range 10-85% RH and 0 to 40°C).

The wood samples used had a dimension of 200 x 45 x 45 mm and three holes were drilled in each of the samples to the different depths. By inserting a sensor in the bottom of the hole and sealing it from the reverse side, the influence of RH and T on the sensor came from the opposite side (front side) of the wood sample (Figures 4 and 5).

Each sensor was placed in an acrylic tube and sealed by discs, cut from silicon stoppers (conical stoppers, Versilic®, VWR). The remaining part of the acrylic tube was filled with cotton wool to protect the data logger cord from sharp bending (Figure 4). Finally a wood plug made from the same Scots pine as the wood sample was inserted. The diameter of the drilled holes was 15 mm.

2.4 Modelling and Analysis

To investigate the validity of the two methods, the measurement data sets were fitted to a mathematical model for moisture diffusion. The model chosen is a simple Fickian diffusion model for moisture with constant coefficients. This one-dimensional model assumes that moisture diffusion takes place only in the depth-direction from the front side and that MC is constant across the width and height of the sample. This is a reasonable assumption since the sample is insulated on all sides but one. The complete model, with notation as in Krabbenhoft and Damkilde[14], is:

$$\frac{\partial m}{\partial t} = D_m \frac{\partial^2 m}{\partial x^2} \qquad (1)$$

where m(x,t) is the MC, which is a function of the time t and the depth x into the sample. The only model parameter is the moisture diffusion coefficient D_m. For the purpose of this work, the diffusion coefficient was assumed to be constant, independent of T, MC and spatial coordinate. The value of the diffusion coefficient was fitted to the experimental data. The boundary conditions were:

$$\begin{aligned} m(0,t) &= m_b(t) \\ \frac{\partial m}{\partial x}(L,t) &= 0 \end{aligned} \qquad (2)$$

Where m_b is the given boundary value for MC, determined either from measurements of ambient RH and T, or from extrapolation of measurements inside the sample, see below. The boundary conditions at x=L model the insulated reverse side of the sample.

At time t=0, the MC m(x,0) was initialized by fitting a fourth-order polynomial to the measured data points at 1, 4 and 7 mm depth as well as the boundary value at x=0 and the value of m(L,0) which was a parameter in the fitting procedure. The boundary condition at x=L in Equation 2 was also adhered to. One example of m(x,0) can be seen in Figure 10.

Some tests were also performed with a more complicated mathematical model by Luikov and Mikhailov involving coupled moisture diffusion and thermal transport[26]. However, due to the fast thermal transport the temperature gradients were very small, resulting in only minor effects on the moisture transport. Using the coupled model did not alter the conclusions of this study, and therefore the Fickian model in Equation 1 was used throughout.

2.4.1 Conversion of RH-data to MC

Since the model is formulated in terms of moisture content, *m*, as shown above, while the inserted RH sensor and ambient sensors measured RH in air, an essential part of the comparison between model and data was the conversion of RH-data to MC at the wood surface near the sensor location. The conversion was made using sorption isotherm data for spruce at 21°C from Hedlin[27] taking into account both hysteresis effects and T dependence of the MC. The reason for using spruce data was due to lack of pine data at low T. The hysteresis was handled using the method of scanning curves from Frandsen et al.[17], where the MC follows a path (scanning curve) between two boundary isotherms when the RH changes. The lower and upper boundary curves were computed by fitting a function to the adsorption and desorption isotherm data in Hedlin[27], as was also done by Frandsen et al.[17]. The temperature dependence of the MC was handled using the method of Rode and Clorius[28], modifying the upper limiting isotherm assuming a linear dependence of MC on T for constant RH, derived from data by Kelsey[29]. The lower limiting isotherm was assumed to change negligibly with T, as in Hill et al.[16]. Using this method, MC increases when T decreases due to the change in the upper boundary isotherm.

Each of the RH data sets from the inserted sensor and the ambient RH data sets were converted to MC using the above method, using corresponding T data. The starting point for the scanning curves was assumed to be mid-way between the adsorption and desorption isotherms at the initial RH and T for each data set. An example of how the MC changes with RH during an experiment can be seen in Figure 1.

2.4.2 Boundary and Initial Data

Initially, measurement data of ambient RH in the climate chamber was used as boundary condition at x=0 after conversion to MC. However, the ambient RH data did not agree well with the data from inside the wood. This was seen in Figure. 6 where the MC curve at 1 mm rises above MC at the surface (calculated from the ambient RH), while there is no driving force for it to do so, as measured MC values are lower both outside and further inside the sample. For this reason, the resulting fit of the model also yielded poor results. Therefore, two other methods to compute the boundary value were tried. The first method was to use the average of the measured ambient MC and the MC value at 1 mm, and the second was to extrapolate the boundary value linearly from the measurements at 1 and 4 mm. The two methods gave similar results and the same conclusions and therefore only results using the first method are presented below.

2.4.3 Parameter Fitting

The two parameters D_m and m(L,0) were fitted using the particle swarm method[30], which is suitable for optimization with several parameters and for problems with multiple local minima and relatively high computational cost for evaluating the objective function. The objective function in this case was computed by solving the system of differential Equations. 1 and 2 and computing the sum of squares of the differences between model and measurement data for each data point, in both MC and T. The method was implemented in Matlab (The MathWorks, Inc., Natick, Massachusetts, USA). A population of 12 particles was used.

3 Results

The results shown are typical of recordings performed during climate chamber experiments between 2009 and 2014. The diagrams show both RH step-changes over periods of ten days (long-term fluctuation) and daily fluctuations (short-term fluctuation). RH was fluctuated between 40 and 70 % RH and T between 7 and 17 °C (long-term fluctuations) as well as between 15 and 25 °C (short-term fluctuations).

3.1 RH and T Sensor Recordings

The two methods gave quite different results. The converted recordings by the RH and T sensors (Figures 6 and 7) responded quickly to changes of the ambient RH fluctuations. As expected, the 1 mm curve shows the largest and fastest response while the 7 mm curve shows the smallest and slowest. Upon adsorption the three recorded curves from the different depths are approaching each other and are almost levelled out while this is not the case during desorption (Figure. 6). The same pattern is seen in the short term fluctuations in Figure 7. The general trend of MC in Figure 7 is declining for all the three monitored depths.

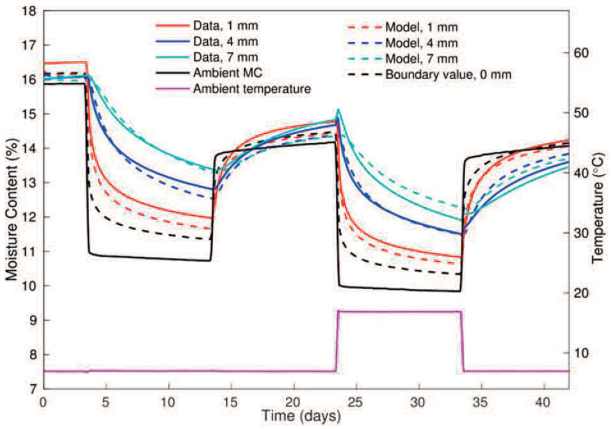

Figure 6: The results of the experiment performed on the 10-days step changes in RH and T. Comparison of MC from the converted RH and T recordings from inside the wood (solid lines) and the output of the mathematical model (dashed lines) using the fitted parameters. The boundary value is the average of the ambient MC and MC data at 1 mm depth.

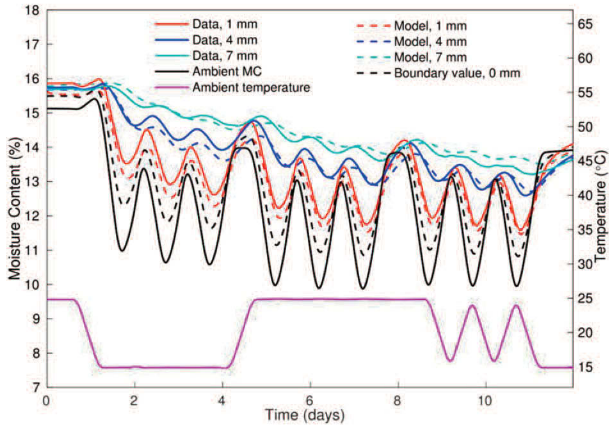

Figure 7: The results of the daily RH and T fluctuation experiments. Comparison of MC from the converted RH and T recordings from inside wood (solid lines) and the output of the mathematical model (dashed lines) using the fitted parameters. The boundary value is the average of the ambient MC and MC data at 1 mm depth.

Sorets effect (thermally induced mass transfer) should be considered when studying moisture profiles in wood[31] as T gradients influence both the RH and hence indirectly MC in the interior of the wood. The RH and T sensor method monitors T at the different depths in the wood. The response on changes inside the wood was fast, followed closely the ambient T in the climate chamber and showed insignificant thermal gradients over the short distances from the surface and inwards used in this study.

3.2 Recordings with the Resistance Method

For the MC recordings by the resistance meter, the results are not as clear as the results from the miniature RH and T sensors. It should be kept in mind that the results are afflicted with considerable measuring faults as described in the introduction but should still be usable for comparisons. As seen in Figures 8 and 9

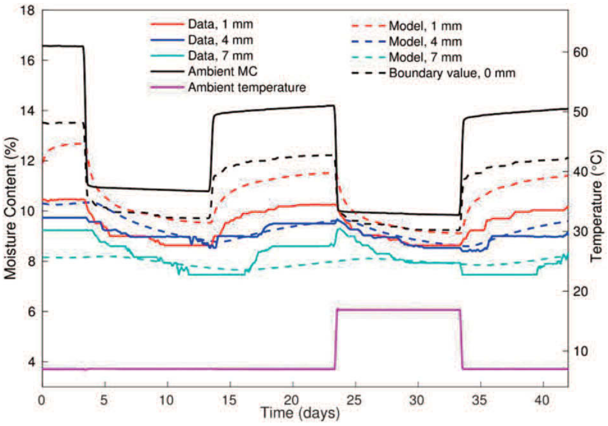

Figure 8: The results of the experiment performed on the 10-days step changes in RH and T using the resistance method. Comparison of the monitored data is shown as solid lines and the output of the mathematical model as dashed lines using the fitted model parameters. The boundary value is the average of the ambient MC and the MC data at 1 mm depth.

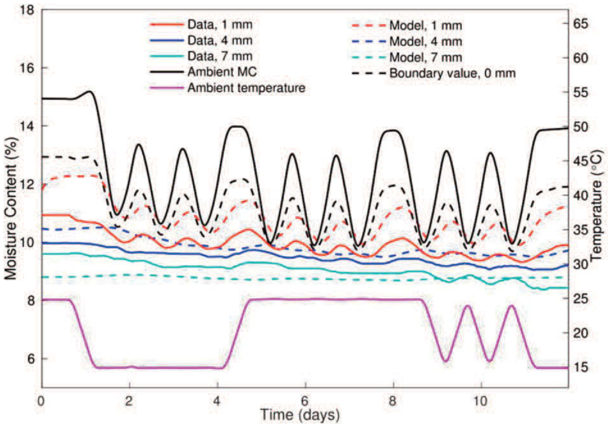

Figure 9: The results of the daily RH and T fluctuation experiments using the resistance method. Comparison of the monitored data is shown as solid lines and the output of the mathematical model as dashed lines using the fitted model parameters. The boundary value is the average of the ambient MC and the MC data at 1 mm depth.

the initial MC values for the three depths are not equal and this influences the range and the order of the three curves. Earlier tests showed that, not even in a time span of up to six weeks, was it possible to acclimatise the wood specimens to an MC equal for the three monitored depths. Moreover, in the same period, none of the depths reached the same MC according to this method.

The response for all monitored depths are much slower and inertial compared to the recordings with the RH and T sensors. The different curves for the recorded depths do not change position on fluctuation as one could expect, but instead the 1 mm curve consistently shows the highest MC values and the 7 mm recordings the lowest at both the ten-day and daily fluctuations. The general trend in Figure 9, is decreasing for the three monitored depths, although not as pronounced as with the RH and T sensor method.

3.3 Data Fitting

The resulting diffusion coefficient after fitting to the RH and T data from inside wood over four measurement periods is shown in Table 1, and the corresponding model output for MC is compared to the experimental data in Figures 6 and 7. The MC data is seen to agree rather well, although there is no perfect fit. The fitted diffusion coefficient in Table 1 is in a reasonable range compared to literature[32, 33, 34] and hence the modelling suggests the RH and T sensor method for MC generates reliable data. In Figure 10, the MC profile with the depth into the sample is shown. The shape of the initial condition can be seen, as well as the profile at a later time point. It is clear that despite large changes in MC at the surface, MC further inside the sample has changed only very little.

Parameter	D_m [m^2/s]
Data from the RH and T measuring method	$1.4 \times 10^{-10} \pm 4.9 \times 10^{-11}$
Data from the Resistance measuring method	$4.4 \times 10^{-11} \pm 2.4 \times 10^{-11}$

Table 1: Average values and standard deviations for the fitted diffusion coefficient in Equation 1. The model was fitted independently to four sets of measurement data for each of the methods.

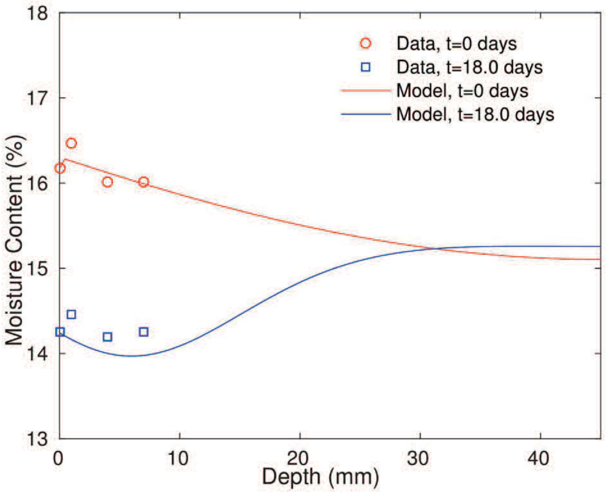

Figure 10: The MC profile with data from RH and T sensors from the mathematical model with the depth into the wood sample at *t*=0 days and *t*=18 days, compared to experimental data at t=0 days and *t*=18 days from the dataset in Figure 6.

The corresponding results for the data from the resistance method are shown in Table 1 and Figures 8 and 9**.** In contrast to the converted RH and T data, the model does not fit the data very well, despite being helped by the boundary conditions being computed from the data and the fitting of the initial MC profile. The order of the curves at different depths is not the same in the model and the data, and the relative changes in MC at different depths do not agree. The fitted diffusion coefficient in Table 1 is lower than expected from literature[32, 33, 34], and a closer inspection of the fitted initial MC profiles shows unreasonable results in several cases (data not shown). This shows the difficulty of fitting the model to the data from the resistance method.

4 Discussion

Due to revealed uncertainties with the resistance method for moisture content measurements, a second method was introduced and evaluated for comparison involving small RH and T sensors which were inserted in drilled holes in the wood. To the best of our knowledge, a method based on this principle has not been used in wood research earlier although a similar approach has been used when studying curing or weathering of concrete[35].

The Protimeter Hygrotrac method is associated with a number of factors which may influence the monitored results. Our measurements ranged from 7.5 to 11.0% MC when monitoring the 40 to 70% RH interval. According to the product information by OmniSense, a large number of our readings fall outside the most accurate measuring range of 10 to 25% MC. It is also possible that the tips of the electrodes are too coarse to use for monitoring small differences in depths as used in this study. Purposely-made resistance methods, like the one presented by Fredriksson et al.[22], would likely give more accurate and reliable results. Even more accurate results are received by MRI methods both when it comes to measuring precise distances from the surface as well as correct MC values. However, MRI is probably not suited for long time series during in situ monitoring although it could be useful to validate the results of other methods.

MC measurements with the Protimeter Hygrotrac method have been tested by Technical Research Institute of Sweden (SP Trätek). It has the advantages of in situ and continuous wireless monitoring in wood and buildings for the purpose of verifying computer models on climate impact as studied by Isaksson and Thelandersson[36]. However, they concluded that Protimeter Hygrotrac readings provided by OmniSense were generally too low, being up to 8% lower than their own adjusted results, with a mean difference of -3.9% MC. An adjustment of the method by SP Trätek compensating for wood species and T from the original resistance data received from OmniSense gave an improvement to a difference of -0.4% MC compared to the dry weight method. If using the compensating method suggested by Isaksson and Thelandersson, it is possible that our results would rise and hence improve the accuracy. However, such an adjustment was not possible within this project. Although the method does not give perfect results without the compensation, it can still be used for relative comparisons[36].

The data from the RH and T sensor method introduced here are more in agreement with what could be expected, with the largest fluctuations closer to the surface as a result of RH and T fluctuations in the ambient air. Further inside, in the sample, the ambient influence is smaller. However, the method needs to be further validated. In this study the term *moisture content*, MC, has consequently been used for the monitored and calculated moisture levels in the wood samples since EMC*, moisture content at full equilibrium*, is normally associated with a constant and equal moisture content through the entire volume of the wooden sample at a specific and constant RH. As been shown here, the moisture gradients are predominant. However, for the purpose of modelling, EMC values are required, and therefore it has been assumed that at the wood in the bottom of the holes the wood is in equilibrium with the RH in the holes.

Thus the two monitoring devices, the commercial resistance meter and the RH and T monitoring sensor method gave different results. The modelling results indicated that the RH and T monitoring method appear to be the more reliable of the two.

In general, the model fits the behaviour of the data generated by the RH and T measuring method, indicating that the method yields very reasonable and consistent results. To improve the fit and eventually to use the model as a predictive tool, a number of issues could be addressed. More attention could be paid to the measurements of ambient RH, ensuring that ambient RH could be used for boundary data in the model. Another uncertainty factor is the initial data to use for the model. In this study, the initial data was fitted to the measurement data at time t=0. However, since measurement data is only given to 7 mm from the surface, there is a large uncertainty regarding the initial moisture content further into the wood sample, which does have a significant effect on the model output. The situation was improved by including a parameter for the initial moisture content profile in the fitting procedure, but to be sure one would need a set-up to acquire data also further into the sample.

Finally, in order for the model to behave correctly under changes in T, one would need to address two questions. In order to convert the raw RH data from the miniature RH and T sensors to MC values correctly, the dependence of sorption curves and the hysteresis model under changing T should be further studied. The method employed in this study performs reasonably well, but looking closely at the MC curves for step changes in T, it seems the method could be further improved. The second question regards the T and MC dependence on the diffusion coefficient. It is known that it does depend on T and MC [32] and implementing this in the model could potentially improve the fit. Initial tests indicate that for our data, the moisture diffusion coefficient, D_m, increases with about 5% per Kelvin. However, due to the other uncertainties in the modelling, a detailed study of this was considered outside the scope of this work.

Both methods for MC measurement are, from a practical point of view, possible to use for monitoring MC of wood in cultural heritage properties for long periods of time. The RH and T sensor method for MC determination appears to be the more reliable method but, as it has not been used earlier it needs to be further tested. Correlation studies between the RH and T sensor method and simultaneously monitoring strain in wood would be useful to further validate this method.

5 Conclusions

Moisture content profiles in Scots pine wood were monitored at three different depths (1, 4 and 7 mm from the surface) employing two different methods. A resistance method and a method using RH and T sensors inserted in drilled holes in the wood were compared. The results of the two methods did not coincide. A mathematical model with Fickian diffusion of moisture was chosen to verify the monitored results. It showed poor fit with the resistance method but a reasonably good fit with the RH and T sensor method. The results of the latter method are promising and should be suitable to use for increased understanding of dynamic moisture transport in cultural heritage wooden objects, in the laboratory as well as in wood samples placed in situ. The method can be further developed and used, for instance, for studying moisture transport in wood of different species, age or with different surface coatings during dynamic conditions.

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