Experimental study of electrode effects of resistance type electrodes for monitoring wood drying process above fibre saturation point

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Abstract. Due to practical need to improve the accuracy of measurement of wood electrical resistance via creating multivariate calibration models the study of electrode effects was carried out. The experiments were made in DC mode and five types of electrode effects were measured: electrical resistance of the galvanic contact between the measuring electrode and wood, corrosion of measuring electrodes in wet wood, polarization and depolarization of the double layer forming on the surface of the measuring electrodes, residual polarization voltage between measuring electrodes and effect of repeated use of measuring electrodes. For multi-channel measurement mode effect of neighbouring electrodes was measured. Behind each of these factors is a complex transfer mechanism of free and bounded charge carriers from wood to measuring electrodes. Among the factors, polarization and depolarization have an immediate effect (duration of the processes in seconds) while resistance of electrode/wood contact, corrosion of electrodes and residual polarization have a slow effect (duration of processes in hours). For pine sapwood, coefficients of the Stamm formula were found in moisture contents (MC) above the fibre saturation point. It was determined that wood polarization and depolarization indicators are dependent on wood moisture content as is the case with wood electrical resistance. Compared to wood electrical resistance, wood polarization proved approximately four times and depolarization approximately eight times less sensitive to moisture content variation.

Key words: wood drying, above FSP, corrosion, polarization.

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Introduction

The electrical resistance method is widely used for monitoring wood drying since the method is economical and reliable (Tronstad *et al.*, 2001, Onysko *et al.*, 2008). But above fiber saturation point FSP (MC 30%) the measurement is complicated as the measuring accuracy is insufficient and starts decreasing correspondingly to an increase in wood moisture content (Edwards, 1974;

Vermaas, 2002). The decrease in measuring accuracy can also be described quantitatively, by the 2S-value (Rozema, 2010). Insufficient measuring accuracy above FSP also reduces the accuracy of effective diffusion coefficient monitoring in the process of wood drying (Tamme *et al.*, 2010, 2011). For precise determination of moisture content it is recommended to combine moisture meter measurements with the oven dry method for the measuring range above FSP

(Brookhuis, 2009). This recommendation has been taken into account in this study.

The main empirical relationships and definitions of the resistance method have been given in studies (Stamm, 1927; Norberg, 1999).

The moisture content MC of wood, M , is generally defined as the ratio of the mass of water to the mass of dry wood:

$$M = m_{\text{water}}/m_{\text{dw}} \quad (1)$$

where

m_{water} – mass of water

m_{dw} – mass of dry wood.

$$w = 100M, \quad (2)$$

where

w – moisture content, MC, in [%].

The common relationship, originally proposed by Stamm (Stamm, 1927) expresses the effect of the wood MC on resistivity at a constant temperature:

$$\log \rho = C + D \log M, \quad (3)$$

where

ρ – resistivity

M – moisture content, MC

C and D – constants at constant temperature.

This expression (3) was found to work satisfactorily within the typical range of the MC, where electric moisture meters are used, *i.e.* 7–30%.

In the case of electrical moisture meters, the MC is related to the resistance obtained for the given electrode configuration and for the given equivalent DC circuit.

For a given electrode configuration in the first approach:

$$R = \rho (L/A) = K \rho, \quad (4)$$

where

R – resistance

K – cell constant, or measuring volume constant

L/A – cell constant for the particular electrode configuration

A – electrode/wood contact area, mm^2

L – length between two electrodes.

Taking into account formulas (2), (3) and (4), ratio (3) may be replaced with an equivalent, yet a more convenient ratio for practical use:

$$\log R = C_1 + D \log w, \quad (5)$$

where

D – constant at a constant temperature and the modified constant at a constant temperature

$$C_1 = C + \log K - 2D \quad (6)$$

MC up to 40% of Douglas Fir can be calculated by the following equation (Straube *et al.*, 2002):

$$\log w = 2.99 - 2.113(\log (\log R)), \quad (5a)$$

where

w – moisture content in mass %

R – resistance in Ohms (Ω).

In the measurement of wood DC resistance, the following factors are important:

a) electrical resistance of the galvanic contact between the measuring electrode and wood, b) corrosion of measuring electrodes in wet wood, c) polarization and depolarization of the double layer forming on the surface of the measuring electrodes (Metrohm Autolab B.V., Eco Chemie, <http://www.ecochemie.nl>) and of the polar molecules of wood itself, d) residual polarization voltage between measuring electrodes, and lastly, e) effect of repeated application (repeated measurements) of measuring electrodes. Behind each of these factors is a complex transfer mechanism of free and bounded charge carriers from wood to measuring electrodes (James, 1975). Among the factors, polarization and depolarization have an immediate effect (duration of processes can be measured in seconds); whereas resistance of electrode/wood contact, corrosion of electrodes and residual polarization have a slow effect (duration of processes can be measured in hours).

These mechanisms can be examined in more detail with the help of certain alternate current (AC) equivalent circuits using electrical impedance spectrometry (EIS) (Zelinka, 2006, 2007; Metrohm Autolab B.V., Eco Chemie, <http://www.ecochemie.nl>). The experience showed that the electrode effects involved in measuring wood electrical resistance should be observed in DC mode in order to avoid problems in using

results obtained in AC mode for DC circuits.

Several experiments in DC mode were carried out during this research, the purpose of which was to assess five types of electrode effects both in terms of quantity and quality, mostly due to the practical need to minimise measurement errors in wood electrical resistance and also for creating multivariate calibration models.

Material and Methods

In studying electrode effects on a raw data file (set of unprocessed measurement data with numeric or analogous filters) of electrical resistance measurement (Fig. 4), a pine sapwood specimen with the dimensions of 100×60×60 mm (length × width × thickness) was used. It was dried in the climatic test chamber Feutron (Feutron, <http://www.feutron.de>) at room temperature (20 °C, 96% RH) in the stationary air for 90 hours and thereafter at 32 °C and 96% RH at the air velocity 0.4 m s⁻¹ for another 244 hours. The specimen drying process lasted a total of 334 hours during which the wood MC was reduced from 146% to 36.4%.

For slow processes like the resistance of electrode/wood contact and corrosion, the resistance meter Scanntronik Material Moisture Gigamodule with Scanntronik Thermofox data logger was used (Scanntronik Mugrauer Gmb, www.scanntronik.de). For measuring the voltage of the slow process of residual polarization, the profi-tester Meterman 38 XR was used (The Test Equipment Depot, <http://www.testequipmentdepot.com/meterman/dmm/38xr.htm>). In measuring slow processes, the minimum interval between two measurements was 1 hour. For measuring the fast process of polarization resistance, the resistance meter AlphaLab Inc. (<http://www.trifield.com>) was used within the measurement range of 0–20 MΩ, with a measuring accuracy of ± 2%. For saving measurement data in the data logger

Ahlborn (Type ALMEMO 2590-9) (Ahlborn, <http://www.ahlborn.com/>), an analogue output (with a range of 0–1 V), which had a linear connection with the resistance measuring range of 0–20 MΩ, was attached to the resistance meter AlphaLab. Readings of the analogue output and Alphalab display were related by the following formula: 10 (analogue output reading in volts (V) = display reading in megaohms (MΩ)). The voltage of the analogue output could be measured at a speed of 10 measurements per second or 1 measurement per second by using the Ahlborn DC voltmeter ZA9000FS3. For measuring the voltage of another fast process, depolarization, the Meterman 38 XR profi-tester with an input resistance of 10 MΩ was used, which enabled the measurement speed of 1 measurement per second. For the measurement during the experiments insulated pin electrodes were used (ram-in electrode M18, 60 mm, manufactured by Gann).

In the measurement of electrical resistance, polarization resistance, depolarization process and residual polarization, electrodes e1 and e2 were used at a distance of $L = 30$ mm (measuring direction was across the grain) (see Fig. 2). In examining electrode/wood resistance R_c and electrode corrosion, electrodes e1 and e2 as well as an extra pair of electrodes e3 and e4 were used at a distance of $L/2 = 15$ mm. The distance between the main measuring electrodes (e1, e2) and extra electrodes (e3, e4) was $D = 40$ mm. Distance D was experimentally selected in order to avoid interaction between neighbouring electrodes, i.e. transmission of electrical potential by wet (143% MC) wood. The difference between transmitted potentials (electrical voltage) was measured in dead neighbouring electrodes, which was below 1/30 measuring voltage in the case of $D = 40$ mm.

The specimen was weighed with a scale manufactured by KERN (Model KERN EW B 620-M, resolution 0.01 g) (Kern & Sohn GmbH, <http://www.kern-sohn.com>) at 24-hour intervals on average; the oven dry

Figure 1. Experimental setup.

- 1 – AlphaLab resistance meter,
- 2 – Scanntronic 8 channel resistance meter,
- 3 – box of reference resistances,
- 4 – switching box,
- 5 – climatic chamber Feutron.

Joonis 1. Eksperimendi aparatuur.

- 1 – AlphaLab takistumõõtja,
- 2 – Scanntronic 8 kanliga takistumõõtja,
- 3 – võrdlustakistite salv,
- 4 – lülituspaneel,
- 5 – kliimakamber Feutron.

Figure 2. Arrangement of measuring electrodes on the examined specimen. All electrodes were placed at a depth of 20 mm from the surface of the specimen.

Joonis 2. Mõõteelektroodide paigutus uuritava katsekehal. Kõik elektroodid olid paigutatud 20 mm sügavusele katsekeha pinnast.

weight of the specimen was determined with the same scale.

Gann HT 85 T (Gann Mess- u. Regeltechnik GmbH, <http://www.gann.de>), NDT James Moisture Master (James Instruments Inc., <http://www.ndtjames.com>) and Brookhuis FMD-6 (Brookhuis, <http://www.brookhuis.com>) resistance type wood moisture meters were used in the experiments.

Unfortunately, the electrical resistance measurement raw file volume and internal data processing algorithm in the resistance meter Scanntronic Gigamodule and in the resistance type wood moisture meters used in the experiments remained hidden

from the user. The experimental setup is depicted in Figure 1.

Interaction registration methodology

The methodological prerequisite for the registration of interactions in the research was the measurement of all examined interactions by DC measuring instruments with the same operating principle. That methodological restriction was necessary to work out a novel precise calibration method of a DC measuring instrument (but not an AC measuring instrument such as the EIS) of wood moisture:

- a) resistance of electrode/wood contact on DC and b) electrode corrosion.

According to studies (Norberg, 1999) and (James, 1993), R_c , resistance associated with the wood/electrode interface, and R_v , volume resistance, are series connected. By varying the distance L between electrodes (see Fig. 2), a linear system of equation (7) may be proposed for the four-electrode measuring system:

$$\begin{aligned} R_1 &= 2R_c + R_v \\ R_2 &= 2R_c + 0.5R_v \end{aligned} \quad (7)$$

the solutions of which are:

$$R_c = R_2 - 0.5R_1, \quad (7a)$$

and

$$R_v = 2(R_1 - R_2), \quad (7b)$$

where

R_1 – resistance measured between electrodes (e1) and (e2) (see Fig. 2)

R_2 – resistance measured between electrodes (e3) and (e4)

R_c – resistance of a single electrode/wood contact

R_v – volume resistance.

The solution (7b) may also be the corrosion indicator. Analysis of solution behaviour is given in discussion.

Figure 3. Simplified equivalent circuit for describing the processes of polarization and depolarization.

Joonis 3. Lihtsustatud ekvivalentskeem polarisatsiooni ja depolarisatsiooni protsesside kirjeldamiseks.

c) polarization and depolarization. The polarization of the double surface layer of the electrodes and wood polarization are relaxation processes the simplified equivalent circuit of which is adapted (Onysko, 2008) and given in Figure 3. Polarization is expressed in the DC circuit by an increase in polarization resistance over time. As part of the experiment, the resistance meter AlphaLab allowed to measure it directly. Measuring polarization resistance enables the approximate assessment of the maximum measurement error in wood electrical resistance depending on wood moisture content. In depolarization process, voltage between the electrodes is the easiest to measure with the help of a DC voltmeter with high input resistance. This measuring method is also called a chronopotentiometric measurement (Metrohm Autolab B.V., Eco Chemie, <http://www.ecochemie.nl>). Measuring depolarization voltage allows a practical assessment of the time interval that is safe for beginning the next resistance measurement without risking the occurrence of a measurement error. Initial voltage relation U_1/U_0 (where U_0 is the input voltage of the resistance meter and U_1 is the initial voltage of the depolarization process) and T_{max} , the duration of the depolarization process, may also hypothetically be related to wood moisture content.

d) Residual polarization voltage between the measuring electrodes may hypothetically be caused by the difference between the corrosion potentials of the electrodes. Corrosion potential is usually measured with regard to a reference electrode used in electrochemistry (e.g. the $Ag/AgCl$ reference electrode (Metrohm Autolab B.V., <http://www.metrohm-autolab.com/Products/Echem/Accessories/accessories.html>). Thus, residual polarization could be treated as the combined effect of the corrosion potential, measurement voltage of electrodes and the varied electrical mobility of positive and negative charge carriers. From a practical viewpoint, residual polarization voltage would mean the occurrence

Figure 4. Example of polarization resistance measurement raw file at pine wood MC 146% and 20 °C.
 Joonis 4. Näide polarisatsiooni takistuse mõõtmise toorfailist männi maltspuidus 146% NS ja 20 °C.

of a certain systematic error in measuring wood electrical resistance with a DC measuring device.

e) Effect of repeated application (repeated measurements) of pin electrodes.

The experiments made use of specimens made of five different tree species (Scots pine, Norway spruce, Grey alder, Birch and European aspen) with dimensions (100×60×60 mm) and resistance type wood moisture meters by three different manufacturers (Gann HT 85 T, FMD-6, and NDT James). Measuring electrodes (teflon insulated pins, 60 mm) were tapped with a Gann hammer electrode (RAM- IN electrode M18) to a depth of 20 mm (1/3 of the thickness of the specimen). The number of specimens per each tree species was $n = 60$.

These types of measurements have a significant practical value in terms of moisture meter calibration, yet at the same time, while conducting measurements, several random factors need to be considered (for example, wood structure inhomogeneity, moisture content gradients, etc.). The effect of the repeated use of electrodes is revealed in the moisture meters comparison test. It was assumed that electrode corrosion may

be neglected when conducting short-term measurements of wood moisture content. In distributing moisture meters into accuracy classes by the 2S-value (Rozema, 2010), all other random factors must be kept at an equal a level as possible. The 2S-value indicates the range within which, with a 95% certainty, the actual moisture content will fall if determined according to the oven dry method (Brookhuis, 2009).

In the test of moisture meters the electrical resistance of wood/electrode contact was measured indirectly via calibration and algorithm of processing the raw file of the electrical resistance measurement.

Results and Discussion

By comparing Figures 5 and 7, the figures seem to have a relatively similar shape. Based on this similarity, a hypothesis may be proposed that the resistance method owes its moisture sensitivity mainly to the resistance of the electrode/wood contact.

Figure 6 shows that during the drying process, wood volume resistance R_v turns negative for a certain time period, and then back to positive, and maintains relatively stable (in a logarithmic scale). Reasonably

Figure 5. Monitoring of electrical resistance of pine sapwood specimen by using a four-electrode measuring system and Scantronik Giga-module resistance meter.

Joonis 5. Elektritakistuse monitoring männi maltspuidus, kasutades nelja elektroodiga mõõtesüsteemi ja Scantronik Giga module takistusmõõtljat.

Figure 6. Behaviour of volume resistance of wood.

Joonis 6. Puidu ruumtakistuse muutumine ajas.

Figure 7. Behaviour of electrode/wood contact resistance.

Joonis 7. Elektrood/puit kontakti takistuse muutumine ajas.

(proceeding from general physical considerations), wood volume resistance cannot be effectively zero. This phenomenon may be explained by the following qualitative model of temperature dependent electrode corrosion affecting electrical resistance.

Step 1. For some random reason, accelerating corrosion occurs in one of the electrodes, or a pair of electrodes, and according to the measurement data of four-electrode measuring system it seems that wood volume resistance (in a logarithmic scale) turns negative.

Step 2. Logically, it may be assumed that accelerating corrosion in some electrodes cannot last for very long. Indeed, a more intense corrosion should result in an increase in the resistance of the electrode/wood contact, and thus, current intensity through the more corroded pair of electrodes would decrease.

Step 3. Raising the temperature by 12 °C in the experiment intensified corrosion also in the rest of the electrodes and restored the equal speed of corrosion in all electrodes, thereby turning wood volume resistance back to positive.

When conducting measurements in a four-electrode measuring system (see Fig. 2) in DC mode, experiment results indicate a problem that volume resistance R_v (values calculated according to formula (7b) may be somewhat underestimated. Therefore, volume resistance R_v time graph (see Fig. 6) functions better as an indicator of corrosion. For a more accurate determination of volume resistance R_v , measurements of resistances R_1 and R_2 should be carried out in parallel both in DC mode and AC mode.

Figure 8 suggests that in wood moisture contents above FSP, the relative increment of polarization resistance may reach 120%. If the initial resistance R_0 is viewed as approximately equal to wood resistance, the maximum wood resistance measurement error, upon not considering polarization resistance, may also reach 120%. Figure 8 also shows that polarization resistance as well as the relative increment of polarization resistance, depending on time, is rather well-fitted with the logarithmic function. When measuring resistance in a logarithmic scale, polarization resistance can be quite easily subtracted from wood resistance by using instead of R_0 its calculated value R_{0calc} (regression curve value at time 0.1 sec ($t = 0.1$ sec)). R_{0calc} values given in Table 1 have been calculated on the basis of regression curves adjusted for 60-second intervals. For obtaining R_{0calc} , more frequent measurements could be carried out during the first second of the polarization process as an alternative (e.g. 10–100 measurements per second) and then R_{0calc} may be calculated on the basis of a linear function fitted to measured data.

Table 1 shows intervals of wood resistance plus polarization resistance values in comparison to data measured at the same time with Scanntronik Gigamodule, which have been recalculated from the logarithmic scale $10\log R$ into resistance R , given in megaohms. According to Table 1, coordination between data on different resistance meters is satisfactory. Yet, it is unknown how the polarization resistance raw file in the Scanntronik Gigamodule resistance meter has been processed and whether and in which manner residual polarization volt-

Table 1. Quantities characteristic of the polarization process.

Tabel 1. Polarisatsiooniprotsessi iseloomustavad suurused.

Wood moisture <i>Puidu niiskus (%)</i>	R_0 , (M Ω), $t = 0$ sec	R_{max} (M Ω), $t \sim 600$ sec	R_{0calc} (M Ω), $t = 60$ sec	Gigamodule, R (M Ω)	$((R-R_0) / R_0)$ 100%
146	0.017	0.043	0.011	0.054	126
97.2	0.172	0.227	0.147	0.151	32.6
36.4	0.59	0.73	0.52	0.56	23.7

Figure 8. Relative increment of polarization resistance in pine sapwood at three different moisture contents: MC1 = 146%; MC2 = 97.2% and MC3 = 36.4%

Joonis 8. Polarisatsiooni takistuse suhteline juurdekasv männi maltspuidus erinevatel niiskussisaldustel: NS1 = 146%; NS2 = 97.2% ja NS3 = 36.4%.

age as a possible source of a systematic error has been considered.

Figures 9 and 10 depicts that depolarization lasts longer in the case of wet wood, for ca 600 seconds. Measurements should continue only after the end of the depolarization process. Depolarization initial voltage relation U_1/U_0 and $T_{\max}$, the duration of the depolarization process also depend on wood moisture content according to Figure 9 and Table 2. Instead of using initial voltage U_1 , more accurate calculations would be obtained by using its calculated value $U_{1\text{calc}}$ (that is, the extrapolated value of the regression curve at $t = 0.1$ sec). Based on the above, it may be assumed that in the case of an equivalent circuit highly descriptive of the depolarization process, this process could also be used for measuring wood electrical resistance and wood moisture content.

Figure 11 shows that residual polarization voltage between measuring electrodes is relatively stable (average -28.5 mV), but suggests a downward trend as wood moisture content decreases. For example, residual polarization voltage may lead to a sys-

tematic measurement error when measuring wood resistance at input measuring voltage 3 V of the resistance meter, depending on measuring voltage polarity up to $\pm 1\%$, and at measuring voltage 1 V up to $\pm 3\%$, also in resistance measuring units, because the resistance scale has a linear connection with the input voltage.

Linear dependence (in a logarithmic scale) between moisture content and wood electrical resistance in the pine specimen is shown in Figure 12. Based on data given in Figure 12, it may be suggested that Stamm's well-known empirical relation (formulas 3 and 5) applies also in pine wood moisture contents above FSP (above MC 30%). According to a common belief, this pattern is satisfactory only in the MC range of 7–30% (Norberg 1999). In the future, further research should determine the role played by the specific drying regime used in the experiment and tree species as well as the general (selected independently from the drying regime) empirical relation between wood electrical resistance and moisture content in the area above FSP in producing this quite a surprising result.

Figure 9. Changes in depolarization voltage of pine sapwood at three different moisture contents: MC1 = 146%; MC2 = 97.2% and MC3 = 42.8%

Joonis 9. Depolarisatsiooni pinge muutused männi maltspuidus kolmel erineval niiskusesaldusel: NS1 = 146%; NS2 = 97.2% ja NS3 = 42.8%.

Figure 10. Depolarization initial voltage relation U_1/U_0 (initial voltages U_1 and U_0).

Joonis 10. Depolarisatsiooni algpingete U_1/U_0 suhe (algpinged U_1 ja U_0).

Table 2. Quantities characteristic of the depolarization process.

Tabel 2. Depolarisatsiooni protsessi iseloomustavad suurused.

Wood moisture Puidu niiskus, (%)	(U_1 / U_0) 100%	$T_{\max}(U_1 = 0)$, sec	$(U_{1,calc} / U_0)$ 100%, $t = 60$ sec	$(U_1 / U_0)T_{\max}$, sec
146	7.4	600	10.37	44.4
97.2	4.5	488	6.66	21.96
42.8	2.5	335	3.33	8.38

Figure 11. Changes (variation) in residual polarization voltage measured in the specimen during drying. The moisture content of the specimen varied respectively from 146% to 36.4%.

Joonis 11. Männi maltspuidust katsekeha kuivatamise käigus mõõdetud jääkpolarisatsiooni pinge. Katsekeha niiskussisaldus (NS) muutus alates 146% kuni 36.4%.

Figure 12. Empirical relation between pine sapwood moisture content and electrical resistance at 32 °C. The moisture content of the specimen decreased from 141% to 36.4%.

Joonis 12. Empiiriline seos männi maltspuidu niiskussisalduse ja elektritakistuse vahel temperatuuril 32 °C. Katsekeha niiskussisaldus vähenes 141% kuni 36.4%.

For the specific drying regime and type of pin electrodes used in the experiments, the average electrode/wood contact area of both electrodes was $A = 94.8 \text{ mm}^2$ and distance between electrodes was $L = 30 \text{ mm}$. Based on this data, cell constant K , and based on Figure 1, also constants in formula (5) could be calculated: $C_1 = 7.7783$ and $D = -1.3233$. For the Stamm formula (3), respec-

tive values of the constants are the following: $C = 5.63$ and $D = -1.3233$. Formula (6) was applied for calculating the value of constant C . All constants have been determined for pine sapwood and the constant temperature of 32 °C.

By comparing the figures given in Tables 1 and 2, the estimated average moisture sensitivity of different measuring processes

Table 3. 2S values of MC readings (acc. to Rozema, 2010) of wet and dry wood (above FSP and below FSP) measured with different moisture meters. Number of specimens $n = 60 \times 5$.

Tabel 3. 2S väärtused erinevate niiskumõõtjatega saadud NS lugemitega (vastavalt Rozema, 2010 artiklile).

Type of Moisture meter <i>Niiskumõõtja tüüp</i>	Scots pine heartwood, average actual MC wet 34.2% dry 27% <i>Männi lülipuit keskmise tegelik niiskussisaldus märg kuiv</i>	Norway spruce heartwood, average actual MC wet 31.3% dry 27.1% <i>Kuuse lülipuit keskmise tegelik niiskussisaldus märg kuiv</i>	Grey alder, average actual MC wet 105.7% dry 31.6% <i>Hall lepp keskmise tegelik niiskussisaldus märg kuiv</i>	Birch, average actual MC wet 85.2% dry 30.3% <i>Kask keskmise tegelik niiskussisaldus märg kuiv</i>	European aspen, average actual MC wet 107% dry 29.9% <i>Haab keskmise tegelik niiskussisaldus märg kuiv</i>
GANN HT 85 T 2S-value	3.8 2.4	2.4 1.0	2.6 1.6	4.2 2.8	2.6 3.5
FMD-6 2S-value	3.0 2.2	1.8 1.0	7.4 1.4	2.4 2.2	1.8 3.5
NDT James, 2S-value	2.2 2.6	3.2 2.6	2.2 2.8	2.2 2.8	2.0 2.7

Bold numbers – Not measurable, if 2S-value > 3.5%.(acc. to Rozema, 2010).

MC – moisture content (%), determined by indirect (electrical resistance) and direct (oven-dry) methods.

Paksud numbrid – Mitte mõõdetav, kui 2S-väärtus > 3.5% (vastavalt Rozema, 2010 artiklile).

NS – niiskussisalduse (%), mis on määratud kaudsel (elektritakistuse) ja otsesel (kuivkaalumise) meetodil.

may be determined. A two-fold increase in wood moisture content (97.2% up to 146%) brought about a corresponding increase in depolarization initial voltage relation ($(U_1/U_0)100\%$), a four-fold increase in the relative increment of polarization resistance $((R-R_0)/R_0)100\%$, and an eight-fold increase in the measured electrical resistance R_0 . Thus, the measurement of electrical resistance seems to involve the highest moisture sensitivity, followed by the measurement of the relative increment of polarization resistance, and lastly, the measurement of depolarization initial voltage relation. In the practical use of the methods for measuring wood moisture content, the moisture sensitivity of a method is not the only selection criterion. It is also essential to minimize the variance of the measurement data recorded. A more detailed research of moisture sensitivity and variance would require more measurement data.

A comparison of the values of quantity 2S by tree species in Table 3 indicates a trend in all tree species that 2S values decrease in accordance with a decrease in wood moisture content. Aspen wood is the only exception with its increasing 2S val-

ues. It might be that drying results in larger moisture gradients in aspen wood compared to other tree species. This phenomenon with aspen wood requires in-depth future research.

The analysis by DC measuring mode enables adding the following variables in the multivariate statistical model for calibration: 1) gravimetric wood MC, 2) wood/electrode contact resistance, 3) volumetric resistance of wood, 4) relative increment of polarization resistance, 5) time constant of the polarization process at given wood moisture levels, 6) depolarization initial voltage relation, 7) time constant of the depolarization process at given wood moisture levels, 8) multiplication of the depolarization initial voltage relation and total process time, 9) residual polarization voltage (or charge). All variables are defined on the assumption that the temperature is constant.

Conclusions

Knowledge of electrode effects enables improved consideration and prevention of random factors reducing calibration quality

of resistance type wood moisture meters in wood moisture contents above FSP.

To improve the accuracy of measurement of wood electrical resistance the study presented a novel approach. The additional variables were generated for the multivariate statistical model for calibration. Application of these variables presumably improves the R^2 value of the model and minimises its standard error compared to the simple calibration model with one independent variable ($y \sim x$).

The outcomes of the study were approximate error estimates and suggestions for five different types of electrode effects, which should be considered when organising the calibration process of resistance type wood moisture meters in the range above FSP.

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Elektroodefektide uurimine puidu kuivatamisel niiskussisaldustel üle kiu küllastuspunkti

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Kokkuvõte

Puidu kuivatuse monitooringul on elektriline takistusmeetod laialdaselt kasutusel. Kuid probleeme tekitab puidu niiskussisalduse (NS) määramine üle kiu küllastuspunkti (s.o. NS vahemikus 30% kuni 170% puidu kuivkaalu suhtes), kus on põhilisteks probleemideks ebapiisav mõõtetäpsus ja tulemuste vähenemine korratavus, mille tõttu pole seni õnnestunud saada sellele meetodile mainitud piirkonnas rahuldavat kalibreerimiskõverat. Selle artikli eesmärgiks oli eksperimentaalselt uurida puidu ja mõõteelektroodide vastastikust toimet. Elektroodefekte uuriti puidu kuivatamisel üle kiu küllastuspunkti, madalatel temperatuuridel (20 °C ja 30 °C) ja leebetel kuivatusrežiimidel (98% RH ja 96% RH õhu suhtelisel niiskussisaldusel). Katsetes kasutati kahe erineva tootja elektrilise takistuse mõõtjat ja kolme erineva tootja takistus-tüüpi puidu niiskuse mõõtjat. Ühesugustes tingimustes (32 °C ja 96% RH ja puidu NS piirkonnas üle kiu küllastuspunkti), katsekehi kuivatati ja teatud ajavahemike järel mõõdeti niiskussisaldusi viiest erinevast puiduliigist (*Pinus sylvestris*, *Picea abies*, *Alnus glutinosa*, *Betula pendula*, *Populus tremula*) valmistatud katsekehadel mõõtmatega 100×60×60 mm (pikkus, laius, paksus). Kokku oli eksperimendis 500 katsekeha. Statistiliselt analüüsiti elektroodide korduva paigaldamise mõju mõõtmistulemuste korratavusele. Märgi maltspuidus (niiskussisalduste piirkonnas üle

kiu küllastuspunkti) uuriti lisaks ka mõõteelektroodide korrosiooni, polarisatsiooni ja depolarisatsiooni protsesside mõju elektritakistuse mõõtetulemustele. Selle uurimuse peamiste tulemustena võib esile tõsta järgmisi tulemusi: 1) Määrati eksperimentaalselt Stamm'i valem koefitsiendid uuritava (üle kiu küllastuspunkti) puidu niiskuste vahemiku jaoks. 2) Stamm'i valem annab funktsionaalse sõltuvuse puidu niiskussisalduse ja puidu elektritakistuse vahel. Lisaks sellele sõltuvusele (nn. Stamm'i protsess), leiti veel kaks protsessi (polarisatsiooni ja depolarisatsiooni protsessid), mis samuti osutusid puidu niiskusest sõltuvaks. Kõigi kolme protsessi jaoks leiti ligikaudsed niiskustundlikkuste suhtarvud. 3) Leiti lihtne protseduur puit/elektrood kontakti takistuse ja puidu ruumtakistuse eraldamiseks (e. separeerimiseks). 4) Katsetulemuste alusel valiti välja olulisemad füüsikalised parameetrid, mis võivad edaspidi leida rakendust puidu niiskusemõõtjate kalibreerimisel mitme muutujaga statistilistes mudelites. Selles uurimuse tulemuste interpreteerimise käigus püstitati ka kaks hüpoteesi – üks jääkpolarisatsiooni nähtuse selgituseks, ja teine Stamm'i protsessi niiskustundlikkuse selgituseks. Selle uurimuse tulemusi on võimalik kasutada takistus-tüüpi puidu niiskusemõõtjate kalibreerimise protseduuri organiseerimisel puidu niiskussisaldustel üle kiu küllastuspunkti.

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