

Research paper

Optimizing the pine wood drying process using a critical diffusion coefficient and a timed moistening impulse

Hannes Tamme*, Peeter Muiste and Valdek Tamme

Tamme, H., Muiste, P., Tamme, V. 2021. Optimizing the pine wood drying process using a critical diffusion coefficient and a timed moistening impulse. – Forestry Studies | Metsanduslikud Uurimused 75, 150–165, ISSN 1406-9954. Journal homepage: <http://mi.emu.ee/forestry.studies>

Abstract. This article demonstrates that it is possible to optimize the drying process for pine wood in two independent ways. Those ways involve either the use of the critical diffusion coefficient (DC) which is determined by the experiment shown below, and/or the drying air moistening impulse in the second drying phase. When processing data which has been gained from the pine wood drying experiment, both coincidences and differences were found when compared to the results from a simulation of the drying process which was carried out using the same drying schedule. There is a relatively good level of agreement between the drying experiment and the simulation results of TORKSIM v5.11 simulation program in the case of the simulated and experimentally determined drying curves. The magnitude of numerical values for the DC agrees with this finding, as do the wood's moisture profile in the final phase of the drying experiment at 142 hours, the simulated and measured wood surface temperatures from the beginning of drying to a point at 60 hours into the process, and the simulated wood stresses when compared with the maximum values for the electrical surface-core ratio (ESCR) graph, as determined by the experiment. It was found that the DC's numerical value decreases sharply by about 1.5 times after transitioning from the first drying phase to the second drying phase.

Key words: critical diffusion coefficient, moistening impulse, optimization, wood drying.

Authors' address: Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Kreutzwaldi 5, 51006 Tartu, Estonia; *e-mail: hannes.tamme@student.emu.ee

Introduction

In order to add value to wood as a renewable resource, the process of convective drying for sawn timber is one of the key steps in the further use of wood in the construction trade and in the furniture industry, as well as in the production of thermowood (Kask *et al.*, 2021). The purpose behind the wood drying process is to reduce the aver-

age moisture content in the wood (with a final moisture content level of up to 7–12% MC). The accompanying goal is to disinfect the wood material at temperatures between 50–70°C, without causing discoloration (Tamme *et al.*, 2021). The main measurable quantity to have been monitored in the industrial wood drying process is the wood average moisture content (MC), the changing over time of which provides what is

DOI: 10.2478/fsmu-2021-0017



© 2021 by the authors. Licensee Estonian University of Life Sciences, Tartu, Estonia. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

known as the wood drying curve (Tamme *et al.*, 2011; Tronstad *et al.*, 2001; Tamme, 2016; Mändoja, 2015; Poljakov, 2013). The validity of the stress readings, which have been found in the industrial drying simulation, has also been checked by means of a case-hardening test (Mändoja, 2015; Poljakov, 2013). Unfortunately, it is not possible to decide on the basis of the drying curve and the case-hardening test alone whether or not the wood drying process is optimal in terms of the desired quality and energy consumption levels. In fact, the standard equipment being used for wood dryers (in the form of kilns) does not include specific surface MC and deformation sensors, both of which are important when it comes to solving the optimization task, but which would also be unlikely to withstand the extreme climatic conditions which prevail inside the drying chamber. An attempt has also been made to resolve the problem of optimizing the wood drying process with the help of the wood drying simulation program, TORKSIM (Salin, 1990; Salin, 2007). The TORKSIM program provides an upper limit when it comes to the allowable tensile stresses, which should not exceed one third (0.33) of the maximum stress point which will produce a rupture in the tangential direction of the wood fibre. This program has been selected as the main criterion for optimizing the drying process (Salin, 2007). The commercial process optimization program, StatEase Design-Expert, includes what is known as the desirability function as an optimization criterion. The wood drying simulation program, TORKSIM v5.11, and the optimization program, StatEase Design Expert (DE) v9 and v11, were both used to resolve the problem of optimizing wood drying times in Sova *et al.* (2016), and in Tamme *et al.* (2021). DE requires for its drying tensions the use of time-constant drying modes as an input for the optimization process, which unfortunately causes drying stresses which are higher than 0.33 for material which is thicker than 20 mm, thereby creating a substantial contradiction

between the TORKSIM and DE optimization criteria (Tamme *et al.*, 2021).

The aim of this paper is to investigate the possibilities involved in the process of being able to optimize drying stresses and drying time during the convective drying of wood, by experimentally determining the optimum water vapour diffusion coefficients in the drying process and using a timed moistening impulse. To this end, novel sensors were developed for wood surface moisture content and wood surface deformation, and these were calibrated for use in the harsh climatic conditions of a wood kiln.

Material and Methods

Theoretical background

The local diffusion coefficient can be experimentally determined according to Fick's first law (Fick, 1855; Crank, 1956; Salin, 1990; Tamme, 2016):

$$F = -D \frac{\partial u}{\partial x}, \quad (1)$$

where F – mass flux, (kg/m²s); D – diffusion coefficient, (m²/s); u – mass concentration, (kg/m³); x – coordinate, (m).

During the convective drying of wood, heat is transferred from the surrounding air through the surface to the interior of the wood and, at the expense of the heat energy being transferred to it, the moisture evaporates from the wood, i.e., the wood is dried. The main equations for describing the heat flow of dry air which is transferred to wood and the heat flow of moist air which leaves the wood are as follows (Salin, 1990):

$$\dot{Q}_1 = \alpha S(T_0 - T), \quad (2)$$

$$\dot{Q}_2 = \beta c_p S(T_0 - T), \quad (3)$$

where $\dot{Q}_1$ and $\dot{Q}_2$ – heat flow (W); α – heat

transfer coefficient ($W/m^2 \text{ } ^\circ C$); β – mass transfer coefficient (m^2/s); c_p – the specific heat of humid air in equilibrium with the wood's surface ($J/^\circ C \text{ } m^3$); S – the surface area of the specimen (m^2); T_0 – surrounding air temperature ($^\circ C$); T – wood surface temperature ($^\circ C$).

Materials and cross-sections of wood specimens used in the study

As part of the laboratory drying experiment, three pine sapwood specimens were used which had been cut from the same board with a cross-section of 35 mm (thickness) $\times$ 150 mm (width) and a length of 100 mm along the wood fibres. Sensors were attached to specimen a) to monitor the drying process; and with specimen b) being the reference specimen for determining the drying curve by weighing; while specimen c) was used to determine the moisture content of the wood at different depths by the slicing method (Tremblay *et al.*, 2000; Tamme *et al.*, 2021).

Description of the methodology used in the investigation

For a wood drying optimization system, it is first necessary to develop reliable and accurate sensors to be able to record the average moisture, local moisture, and surface moisture levels in the wood, as well as including a sensor to record the deformation of the wood's surface. These sensors must simultaneously withstand temperatures of 50–80 $^\circ C$ and high relative humidity levels of 95–100% RH which are characteristic of a convective kiln (Tamme *et al.*, 2021). In addition to the laboratory drying experiment, it is necessary to carry out various simulations using the commercial program, TORKSIM v5.11 for the optimization process. As there are no specified sensors in the standard equipment of any industrial wood dryers as supplied which would allow any optimization, it makes sense under laboratory conditions to optimize a specific drying recipe (i.e., create a drying plan) which is to be used in an industrial

dryer, and then to incorporate the laboratory-optimized method into standard industry practices once it has been proved to be the right choice.

The methodology for the experiment is described in more detail, together with photos, in the final report for the EIC contract No 16200 (Tamme *et al.*, 2021). The basic scheme for the experiment is shown in Figure 1(a) and Figure 1(b) in the photograph.

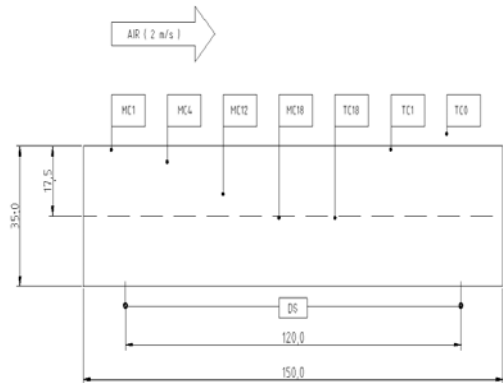


Figure 1. (a) Schematic diagram of the drying experiment and some insight into the Feutron working space of the climatic chamber (Feutron Klimasimulation GmbH, 2021).



Figure 1. (b) Three specimens were used in the experiment being shown here. Sensors were attached to specimen a) to monitor the drying process; specimen b) was a reference specimen which was being used to determine the drying curve by means of weighing; and specimen c) was used to determine the moisture content of the wood at different depths by means of slicing.

For monitoring the drying process, the 9-channel data logger Almemo 2890-9 manufactured by Ahlborn (Ahlborn, 2021) as well as the 8-channel data loggers Thermofox and Gigamodule produced by Scanntronik (Scanntronik, 2021) were used. Drying simulation was done with the program TORKSIM v5.11. For entering the simulation results and experiment log files in the data processing aggregate table, the so-called robot laboratory assistant was used to reduce manual processes and avoid human error in data entry (Tamme, 2013; Romann *et al.*, 2014). For data processing and figure formatting, the spreadsheet program Excel and freeware program MatPlotLib v. 3.4.3. were applied.

Results and Discussion

The calibration of electrical resistance sensors for wood MC detection sensors

When calibrating electrical resistance sensors for wood MC monitoring sensors, a cross-section linear calibration function was used, an example of which is shown in Figure 2 at depth levels of 1 mm and 4 mm

mm below the wood's surface. The points A, B, C, and D which are shown in Figure 2 are known as calibration points with corresponding coordinates ($x = 10\text{LogR}$; $y = \text{MC}\%$). For sections AB, BC, and CD, the calibration function was presented in a generalised form (Tamme *et al.*, 2021):

$$\frac{y - y_1}{y_2 - y_1} = \frac{x - x_1}{x_2 - x_1} . \quad (4)$$

From Formula (4), one calibration function was derived for each section at a particular depth level. Corresponding calibration functions are shown in Table 1. To calibrate the electrodes being used in the experiment at depths of 1 mm, 4 mm, 8 mm, 12 mm, and 18 mm into the wood's MC sensors, three calibration functions are required for each depth level, so that a total of fifteen calibration functions were derived in order to be able to monitor the wood's MC through five depth electrodes. Six of them are presented in Table 1. The feasibility of using the cross-section linear calibration function was proven by means of modelling for two papers (Tamme *et al.*, 2014; Tamme, 2016).

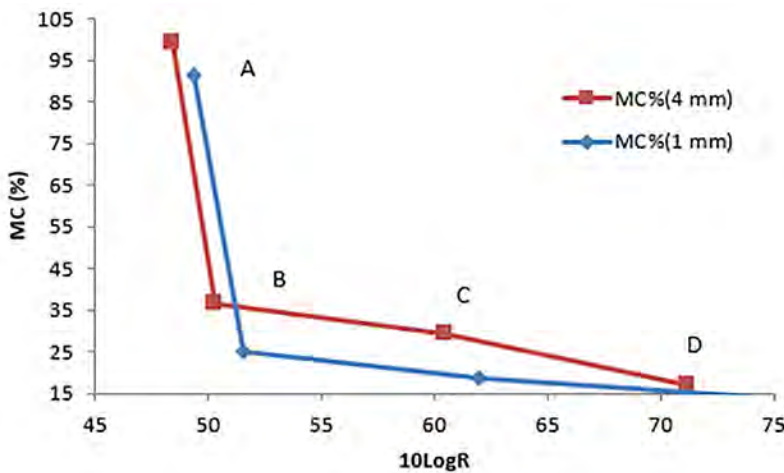


Figure 2. A cross-section linear calibration function for the calibration of resistance-type sensors into the wood's MC sensors. Points A, B, C and D are the endpoints of the line segment.

Table 1. Calibration functions were derived from Formula (4) for electrical resistance sensors at depths of 1 mm and 4 mm from the surface of the wood in sections AB, BC, and CD.

Depth (mm)	AB	BC	CD
1 mm	$y = -30.277x + 1584.9$	$y = -0.6058x + 56.458$	$y = -0.3867x + 42.873$
4 mm	$y = -32.895x + 1691.4$	$y = -0.7255x + 73.292$	$y = -1.1495x + 98.947$

A determination of the optimal diffusion coefficient, experimentally and through simulations

In the laboratory drying experiment and the drying simulation, an industrial drying schedule was used for pine wood specifically, which is presented in Table 2.

Table 2. Industrial 35 mm pine wood drying schedule used in the experiment and the simulation section.

Time (h)	Air temp. (°C)	Air RH (%)
0	20	93
1	47	93
12	47	93
36	50	90
60	52	85
84	52	80
108	52	69
132	52	59
156	52	49
180	52	39
204	52	39

The diffusion coefficient was determined from Fick's first law according to Formula (1) (Tamme *et al.*, 2011). Fick's first law, in the form of a partial derivative differential equation Formula (1), is not directly suitable for processing experimental data or the simulation data. Firstly, in Formula (1) the partial derivatives must be adjusted for finite increments in order to process the experimental and simulation data. Secondly, the experiment and simulation data are dimensionless with relative units (MC %). In order for the diffusion coefficient (DC) which is found in finite increments to ac-

quire the correct dimensions (m^2/s), a constant which contains the dimensions of the units of measurement must be introduced into the formula for practical use. Thirdly, both the experimental data and the simulation data contain random errors, which must be carefully filtered out prior to calculating the DC. In principle, the diffusion coefficient DC can be given according to Formula (1) as the ratio of the mass flux to the gradient:

$$D = -\frac{\text{Massflux}}{\text{Gradient}}, \quad (5)$$

$$\text{Massflux} = -\Delta(\text{MC}\%) \frac{m_{\text{dry}}}{\Delta t * S}, \quad (6)$$

$$\text{Gradient} = \Delta(\text{MC}\%) \frac{\rho_{\text{wood, dry}}}{\Delta x}, \quad (7)$$

where D – diffusion coefficient (DC) (m^2/s); $\Delta(\text{MC}\%)$ – the finite increment of the wood's MC% on the time axis for the mass flux and in the material thickness (x -axis) for the gradient (MC%); m_{dry} – the wood's dry mass (kg); S – the specimen's surface area (m^2); Δt – the time increment (s); $\rho_{\text{wood, dry}}$ – the wood's dry density (kg/m^3); Δx – the x coordinate's increment (m).

After filtering out the random errors, the DC calculation is presented schematically using the four-point method shown in Figure 3. The coordinates of the points which have been marked with the 'diamond' marker in Figure 3 are presented in Table 3. The principle of the four-point method is that, initially, two mass flux val-

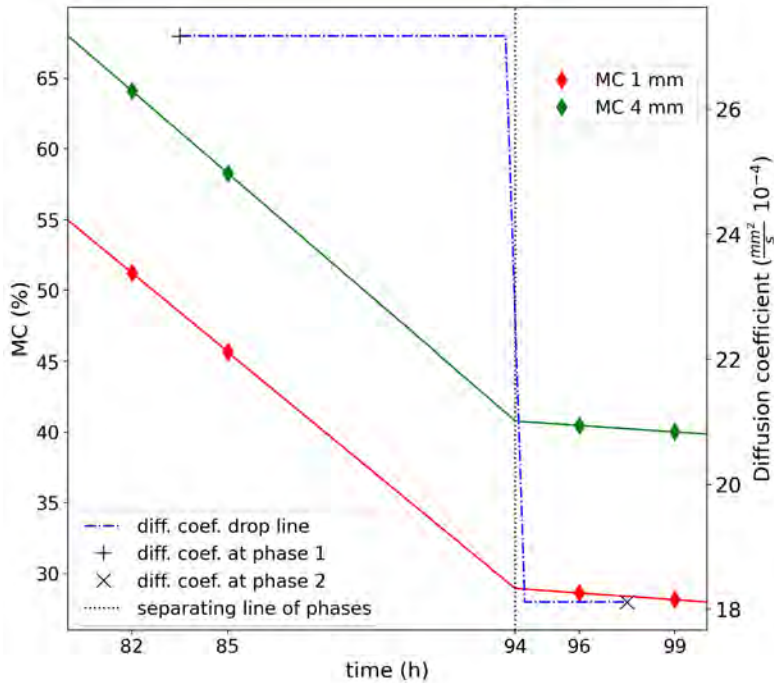


Figure 3. A schematic for calculating the diffusion coefficients in the first and second drying phases, using the four-point method based on experimental data.

ues were obtained at depths of 1 mm and 4 mm, from which the arithmetic mean mass flux was obtained following averaging. Two gradients were also obtained at two different time points, which were then arithmetically averaged. Finally, the average DC at the average depth, i.e., $(1 + 4) / 2 = 2.5$ mm deep from the wood's surface, was calculated according to Formula (5).

After carrying out these calculations, the values of the experimental DC were following: $DC_{1ph.} = 27 \cdot 10^{-4} \text{ mm}^2/\text{s}$ in the first drying phase and $DC_{2ph.} = 18 \cdot 10^{-4} \text{ mm}^2/\text{s}$ in the second drying phase (Tamme *et al.*, 2021). At the end of the first drying phase and at the beginning of the second drying phase, the simulated DC has an almost equal value (i.e., $11.8 \cdot 10^{-4} \text{ mm}^2/\text{s}$).

As the drying process passes from the first drying phase to the second drying phase, a sharp decrease in the numerical value of DC occurs at 94 hours. From Figure 3 it can be concluded that there is a sharp decrease in mass flux in the second drying

phase when compared with the first drying phase. The gradient is approximately constant in the first drying phase, and there is a minimal decrease in the average gradient in the second drying phase. Consequently, the sharp decrease in DC is due to the sharp decrease in mass flux in the second drying phase. Consequently, in order to optimize the drying process, the first drying phase should remain within the region of the maximum mass flux for as long as possible. This fact should be taken into account when optimizing the drying schedule. The maximum value of the diffusion coefficient immediately before entering into the second drying phase was named the *critical diffusion coefficient*. Mass flux, gradient, and critical DC are values which are difficult to determine under industrial wood drying conditions. Therefore, based on the separating line of the first and second drying phase, it makes more sense to determine the critical relative humidity (RH) of the drying air on the basis of the

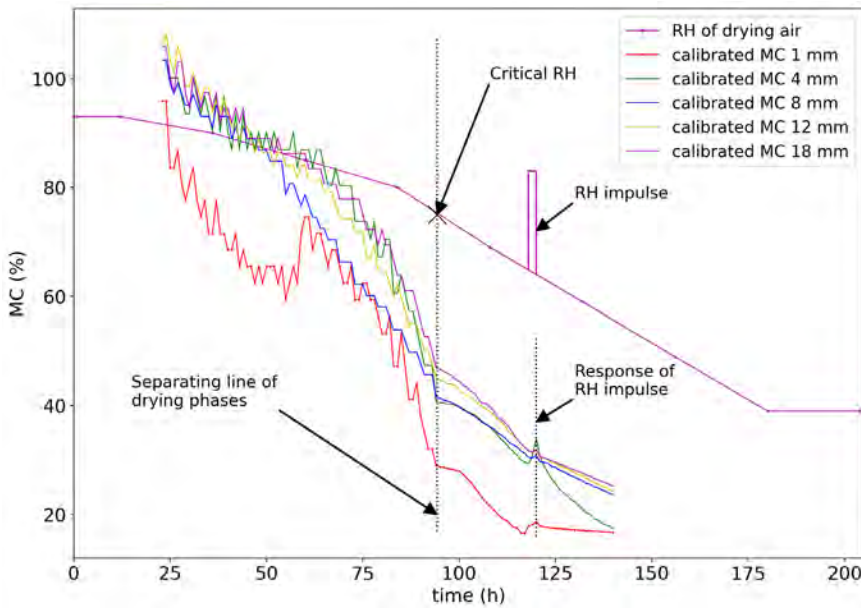


Figure 4. Identification of the critical RH of the drying air according to the separating line of the first and second drying phase.

laboratory test, below which the drying process enters the second drying phase. Monitoring the critical RH value is not a problem in industrial conditions, as wood dryers are usually standard-equipped with a corresponding sensor and a logging option. The determination of critical RH is shown schematically in Figure 4.

Options involved in terms of distinguishing between the first and second drying phases on the basis of sensor readings and log files

The ability to be able to determine the critical RH on the basis of sensor readings alone would be of great practical value under industrial conditions, as the somewhat complex procedure for calibrating the sensors and the equally complex procedure for determining the critical DC would both be eliminated.

The distinction between the first and second drying phase based on the log file of an electrical resistance sensor (i.e., before calibrating into a sensor for the wood's MC) is illustrated in Figure 5. Figure 5

shows that, at 1 mm and 4 mm, electrical resistance starts to increase systematically from 94 hours (i.e., at the transition point to the second drying phase), when compared to the linear trend line for the average electrical resistance in the first drying phase.

The distinction between the first and the second drying phases is illustrated in Figure 6, based on the log files of three sets of temperature sensors and the displacement sensor. It can be seen from Figure 6 that, at the beginning of the second drying phase, the thermocouple readings from the wood's surface and from the centre part begin to diverge. At the same time, the readings from the displacement sensor, which registers the shrinkage of the wood surface, begin to decrease. Both changes in the sensor readings start at 94 hours of drying. Therefore, the first and second drying phase can experimentally be distinguished in four independent ways: according to (a) uncalibrated and (b) calibrated electrical resistance sensors, (c) a displacement sensor, and (d) log files of three temperature sensors.

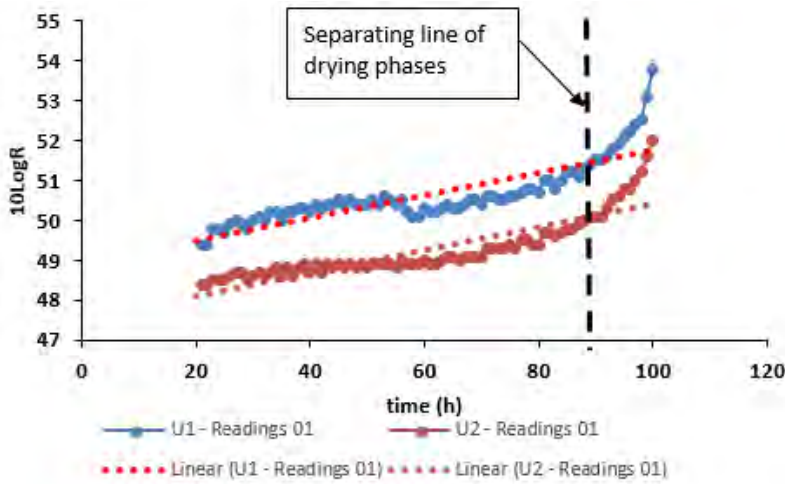


Figure 5. The response for uncalibrated electrical resistance sensors (at depths of 1 mm and 4 mm) upon transition from the first drying phase to the second drying phase.

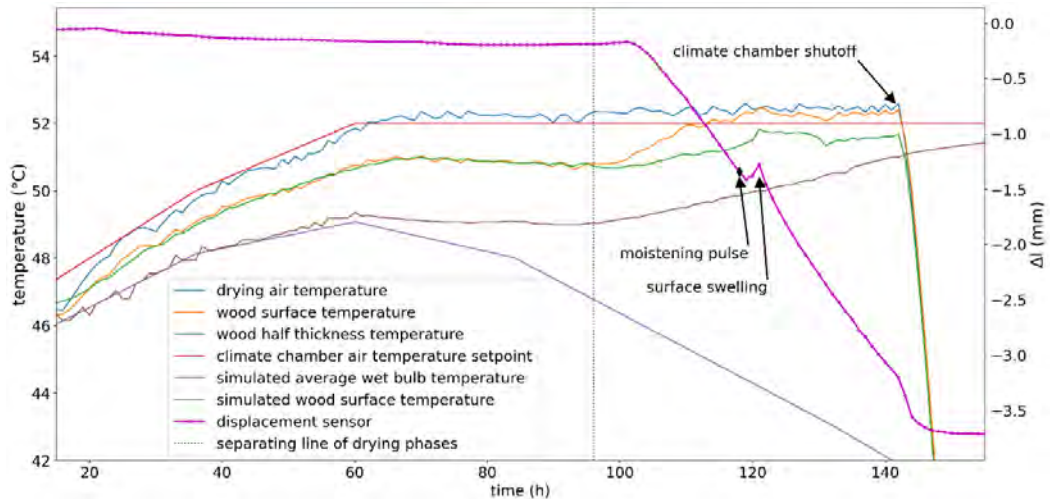


Figure 6. A distinction between the first and the second drying phases based on the log files of three Ahlborn thermocouples and an Ahlborn displacement sensor.

Sensor responses to a short-term increase in the RH of the drying air, i.e., the so-called moistening impulse

A short three-hour moistening impulse was generated during the experiment, in the second phase of drying, starting at 116 hours, in order to verify the response of, and delay inherent in the sensors. From the initial level of RH = 65.1% at 116 hours, the relative humidity RH of the climate cham-

ber air was increased to 95% by opening the valve with a manually operated humidifier, and was maintained at this level for three hours. The humidifier valve was then closed, and the climate chamber's automation quickly restored the RH value of the air in the chamber as prescribed by the drying program. The effect of the moistening impulse on the electrical resistance sensors is shown in an enlarged format

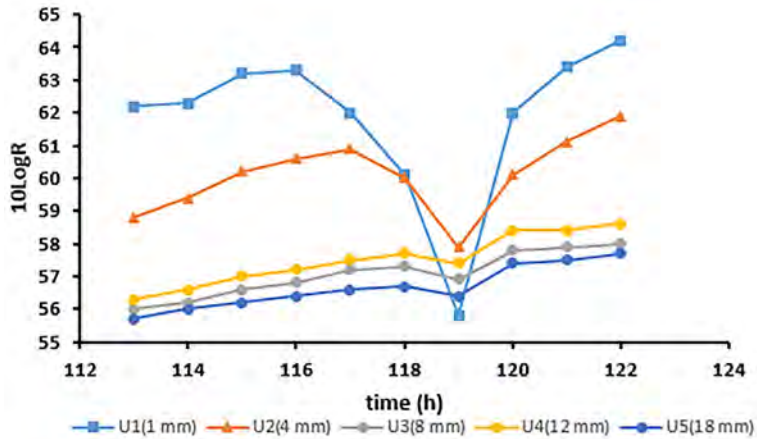


Figure 7. Effect of moistening impulse on the electrical resistance sensors.

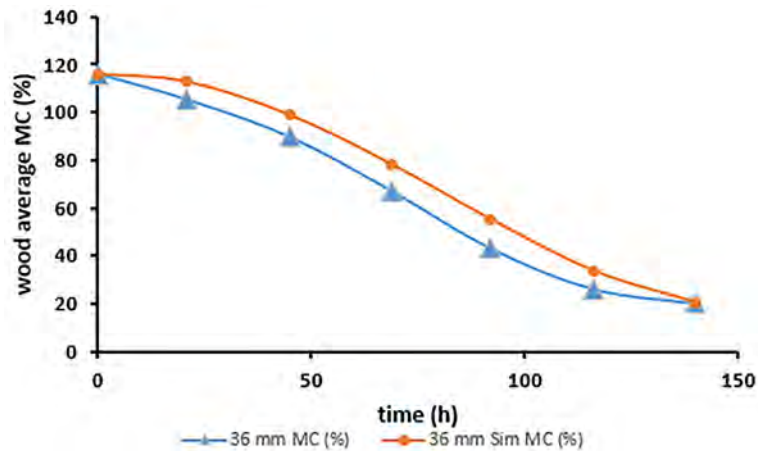


Figure 8. A comparison of drying curves under simulation and during experimentation as determined on the basis of the industrial drying schedule.

in Figure 7. The real effect of the moistening impulse on the displacement sensor is shown in Figure 6. Figure 6 shows that the moistening impulse essentially has no effect on the temperature sensors (thermocouples).

The expansion of the wood's surface layer which was identified in Figure 6 counteracts the tensile stresses in the surface layer which are caused by drying. Consequently, a precisely timed moistening impulse based on a simulation could in practice be used to alleviate the maximum tensile stresses to a safe limit (0.33) in the

surface layer, thereby reducing the risk of drying cracks appearing due to tensile stresses.

The results from optimizing the industrial pine wood drying schedule

The industrial drying schedule (see Table 2) shows that the drying schedule satisfies the main optimization conditions which were set in the TORKSIM program, i.e., the maximum relative tensile stresses in the surface layer are less than the maximum allowable value of 0.33 (Salin 2007; Tamme *et al.*, 2021). Whether the industrial drying

schedule being used in the experiment is also the optimum one in terms of drying time is something which still needs to be confirmed. To this end a new drying schedule was drawn up, based on the definitions of critical DC and its associated critical RH. A corresponding optimized drying schedule (Tamme *et al.*, 2021) is presented in Table 3, and the drying results which were simulated with the optimized drying schedule are shown in Figure 8.

Table 3. Optimized industrial pine wood drying schedule based on the definition of critical DC and critical RH.

Time (h)	Air temp. (°C)	Air RH (%)
0	20	60
1	47	83
113	52	81
132	52	59
156	52	49
180	52	39
204	52	39

Figure 9 shows that an optimized drying schedule can provide an MC in the wood which is up to 30.9 % lower with the same drying time when compared to an unop-

timized drying schedule at virtually the same relative stress levels (0.25) (Tamme *et al.*, 2021).

Another way to shorten the drying time is to force the drying process (Tamme *et al.*, 2011). The drying time in the initial drying schedule was reduced by using as a basis the consideration that the relative humidity of the drying air would decrease by 16% RH per day (Tamme *et al.*, 2011). Forced drying of this type would reduce the overall drying time by about 3.5 days when compared to the original industrial drying regime (see Table 5). In principle, the same thing was done using the StatEase Design Expert program, when the drying time was randomly varied within a predetermined range (Sova *et al.*, 2016, Tamme *et al.*, 2021). Usually, an arbitrary shortening of the drying time in the drying schedule, i.e., forcing the drying process, leads to an increase in the drying stresses above the dangerous level (0.33). According to the results which were obtained previously, dangerous stresses can be neutralised by means of a precisely timed moistening impulse in the second drying phase. The forced drying schedule is presented in Table 4. The corresponding simulation results for the forced drying schedule are presented in Figure 10.

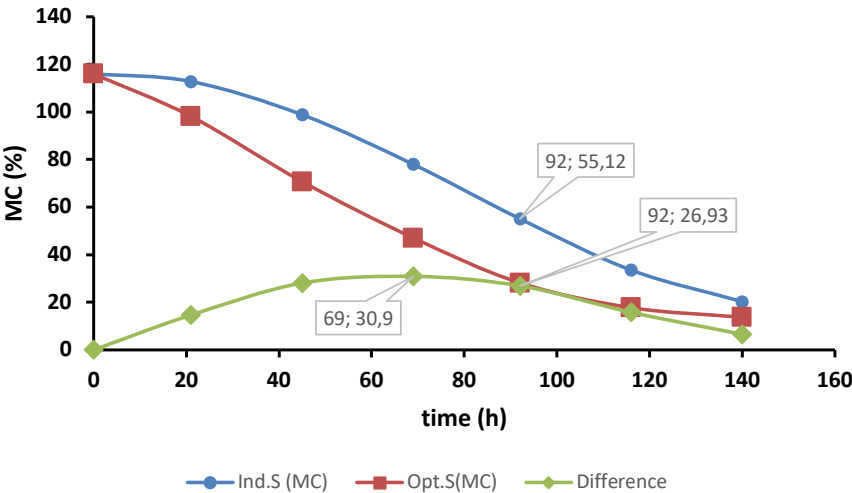


Figure 9. The results of simulations regarding optimized and unoptimized drying schedules.

Table 4. A forced drying schedule for pine wood. Data regarding the stages of the moistening impulse are given in parenthesis in the table.

Time (h)	Air temp. (°C)	Air RH (%)
0	20	93
1	47	93
24	47	77
48	50	61
72	52	45
(90)	(52)	(40)
96	52	29
120	52	13

Figure 10 and Table 4 indicate that, due to the forcing of the drying schedule, the total drying time decreased by 84 hours but, due to the moistening impulse which was added to the drying schedule, the drying time increased by ca 1 h, and the simulated stress decreased by 0.30. Therefore the savings in the drying time at safe stresses (0.30) in order to achieve the same final moisture content of 12% MC was set at 83 hours.

The statistical processing of experimental data

The statistical processing phase should at least broadly reflect the causal rela-

tionships between the physical processes which take place during the drying of the wood. From this general point of view, it would be interesting to be able to study the compatibility of the 'electric fingerprint' of wood drying, i.e., the log files regarding the wood's electrical resistance levels, and the relative stresses in simulated wood, in two cases shown in detail below: a) by examining on a non-statistical basis the coincidence of the maximum point of the electrical indicator on the drying time scale; and b) by compiling a linear model of the relationship between the electrical indicators of the behaviour of the wood's surface layer and its central part.

The electrical surface-core ratio (ESCR) was chosen as an electrical indicator of the behaviour of the wood's surface layer and inner layer, defined as follows:

$$(ESCR) = (10\text{Log}R_{1\text{mm}} + 10\text{Log}R_{4\text{mm}}) / (10\text{Log}R_{8\text{mm}} + 10\text{Log}R_{12\text{mm}} + 10\text{Log}R_{18\text{mm}}). \quad (8)$$

Using the Scanntronik Gigamodule measurement channel designations in the electrical resistance log file, the formula can be shortened:

$$ESCR = (U1 + U2) / (U3 + U4 + U5). \quad (9)$$

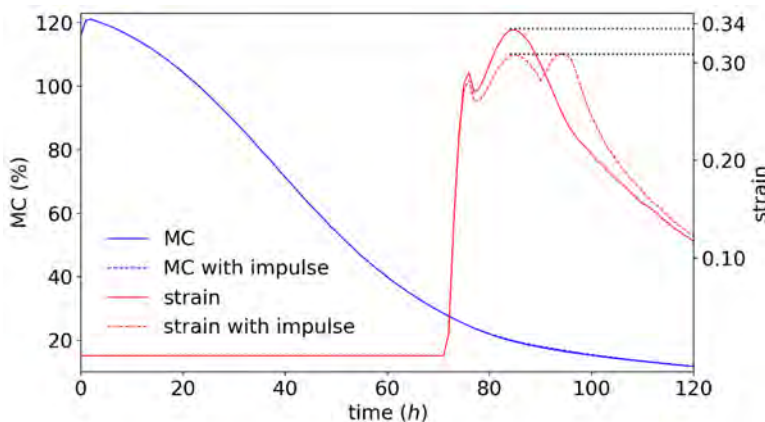


Figure 10. The forced drying schedules simulation graphs without the moistening impulse, and with the moistening impulse.

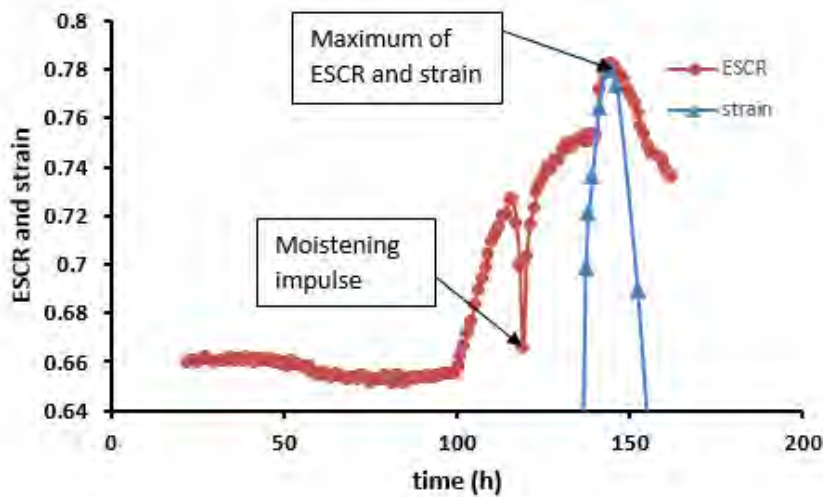


Figure 11. Dependencies of the ESCR value and the TORKSIM v5.11 simulated relative drying stresses on drying time. For a better visual comparison, the simulated relative stresses are multiplied by a factor of 3.12.

In Figure 11, the drying time scale on the ESCR graph shows three clearly distinguishable elements of the laboratory drying experiment, with the correct turnout time: firstly, the transition from the first drying phase to the second drying phase at 92 hours. (Note: the transition of the drying phases begins at 94 hours, with a slow rise, and only becomes noticeable at 100 hours in Figure 11); secondly: the start of the moistening impulse at 116 hours; third:

the full coincidence of the maximum ESCR and the maximum simulated relative stress at 143 hours.

In the linear model of electrical indicators for the wood's surface layer and inner layer in Figure 12, the determination coefficient is $R^2 = 0.9838$, which indicates the existence of a strong causal relationship between the wood's surface layer and inner layer in the drying test. Based on the model, it can be assumed that the moisture

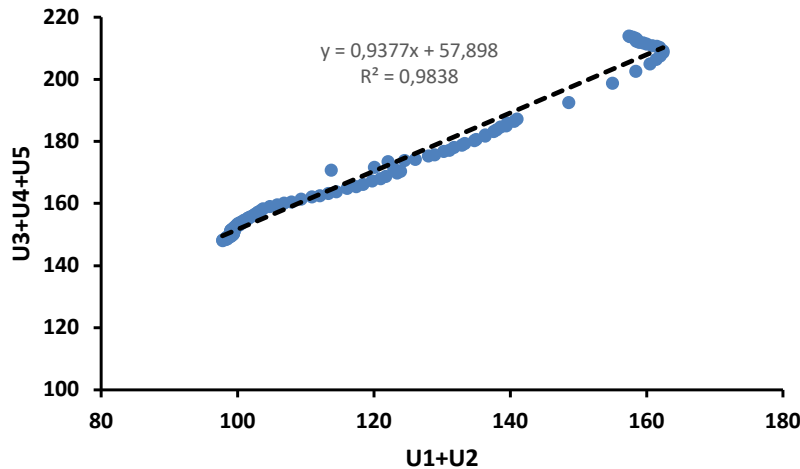


Figure 12. A linear model of the relationship between the electrical indicator for the surface layer and the electrical indicator for the inner layer.

content of the wood's surface layer controls the moisture content of its inner layer.

The potential advantages of the wood tension indicator which is presented in Figure 11 over an indicator which is based on acoustic emission (AE) (Tiitta *et al.*, 2010) include a simpler technical implementation, better reliability in the harsh climatic conditions of a wood dryer, and higher sensitivity levels. However, the advantages and disadvantages of both indicators would be identified by the use of a benchmark.

An analysis of coincidences and differences in the results of the experiment and the TORKSIM v5.11 simulation programs

There is relatively good agreement between the drying experiment and the simulation results in the simulated and experimentally determined drying curves (see Figure 8), the wood's moisture profile before the end of the second phase of the drying experiment at 142 hours (see Figure 13 (b)), the wood's surface simulated and measured in terms of temperature from

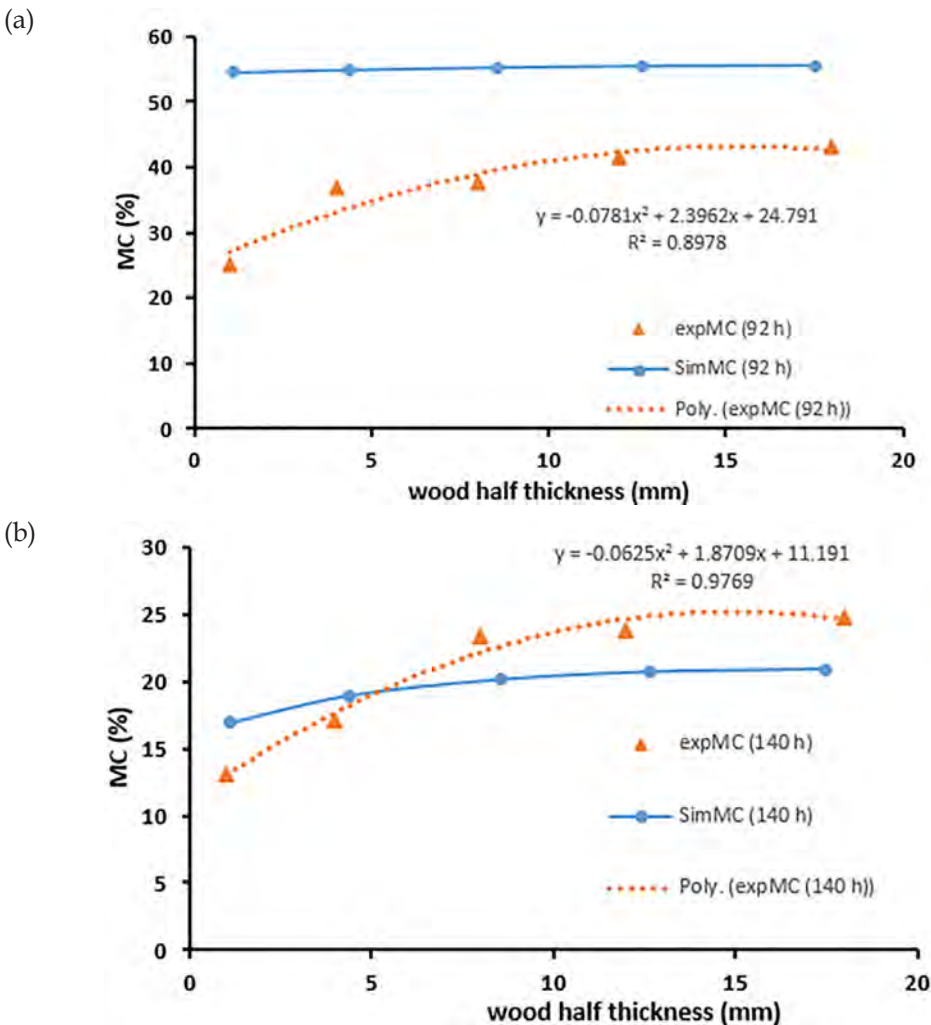


Figure 13. Comparison of experimental and simulated moisture profiles in pine wood: a) after 92 hours b) after 142 hours. Figure 13. Comparison of experimental and simulated moisture profiles in pine wood: a) after 92 hours b) after 142 hours.

the start of drying to 60 hours into the process (see Figure 6), and at simulated wood stresses at the maximum level of the ESCR graph as determined through the experiment (Figure 11).

The critical DC, which is something that is characteristic of the experiment (see Figure 3), is very weakly expressed based on the simulation results. At the end of the first drying phase and at the beginning of the second drying phase, the simulated DC (diffusion coefficient) has an almost equal value (i.e., $11.8 \cdot 10^{-4} \text{ mm}^2/\text{s}$).

The DC's numerical values as determined and simulated through the experiment also differ significantly both ten hours before and ten hours after the 94-hour mark, which is when the transition from the first drying phase to the second drying phase takes place (accordingly: $\text{DC1ph.} = 27 \cdot 10^{-4} \text{ mm}^2/\text{s}$, $\text{DC2ph.} = 18 \cdot 10^{-4} \text{ mm}^2/\text{s}$, and $\text{DCsim.} = 11.8 \cdot 10^{-4} \text{ mm}^2/\text{s}$). There is also no agreement between the wood MC profiles which have been simulated and determined from the experiment at 92 hours (Figure 13 (a)), at the measured and simulated wood surface temperatures after 60 hours until the end of the drying experiment (Figure 6). From the significant difference between the simulated and measured wood surface temperatures it can be concluded that the heat transfer coefficient and mass transfer coefficient in theoretical background Formulas (2) and (3) are no longer constant after 60 hours, but instead depend upon the wood moisture content.

Conclusions

When processing the data from the drying experiment, both coincidences and significant differences were found when comparing this experiment with the results from the simulation run on the basis of the same drying schedule. It was shown that it is possible to optimize the wood drying process in two independent ways, i.e., using a critical DC and/or using a moistening im-

pulse for the drying air in the second drying phase. From the point of view of monitoring the drying experiment, it seems expedient that the minimum number of resistance-type wood moisture sensors is five, and the optimum number of temperature sensors (thermocouples) is three. There should be at least one displacement sensor placed in the drying experiment. Based on the raw files of the electrical resistance measuring channels, a rather expressive drying tensile stress indicator can be constructed in graphical form.

Acknowledgements. This work was supported by the Environmental Investment Centre of Estonia (Grant No. 16200).

References

- Ahlborn. [WWW document]. – URL <http://www.ahlborn.com>. [Accessed 22 October 2021].
- Crank, J. 1956. *The Mathematics of Diffusion*. Oxford, Clarendon Press. 347 pp.
- Feutron Klimasimulation GmbH. [WWW document]. – URL <https://www.feutron.de/en/weathering-chamber/>. [Accessed 22 October 2021].
- Fick, A. 1855. Ueber Diffusion. – Pogendorff, J.C. (ed.). *Annalen der Physik und Chemie*, Vol. 94, 59–86. (In German).
- Kask, R., Mitt, R. 2021. Increasing the potential for the use of red cored gray alder, black alder and birch wood by heat treatment. (Punasüdamikuga halli lepa-, sanglepa-, ja kasepuidu kasutusvõimaluste suurendamine termilise töötlemise abil.) – KIK metsanduse programmi projekti nr. 16531 lõpparuanne, 33 pp. [WWW document]. – URL <https://mi.emu.ee/teadusinfo/projektide-aruanded/kik-projektid/> [Accessed 22 October 2021]. (In Estonian).
- Mändoja, M. 2015. Wood drying simulation "TORKSIM" adjusting to actual industrial drying curve in order to improve the reliability of tension calculations and electrical humidity sensors. (Puidu kuivatuse simulatsiooniprogrammi "TORKSIM" sobitamise reaalse tööstusliku kuivatuskõvera, eesmärgiga tõsta pinge arvutuste ja elektriliste niiskussandurite usaldusväärsust). – Bachelor thesis. Tartu, Estonian University of Life Sciences. 51 pp. (In Estonian with English summary).

- Poljakov, A. 2013. Wood material comparison of actual moisture content monitoring data in wood dryer "Mühlböck" and "Hekotek". (Puitmaterjali tegeliku niiskussisalduse võrdlus monitooringu andmetega puidu kuivatites "Mühlböck" ja "Hekotek") – Master thesis. Tartu. Estonian University of Life Sciences. 125 pp. (In Estonian).
- Romann, T., Oll, O., Pikma, P., Tamme, H., Lust, E. 2014. Surface chemistry of carbon electrodes in 1-ethyl-3-methylimidazolium tetrafluoroborate ionic liquid - an in situ infrared study. – *Electrochimica Acta*, 125, 183–190.
- Salin, J.G. 1990. Simulation of the timber drying process. Prediction of moisture and quality changes. – Doctoral thesis. Helsinki, EKONO Oy. 103 pp.
- Salin, J.G. 2007. Lectures. Riga, 2007. [WWW document]. – URL <http://www.coste53.net/downloads/WG2/WG2-Riga/Lectures/Riga2007-Salin.pdf>. [Accessed 22 October 2021].
- Scanntronik Mugrauer GmbH. [WWW document]. – URL www.scanntronik.de/. [Accessed 22 October 2021].
- Sova, D., Bedeleian, B., Sandu, V. 2016. Application of Response Surface Methodology to optimization of wood drying conditions in a pilot-scale kiln. – *Baltic Forestry*, 22(2), 348–356.
- Tamme, H. 2013. Process management framework on the example of convective drying of wood and spectroelectrochemistry. – MSc. thesis. Tartu, University of Tartu. 25 pp.
- Tamme, V. 2016. Development of resistance-type control methods for wood drying. – PhD thesis. Tartu, Estonian University of Life Sciences. 135 pp.
- Tamme, V., Muiste, P., Mitt, R., Tamme, H. 2011. Determination of effective diffusion coefficient and mechanical stress of pine wood during convective drying. – *Baltic Forestry*, 17(1), 110–117.
- Tamme, V., Muiste, P., Padari, A., Tamme, H. 2014. Modelling of resistance-type wood moisture meters for three deciduous tree species (black alder, birch, aspen) in moisture contents above fibre saturation point. – *Baltic Forestry*, 20(1), 157–166.
- Tamme, V., Tamme, H., Muiste, P. 2021. Development of experimental and theoretical methodology for optimization of quality and energy consumption of convective drying of wood (chamber drying and tunnel drying. (Puidu konvektiivkuivatuse (kamberkuivatuse ja tunnelkuivatuse) kvaliteedi ja energiakulu optimeerimise eksperimentaalse ja teoreetilise meetodika välja töötamine.) – KIK metsanduse programmi projekti nr. 16200 lõpparuanne, 44 pp. [WWW document]. – URL <https://mi.emu.ee/userfiles/instituudid/mi/MI/Projektid/Projekt1620.pdf>. [Accessed 22 October 2021]. (In Estonian).
- Tiitta, M., Tomppo, L., Lappalainen, R. 2010. Combined method for monitoring wood drying process. – Proceedings of 11th International IUFRO Wood Drying Conference, Sweden, 18–22 January. Skellefteå. 76–80.
- Tremblay, C., Cloutier, A., Fortin, Y. 2000. Experimental determination of the convective heat and mass transfer coefficients for wood drying. – *Wood Science and Technology*, 34(3), 253–276. <https://doi.org/10.1007/s002260000045>.
- Tronstad, S., Sandland, K.M., Toverød, H. 2001. Drying quality of softwood based on 140 industrial tests in Norwegian sawmills and actions to improve the quality. – Proceedings of the 3 rd workshop of COST Action E15 on softwood drying to specific end-uses. Advances in the drying of wood (1999–2003). Finland, 11–13 June, Helsinki, 13 pp.

Männipuidu kuivatuse protsessi optimeerimine, kasutades kriitilist difusiooni konstanti ja ajastatud niisutusimpulssi

Hannes Tamme, Peeter Muiste ja Valdek Tamme

Kokkuvõte

Selles artiklis näidati, et männipuidu kuivatuse protsessi optimeerimine on võimalik kahel teineteisest sõltumatul viisil, st kasutades eksperimendist määratud kriitilist difusioonikonstanti DK (DC) ja/või kuivatusõhu niisutusimpulssi teises kuivatusfaasis. Männipuidu kuivatamise eksperimendi andmete töötlemisel leiti nii kokkulangevusi kui ka erinevusi võrreldes sama kuivatusplaani (*drying schedule*) alusel simulatsiooniprogrammiga TORK-SIM v. 5.11 läbi viidud kuivatusprotsessi simulatsiooni tulemustega.

Suhteliselt hea kokkulangevus kuivatuseksperimendi ja simulatsiooni tulemuste vahel on simuleeritud ja eksperimendist määratud kuivamiskõveratel (*drying curve*), DK arvuliste väärtuste suurusjärgul, puidu niiskuspüübil kuivatuseksperimendi lõppfaasis 142. tunnil, puidu pinna simuleeritud ja mõõdetud temperatuuridel kuivatuse algusest kuni 60. tunnini, ja simuleeritud puidu tõmbepingetel (*stress*) eksperimendist määratud *electrical sur-*

face-core ratio ($ESCR$) graafiku maksimumiga.

Leiti, et eksperimendist määratud DK arvuline väärtus väheneb hüppeliselt ca 1,5 korda pärast üleminekut esimesest kuivatusfaasist teise kuivatusfaasi. Artiklis kirjeldati originaalset elektritakistuse logifailidel põhinevat puidu pinnakihi tõmbepingete elektrilist ($ESCR$) indikaatorit, mis võimaldab kuivatusprotsessis reaalajas monitoorida kuivamispingete (*drying stress*) evolutsiooni. Artiklis saadud tulemused on männipuidu tööstusliku kuivatamise optimeerimisel koheselt praktikasse rakendatavad. Samuti on artiklis kirjeldatud eksperimendi metoodika rakendatav lehtpuude kuivatuse uurimisel. Artiklis kirjeldatud eksperimendi metoodika ei eelda ega välista katsetatava puuliigi jaoks kuivatuse simulatsiooni programmi kasutamist, st kuivatuse optimeerimise ülesanne on praktikas edukalt lahendatav ainuüksi eksperimendi tulemustest lähtuvalt.

Received November 17, 2021, accepted December 31, 2021