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QUALITY ASSESSMENT OF LUMBER AFTER LOW TEMPERATURE DRYING FROM THE VIEW OF STOCHASTIC PROCESS CHARACTERISTICS

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ABSTRACT

The quality of lumber drying is traditionally evaluated after the process. This paper proposes the algorithm of quality assessment of low-temperature convection lumber drying in accordance with the target values of the average final moisture content and its dispersion in the stack. The stochastic model of the process with random initial and boundary conditions, which allows calculating the dispersion of the final moisture content (MC) was proposed. To describe the kinetics of the wood drying process in the low-temperature chamber in view of the thermodynamic characteristics, 34 processes of drying of oak and pine lumber with the thickness of 30, 40 and 50 mm were made at the wood-processing enterprises in Ukraine. The theoretical equations of lumber low-temperature drying and the values of the coefficients that characterize the influence of material thickness, temperature and moisture fields' distribution in the material during the drying process were obtained. The check of the proposed models on the uniformity of the average values and dispersion of the current moisture content showed a slight difference between the experimental and calculated values. These models allow predicting the quality of the low-temperature drying on the spread of target moisture content, which enables selection of rational drying schedules.

KEYWORDS: Low temperature drying kinetic, oak lumber, pine lumber, stochastic wood drying model, drying quality assessment.

INTRODUCTION

Before some consumer goods will be made of timber, it must be dried. The drying process is the first step towards obtaining the value-added products. The improper process can reduce the quality of the raw material, lead to such drying defects: end, bedded, internal cracks, twisting, collapse, colour change (Simpson 1991, Rahimi et al. 2011). The use of rational schedules with high relative humidity of the air at the beginning of the process helps to slow down the evaporation of moisture from wood surface. This inhibits the outer layers shrinkage, slows the development of case hardening which may exceed the tensile strength across the grain, and as a result, cracking (Bergman et al. 2010).

The absence of drying defects is not yet evidence about the quality of the process. Products made of not externally damaged dried lumber may deform during the operation. This may be due to the improper destination of the final moisture (Denig et al. 2000), large moisture gradient over the cross section of the material (Kollmann and Côté 1968, Klement et al. 2000, Klement and Huráková 2015), large deviation of moisture of individual planks in the batch of the dried material (Denig et al. 2000), improper storage of the dried material. Final moisture level of wood is determined by the equilibrium moisture content (EMC) level at which they will operate. Only 2 % EMC changing results in a 10 % change in size of oak products in the tangential direction (Denig et al. 2000).

Therefore, the quality of wood drying, in most cases, determines the quality and durability of wood products, contributes to its rational use and forests conservation. The quality of dried wood is influenced by such factors as the quality of raw materials, rational drying technology, production standards and qualification of operators, as well as the design of the chamber, which should provide the uniform distribution of schedule parameters on the stack volume (Denig et al. 2000).

Traditionally, the concept of "drying quality" was determined by the defects absence and most of works (Miniovich 1931, Lubimov 1932, Kollmann and Côté 1968) are dedicated to their prevention. Requirements for the final moisture were limited to the term "desired moisture", the achievement of which determined the time of drying process completion. In view of wood and wood products hygroscopic properties, which are the function of meteorological conditions of operation, the final moisture limits (Seluhin 1936), the drying quality classes of sawn timber intended for the manufacture of particular wood products (Welling 1994, Guzenda et al. 2002, Korkut et al. 2010) were determined. European Drying Group (Welling 2010) defines three levels of drying quality: Standard, medium-quality and highest-quality, each of which is characterized by the standard deviation of the target MC the individual planks from the specified. At the same time 90 % of the dried lumber must comply with these requirements. In the adopted in 2004 standard dealing with drying quality assessment (EN 14298: 2004) there are no drying quality classes. Drying quality assessment is carried out according to the requirements of standard drying taking into account the level of control according to CEN/TS 12169: 2008.

There are three categories of sawn timber drying quality assessment according to Ukraine standard (DSTU 4921: 2008), the requirements for which depend on the type of wood products. The most important products, such as parts of musical instruments, must be dried under the first category of drying quality. In addition to the requirements for the deviation of the actual final

MC from the target, the requirements for the MC dispersion in the dried sawn timber batch in the form of standard deviation at 95 % probability, as well as a conditional indicator of internal stresses were normalized. Some of these provisions are similar to the Brazilian standard for drying quality assessment (Andrade et al. 2012).

The drying quality may be estimated only after the process, when the result has already been obtained and its correction may result in additional energy costs. In some cases there may be a financial loss due to the non-compliance of the quality of the dried material, which leads to further material usage for the manufacture of such less important products as mouldings or packaging. With the increasing shortage of wood raw materials in Ukraine the prediction of the achievements of the target quality of drying is one of the priority areas for development of wood drying technology.

The aim of this study is to simulate the drying lumber process in low-temperature convective chambers for further assessment of drying quality.

MATERIAL AND METHODS

Material

To determine the numerical values of Eqs. 11 coefficients, 34 experimental dryings have been carried out at the Ukrainian sawmills and furniture factories. Pine (*Pinus sylvestris* L.) and oak (*Quercus robur* L.) lumbers as the most common wood species in Ukraine with the thickness of 30, 40 and 50 mm were dried in modern convective industrial chambers of different manufacturers – «Nardi», «Copcal», «Termolegno» (Italy), «Katres» (Czech), «Luka» (Poland). All chambers have an automatic process control. Change control for average lumber moisture content was carried out by means screw electrodes of conductive moisture sensors, buried at 1/3 of the thickness of planks. The number of sensors varied from 6 to 9 depending on the size of dryers. The schedules recommended by chamber manufactures were used. Temperature varied from 40 to 75°C and EMC from 25 to 4 %.

Methods

To describe the process of moisture migration from porous material the Lykov (1967) diffusion equation is usually used:

$$\frac{\partial W}{\partial \tau} = \nabla(D \nabla W) \tag{1}$$

where: W – dry material moisture,
τ – drying time,
D – diffusion coefficient of the moisture ($m^2.s^{-1}$), it is adapted for timber by Sergovskiy (1975):

$$\frac{\partial W}{\partial \tau} = a' \frac{\partial^2 W}{\partial \tau^2} \tag{2}$$

where: a' – wood moisture conductivity coefficient ($m^2.s^{-1}$).

The solution of this equation subject to uniform distribution of initial moisture content over the cross section of drying material and boundary conditions of the third kind allows determining value of the average moisture content of the "average" material for a certain period of time or drying time until the achievement of the desired final moisture content.

Meanwhile, wood is characterized by a large variability of the properties (Kollmann and Côté 1968, Ugolev 2001, Heikkonen et al. 2007), including a significant spread of initial MC (Elustondo and Oliveira 2012). This affects the dispersion of the lumber final MC in the chamber. Furthermore, the uneven dispersion of heat in the chamber associated with non-uniform rate of air circulation through the material (Hågg et al. 2012) increases the unevenness of distribution of final moisture content of dried planks. Eqs. 1 and 2 are unable to reflect the actual conditions of lumber drying process, as they describe the process by the deterministic model with average initial and boundary conditions. It connects with considerable difficulties in solving the diffusion equation with random initial and boundary conditions.

The stochastic model of the drying process of an unlimited plate with random initial and boundary conditions has the following form:

$$\begin{aligned} &\frac{\partial W(\tau,x,\omega)}{\partial \tau} = a' \frac{\partial^2 W(\tau,x,\omega)}{\partial x^2} \\ &W(0,x,\omega) = W_0(\omega) \\ &a' \frac{\partial W(\tau,R,\omega)}{\partial x} = -\alpha(\omega)\left[W(\tau,R,\omega) - \mathrm{W}_{\mathrm{EMC}}(\omega)\right] \\ &\frac{\partial W(\tau,0,\omega)}{\partial x} = 0 \end{aligned} \tag{3}$$

where: R – half of the plank thickness,
W(ω) – random moisture function; random boundary conditions characterizing the unevenness of drying of the material in the chamber: moisture exchange coefficient,
α (ω), sm s^{-1}, equilibrium moisture content W_{EMC} (ω) (ω ∈ Ω, Ω – probability space).

Since the random variable distribution law – the ultimate lumber MC is normal (Guzenda et al. 2002, Pinchevska 2006), it is characterized by moments. It is sufficient to know the first two moments to control the lumber drying process – the mathematical expectation of random variable, which approximately corresponds to the average value of the expected final moisture content, W_f and correlation function, the value of which in some cases corresponds to the dispersion of final MC, d_{Wt}. The solution of moment equations with random initial and boundary conditions leads solution for the mathematical expectation to conventional solution for the third mixed boundary value problem, and for the dispersion to zero in the case of deterministic initial and boundary conditions (Feller 1980).

Final moisture dispersion calculation algorithms based on probabilistic characteristics of only initial MC (Feller 1980), only boundary conditions (Pinchevska 2005), as well as taking into account the probabilistic characteristics of initial and boundary conditions (Feller 1991) were obtained as a result of this approach:

$$d^{(n)}{}_W = \left(\frac{W_{tr}{}^{(n)} - W_{EMC}{}^{(n)}}{W_{tr}{}^{(n-1)} - W_{EMC}{}^{(n)}} \right)^2 d_W{}^{(n-1)} + d^n_{W_{EMC}} \tag{4}$$

where: n – schedule step index,
$W_{tr}{}^{(n)}$ – the value of the transition moisture on the -schedule step,
$W_{tr}{}^{(n-1)}$ – value of the transition moisture in the previous schedule step, for initial conditions $W_{tr}{}^{(n-1)} = W_0$, where W_0 – initial material MC,
$W_{EMC}{}^{(n)}$ – EMC on the n -schedule step,
$d^n{}_{WEMC}$ – EMC dispersion on the n -schedule step,

$d_W^{(n-1)}$ – current MC dispersion on the (n-1) schedule step, when n=0 equals to the dispersion of the initial MC .

The calculations of the expected final MC of sawn timber and its dispersion while drying in industrial chambers with steam heat supply, where moisture content change kinetics is exponential, showed satisfactory agreement with the experimental data. Using the algorithm (4) for low-temperature chamber with air heated by supplying hot water in heaters has shown that calculation results have a significant discrepancy with experimental data. These experimental drying curves are different from the traditional exponential shape and they are shaped like a double exponential. The analysis of the drying process technology in these chambers led to the conclusion that the use of the Eq. 2 for description of the low-temperature drying process incorrectly the nature of moisture content changes of the stack during the whole process, because it does not account for the influence of temperature fields on the redistribution of moisture in wood (Fig. 1). And the greatest error occurs at the beginning of the drying process.

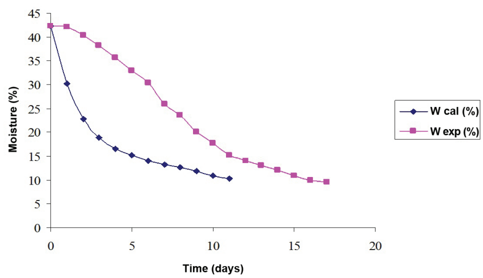

Fig. 1: Changes in average moisture content of pine lumber with the thickness of 50 mm: W_{cal}*, calculated curve obtained by Eq. 2 and the experimental drying curve* W_{exp}*, obtained by drying in industrial chamber with water heat supply.*

In order to account the influence of thermal component on the moisture redistribution process in an unlimited plate (lumber) equation that simulates the effect of temperature fields by introducing conditional source of moisture, which power varies exponentially, was proposed:

$$W = W_0' e^{-k\tau} \tag{5}$$

where: W_0' – maximum power of the moisture source,
k – constant which takes into consideration the relative rate of change of specific capacity of conditional moisture source.

Simulation of the process by introducing moisture source gives the opportunity to slow down the rate of change of MC in the theoretical curve of the drying kinetics. Under these conditions, the task of drying dynamics becomes following:

$$\frac{\partial W}{\partial \tau} = a' \frac{\partial^2 W}{\partial x^2} + \frac{W_0' e^{-k\tau}}{c\rho_0} \tag{6}$$

under initial

$$W(x,0) = W_0 - const \tag{7}$$

$$\frac{\partial W(0,\tau)}{\partial x} = 0 \tag{8}$$

and boundary conditions

$$-a'\frac{\partial W(R,\tau)}{\partial x} + \alpha\left[W_{EMC} - W(R,\tau)\right] = 0 \tag{9}$$

The solution of the Eq. 6 for the determination of the dependence of inter-temporal change of the average moisture content of wood has the following form (Lykov 1967):

$$\overline{E}(\tau) = \frac{W_0 - \overline{W}(\tau)}{W_0 - W_{EMC}} = 1 - \frac{W_0}{(W_0 - W_{EMC})K}\left[1 - \frac{1}{\sqrt{\frac{K}{a}}R\left(ctg\sqrt{\frac{K}{a}}R - \frac{a'}{\alpha}\sqrt{\frac{K}{a}}\right)}\right]e^{-K\tau}$$
$$-\left(1 - \frac{\frac{W_0 R^2}{a'(W_0 - W_{EMC})}}{\mu_n^2 - \frac{K}{a}R^2}\right)B_1 e^{-\mu_1^2\frac{a'\tau}{R^2}} \tag{10}$$

However, the analytical determination of the current MC according to the Eq. 10 requires fairly complex experiments on the determination of wood thermodynamic coefficients. Therefore it was proposed to use the inverse heat conduction and mass transfer method, which is based on the general equation of mass transfer, previously used in the drying process in light and chemical industries (Sazhyn 1984, Lykov 1967, Sazhyn et al. 1968, Temkyn 1973). To determine the current value of saw timber moisture content the Eq. 10 is presented in a convenient form:

$$\overline{W}(\tau) = (W_0 - W_{EMC})\left[B_1 e^{-K_1\tau} - B_2 e^{-K_2\tau}\right] + W_{EMC} \tag{11}$$

where: B_1 and B_2 – pre-exponential factors before $e^{-K_1\tau}$ and $e^{-K_2\tau}$ respectively.

It is necessary to know K_1, K_2, B_2 and $a´$ values. The values of moisture conductivity coefficient $a´$ (accordingly $K_1 = \frac{a'}{r^2}$, where r – 1/3 of lumber thickness that corresponds to the coordinate where the average MC is fixed) depend on the schedule parameters and timber species (Sergovskiy 1975, Schubin 1990). Values K_2, B_2 depend on the duration of established

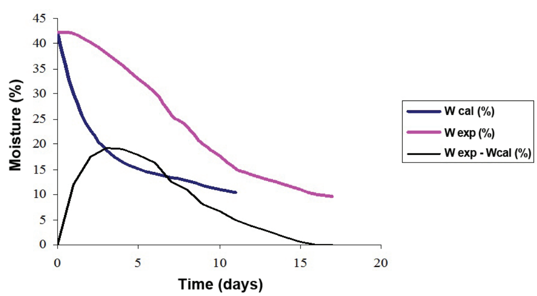

Fig. 2: Curves of drying of pine lumber with the thickness of 50 mm: W_{cal} are calculated by the equation of moisture conductivity; W_{exp} obtained during the drying in chambers with water heating in a production environment; W_{exp} – W_{cal} the difference between the calculated and experimental curves.

temperature fields in accordance with the lumber thickness when changing the drying schedules and power of conditional moisture source, which correspond to a change of wood MC under differential moisture content and temperature fields. Preliminary studies have shown that establishment of temperature field in accordance with the wood cross section is carried out approximately three times faster than the moisture field, therefore K_2 approximately equals to (2...4)K_1 . The theoretical curve of drying kinetics, which is built according to the Eq. 2, can be represented in the form of two components: MC and moisture content source resulting from heat and moisture conductivity (Fig. 2).

RESULTS AND DISCUSSION

Since the change of schedule parameters in chamber did not occur stepwise, but smoothly, the calculation of coefficients was carried out by the actual values of temperature and EMC with 24-hour intervals. Process delay coefficient K_2 was determined by adjusting so that the obtained calculated data were maximally close to the experimental data. At the beginning of the drying process, this coefficient increases with the square law, and after reaching the maximum value decreases exponentially. The results of calculation of K_2 coefficients of the Eq. 11 have confirmed the hypothesis about the decrease in the value of the latter while reducing the average moisture content of the material below the fibre saturation point. This trend was observed for all drying processes. For each experiment the average value of K_2/K_1 coefficients ratio was calculated (Tab. 1), that coefficients were used to construct theoretical drying curves.

Tab.1: Values of K_2/K_1 coefficients ratios.

Wood species	Timber thickness (mm)	1 drying	2 drying	3 drying	4 drying	5 drying	6 drying	Average value
Pine	30	1.44	1.28	1.18	1,59	1.20	–	1.34
	40	1.11	1.40	1.61	1.44	1.73	1.42	1.45
	50	1.79	1.50	1.50	1.42	1.84	1.50	1.59
Oak	30	0.92	0.94	0.95	1.04	1.00	0.79	0.94
	40	1.24	0.82	0.97	1.11	0.92	–	1.01
	50	0.88	1.06	1.50	0.91	1.44	0.91	1.12

The increase of K_2/K_1 coefficients ratio during the increasing timber thickness indicates a slowing of rate of moisture removal due to the long-term impact of conditional moisture source, because the thicker the material the slower the drying process (Schubin 1990, Simpson 1991).

The value of the pre-exponential factor B_1, which was empirically determined for lumber with the thickness of 50 mm amounted to $B_1 = 1.6$. B_2 values were calculated from the conditions $B_2 = \gamma B_1$ and $B_1 - \gamma B_1 = 1$ since at the initial moment there is no effect of the heat and moisture conduction. Power dependence of pre-exponential factor on the lumber thickness *S* was identified:

$$B_1 = 105.06 S^{-1.066} \tag{12}$$

Theoretical equations of drying kinetics for the following lumber of industrial sizes were developed with regard to the calculated coefficients:

Pine	Thickness 30 mm	$W(\tau)=(W_0-W_{EMC})\left[2.8e^{-K_1\tau}-1.8e^{-1.34K_1\tau}\right]+W_{EMC}$	(13)
	Thickness 40 mm	$W(\tau)=(W_0-W_{EMC})\left[2.1e^{-K_1\tau}-1.1e^{-1.45K_1\tau}\right]+W_{EMC}$	(14)
	Thickness 50 mm	$W(\tau)=(W_0-W_{EMC})\left[1.6e^{-K_1\tau}-0.6e^{-1.59K_1\tau}\right]+W_{EMC}$	(15)
Oak	Thickness 30 mm	$W(\tau)=(W_0-W_{EMC})\left[2.8e^{-K_1\tau}-1.8e^{-0.94K_1\tau}\right]+W_{EMC}$	(16)
	Thickness 40 mm	$W(\tau)=(W_0-W_{EMC})\left[2.1e^{-K_1\tau}-1.1e^{-1.01K_1\tau}\right]+W_{EMC}$	(17)
	Thickness 50 mm	$W(\tau)=(W_0-W_{EMC})\left[1.6e^{-K_1\tau}-0.6e^{-1.12K_1\tau}\right]+W_{EMC}$	(18)

which were tested for experimental data adequacy in accordance with the average values uniformity with the use of *Student t-test* and the current MC dispersions using *F-test* (Pizhurin 2004). Herewith the allowable dispersion of the current MC was accepted within the limits of $\pm 2\sigma_W$ (Fig. 3). The results of changing of F_{exp} and t_{exp} during the lumber drying are compared with the data F_T and t_T in Tab. 2.

Tab. 2: The results of statistical processing of the calculations according to the Eqs. 13-18.

Code	Wood species, timber thickness mm	F_{exp}	F_T	t_{exp}	t_T
1	Pine, 30	1.41–5.03	6.39	0.20–1.28	2.31
2	Pine, 40	0.32–4.00	5.05	0.19–2.06	2.23
3	Pine, 50	0.60–3.85	5.05	0.07–1.75	2.23
4	Oak, 30	0.93–3.39	5.05	0.14–2.21	2.23
5	Oak, 40	0.39–4.03	6.39	0.04–1.21	2.31
6	Oak, 50	0.17–4.91	5.05	0.04–2.19	2.23

It is seen that the calculated values of the Student and Fisher criteria, which are obtained as a result of comparing the theoretical curves according to the Eqs. 13-18 with the experimental curves of industrial drying lumber, do not exceed their table values. This gives raise to believe that the adequacy of proposed equations for calculating the lumber MC kinetics while drying in low-temperature chambers with the water heat supply. Under proposed principle can be obtained kinetics equations all wood species.

The widespread use of the low-temperature drying chambers with the heating by means of supplying hot water into the heaters is associated with the need to preserve the natural mechanical properties of wood (Ugolev 2001, Marinescu et al. 2010) and colour (Dzurenda and Deliiski 2012). Lumber drying technology in these chambers is different from the drying technology in steam chambers, where the irregular schedule stage is very small and it is neglected during the process modelling (Schubin 1990). On practice irregular schedule stage in steam chambers is reduced due to the initial heating of the material without MC reducing at the elevated temperature in a saturated environment. This accelerates the removal of moisture from the wood due to the same direction of heat and moisture gradients and the curve of moisture removal kinetics is described by the exponential (Simpson 1991). Implementation of this technology in the low-temperature chambers with "water" heating is irrational, so the initial stage combines timbers heating with moisture removal. Irregular schedule stage increases and the drying kinetics curves acquire S –shaped form (Langrish and Bohm 1997, Watanabe et al. 2013, Tamme et al. 2010). Mathematical description of these curves presupposes the knowledge of quantitative values of inflection points or the process modelling by means of processing of the experimental curves of drying kinetics.

Obtained dependences (13-18) make it possible to implement the algorithm calculation of the dispersion (4) final moisture content of lumber during drying in low temperature chambers.

Fig. 3 shows, as an example of use of the algorithm (4), the calculated curve of changes in lumber moisture content dispersion while drying, as well as the experimentally obtained curve of changes in dispersion of moisture content of pine lumber with the thickness of 50 mm based on the analysis of moisture content meters in the "Termolegno" chamber.

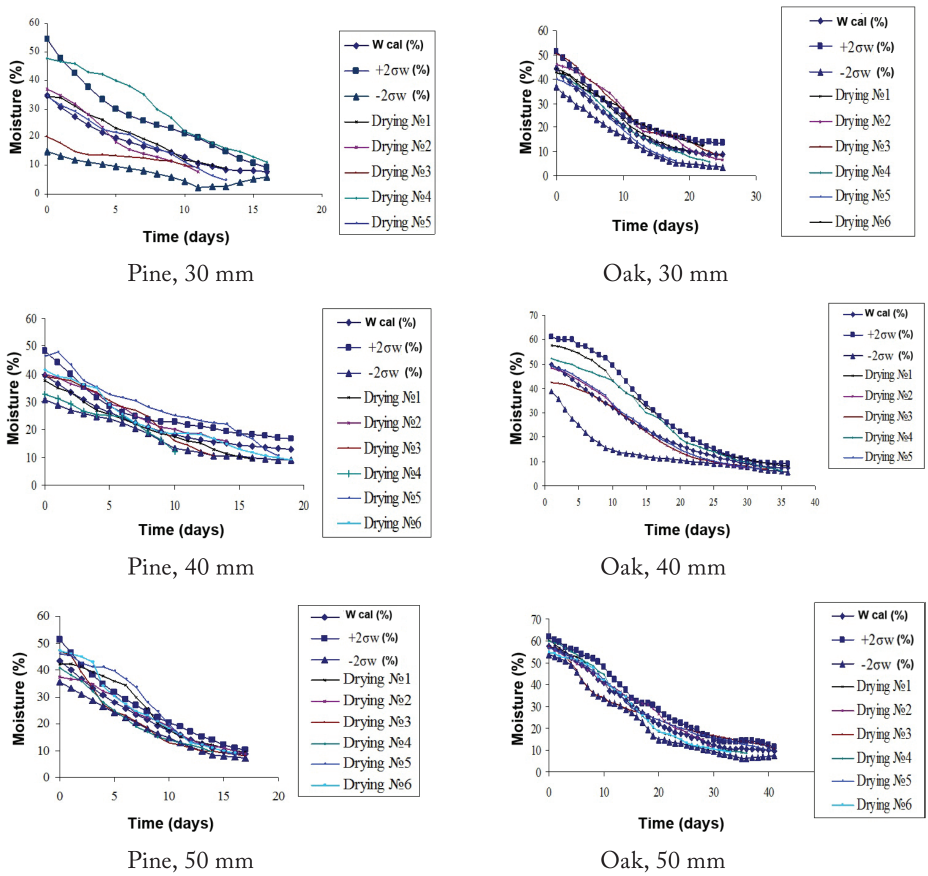

Fig. 3: Comparison of theoretical and experimental curves of drying kinetics.

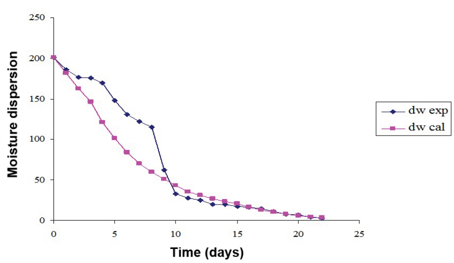

Fig. 4: Curves of changes in dispersion of moisture content of pine lumber with the thickness of 50 mm: The calculated one according to the theoretical drying kinetics curve , experimental one obtained while drying in the "Termolegno" chamber.

Some discrepancy between theoretical and experimental curves is observed on a small area. This is probably due to the feature of the current MC measurement on stack by moisture content meter probes (Tamme et al. 2010) in the initial period the absolute error of measurement of lumber average MC can reach 20 % (Allegretti et al. 2000). Theoretical and experimental dispersion curves of the current moisture content of lumber have shown good agreement during almost the entire second half of the drying period.

CONCLUSIONS

The proposed method of calculation of lumber drying kinetics curves can be used to calculate the expected final moisture content and its dispersion in the batch of material being dried by any schedules in convective kilns. Thus, it is possible to conduct the preliminary assessment of drying quality by the dispersion of final moisture content on the stack in the low-temperature convection chambers of different designs before the drying process. It gives the chance to choose a rational schedule among a plurality of drying schedules, which will provide the required level of drying quality taking into account the lumber initial moisture content dispersion and distribution of thermal fields in the chamber.

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