ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 60(2): 125−134, 2018
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2018.60.2.12

SELECTION OF THE EFFICIENT DRYING SCHEDULE IN CONVENTIONAL CHAMBERS

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ABSTRACT

The drying process of sawn timber is a long and power-consuming process. The production of a high-quality dried material is not guaranteed without abiding by technology, especially the choice of the drying schedule. The method for selecting an efficient drying schedule taking into account the probabilistic aerodynamic characteristics of a chamber and the dispersion of the initial moisture content of the material is discussed in the paper. Research studies on the dispersion of the circulation velocity and temperature of the drying agent on the material were carried out in order to take into account the effect of chamber design. Pine (*Pinus sylvestris* L.) and oak (*Quercus robur* L.) sawn timber with a thickness of 50 mm were dried. Investigations were carried out in chambers of various manufacturers using the schedules recommended by the manufacturers. The use of the algorithm for calculating the dispersion of the final moisture content of sawn-timber obtained as a result of the drying kinetics system – the stochastic model process with random initial and boundary conditions for selecting an efficient drying schedule for parameters such as final moisture content and its dispersion in a batch of the dried material is presented. The proposed method makes it possible to evaluate the quality of drying before the process is carried out and to select the schedule ensuring the required level of drying quality when a particular material in a particular chamber is dried.

Key words: convective drying, oak, pine timbers, stochastic wood drying model, drying quality assessment

INTRODUCTION

One of the basic tasks facing the woodworking industry is the production of the required level of quality with a simultaneous reduction in energy consumption. This is an urgent problem of wood drying as a power-consuming and long-term technological process.

The modern market of drying chambers for wood is widely represented by using large-sized chambers, with a volume more than 50 m^3. A characteristic feature and at the same time a lack of them is the difficulty of ensuring uniform drying of the material throughout the chamber volume. This leads to the fact that not all of the material in the batch corresponds to the necessary technical conditions, for the influence of the design of the chamber itself on the quality of the dried production significantly increases.

The technological process of drying consists of a number of technological and control operations. The basis of the technology of wood drying laid the schedule, the parameters of which depend on the wood species, the thickness of the assortment, moisture content (MC) and the purpose of the material. It is rather difficult to choose the optimal schedule due to the inconsistency of factors influencing its choice as: the intensity of the process and the quality of the material, the duration of the process and the power consumption, etc. Scientists from all over the world were engaged in developing the schedules at different times (KRECHETOV 1949, SOKOLOV 1968, SERGOVSKIY and RASEV 1987, TIEMAN 1917, KEEY *et al*. 2000). The most common principle of construction of wood drying regimes is the section of the parameters of the drying agent, depending on the moisture content of the material.

Each company manufacturer of chambers recommends its own development of drying schedules, which are incorporated into the program of automatic process control. Common to all schedules is that they are built on the principle of preserving the integrity of wood and, accordingly, depend on the physical properties of the material, the main one being density. The density of wood, in turn, depends significantly on the growth conditions, which leads to the need for correcting regimes for other regions in accordance with the physical properties of the wood that grows there (SCHEPASCHENKO *et al*. 2017, CANDEL-PEREZ *et al*. 2018, WATANABE *et al*. 2017, HERMAWAN *et al*. 2012, KLEMENT and VILKOVSKA 2015).

The correct selection of the drying schedule is characterized by the quality of the dried material. An analysis of the effect of drying schedules on the quality of the material has been devoted to a significant number of works (BERROCAL *et al*. 2017, YAMASAKI *et al*. 2017, SCHNABEL *et al*. 2017, ZANUNCIO *et al*. 2017, MILIC and KOLIN 2008, DZURENDA and DELISKI 2012). One of the main indicators that characterize the quality of dried lumber is the magnitude of internal stresses (SOKOLOVSKY Y. *et al*. 2016). Empirically, various methods have been developed to determine internal stresses during the drying of coniferous sawn timber, which will allow us to characterize the quality of dried products (ZHAN and AVRAMIDIS 2017).

A method for assessing drying quality using a simulation tool has been experimentally confirmed for larch wood. This method allows selection the optimal drying regime for larch, taking into account power consumption and material quality. Similar researches have been conducted to improve existing schedules of drying materials from teak (*Tectona grandis* L.) in order to intensify the process. However, a decrease in the quality of the dried material noticed with a reduction in the duration of the process (BERROCAL *et al*. 2017).

Quality assessment is carried out according to the following indicators: MC, deviation of the actual final MC of the material from the specified, dispersion of the MC in the batch of dried sawn timber in the form of the standard deviation $\pm 2\sigma_{W_к}$ conditional indicator of internal stresses. The values of some of them can be determined analytically based on the actual characteristics of the material loaded into the chamber, as well as the chamber's ability to implement the schedule parameters uniformly over the volume of the material. For this, it is necessary to develop a method for simulating the drying process of sawn timber using different regimes that provide the necessary level of drying quality. Given the shortage of wood raw materials, ensuring quality of drying is an important task of resource and energy conservation.

The main aim is to develop a method for selecting a drying schedule taking into account the required level of quality of the dried material.

MATERIAL AND METHODS

Methods

To predict the quality of drying of sawn-timber by such parameters as final MC, W_f, and its dispersion, $\pm 2\sigma_{W_f}$, in a batch of dried material it is efficient to use a model with random initial and boundary conditions (PINCHEVSKA *et al.* 2016). The solution of this problem has the form of moment equations for the mathematical expectation and dispersion of the final MC of sawn timber (Feller 1980). The practical use of these equations is possible after an experimental determination of the dispersion of the wood moisture conductivity coefficient, d_a, the initial MC of the sawn timber, d_{Wi}, the moisture exchange coefficient, and the equilibrium moisture content (EMC) of the wood, d_{EMC}. The definition of these parameters does not cause difficulties. The determination of the variability of the wood moisture conductivity coefficient is currently difficult, since only average values of this parameter are presented in the literature without data on dispersion, and for a limited number of wood species. Therefore, this parameter was adopted as deterministic.

Thus, the algorithm for calculating the dispersion of the final MC of sawn timber is:

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

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, which can be determined from the experimental determination of the disperse of the temperature field in the chamber:

$$d^n_{W_{EMC}} = \left(\frac{V_t^n W_{EMC}{}^n}{100\%} \right)^2 \tag{2}$$

where: $V_t{}^n$ – coefficient of variation of the temperature field of the chamber at the n-th stage of the regime, which is directly influenced by the dispersion of the aerodynamic field $V_v{}^n$ (PINCHEVSKA 2008, BEDELEAN 2014, BEDELEAN 2017, DARABI *et al.* 2015).

Thus, the dispersion of final moisture in a batch of dried material can be determined by the equation:

$$\pm 2\sigma_{W_f} = \pm 2\sqrt{d^{(n)}_{W_f}} \tag{3}$$

Using different drying schedules, the final result can be predicted and selection the most appropriate schedule for a particular chamber and dried material is before the process, which saves energy and time needed for empirical studies.

Material

Appropriate measurements were made in the modern convection chambers of various manufacturers as “Nardi”, “Copcal”, “Termolegno”, “Katres”, “Luka”, “Gorluk K°”, “Gefest”,”UL-2” to determine the average circulation velocity of the drying agent and its dispersion through the material. All chambers are equipped with axial fans located in the upper part of the chamber above the stack of sawn timber. The loading volume of the chambers did not exceed 70 m^3 of the dried material.

Sawn-timber from of oak wood and pine wood of 50 mm thickness were dried. To measure the velocity of airflow, an anemometer with a remote sensing element was used, which makes allowing to determine the air circulation velocity in the range from 0.1 to 20 $m \cdot s^{-1}$. Measurements of the circulation velocity of the drying agent at the outlet from the stack were carried out before the drying process, during the drying process and after it.

In parallel with the measurement of the air circulation rate, measurements were made of its actual temperature in the batch of the dried material throughout the drying process.

Thermocouples were installed in different places of packages of sawn timber so that the sensors were located in gaps between the boards. In total, 20 chambers with a horizontal and vertical circulating drying agent ring installed at Ukrainian enterprises were surveyed. In these chambers, the variance in MC of the sawn timber was also monitored according to the values of the conductometric moisture sensors.

RESULTS AND DISCUSSION

During the drying of the material, the drying speed of the drying agent was practically unchanged, as the fan rotation frequency was constant. The results of measuring the speed and temperature of the drying agent are given in Table 1.

Tab. 1 Experimental data on the determination of aerodynamic and thermal fields of chambers.

Chambers	The actual average speed of air in the stack v, m·s^{-1}	Variation coefficient of air circulation speed V_v, %	The actual average temperature of air in the entrance of stack t,°C	Variation coefficient of air temperature V_t, %
«UL-2»	2.29	40.7	38.3	6.2
			73.4	5.3
			93.6	4.4
«Katres»	3.27	38.0	35.9	3.0
			53.8	2.5
			61.9	2.3
«Luka»	1.27	26.8	46.3	2.8
			53.6	2.4
			57.6	2.3
«Termolegno»	0.85	31.6	44.7	6.9
			50.6	3.7
			57.8	2.5
			61.8	2.3
«Copcal»	0.47	72.1	41.8	15.2
			52.1	12.3
			60.6	9.6
			65.6	5.6
«Nardi»	0.41	25.5	46.3	3.2
			56.1	2.7
			63.4	1.3
«Gorluk K°»	0.57	36.4	39.9	8.5
			53.6	5.1
			62.4	2.8
«Gefest»	0.68	38.9	39.9	8.7
			53.8	5.7
			66.2	2.4

The range of fluctuations in the actual circulation rates of the drying agent at the outlet from the sawn timber stacks in the above chambers was 0.47–3.27 m·s^{-1}. The coefficient of variation was 16.8–72.1%. Stable correlation dependence with a coefficient of correlation between the dispersion of the aerodynamic V_v,% and thermal fields V_t,%, which is described by the equation:

$$V_t = 0.25V_v - 2.85 \quad (4)$$

is significant according to the Student's *t*- criterion $r = 0.88$.

The distribution of the temperature field in chambers was investigated throughout the entire drying process – in the initial period in parallel with the measurement of the air circulation velocity, then in the temperature range corresponding to the middle and final periods. Analysis of measurements results showed, if the density of the drying agent with increasing temperature changes, dispersion of the temperature field over the stack of sawn timber decreases.

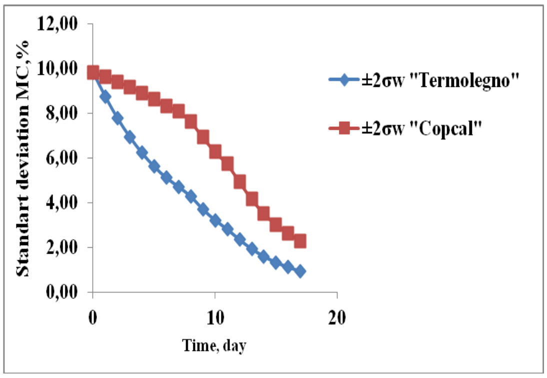
With some approximation, it can be stated, the fact that for chambers with an average circulation velocity of the drying agent through the stack v_{av} within $> 1.0 < v_{av} < 3.0$ m·s^{-1} an increase in the uniformity of the heat field by 1.2–1.4 times is observed with a variation in the average temperature of the drying agent t_{av} in the stack of sawn timber $30 < t_{av} < 80$ °C and for chambers with the range of average air circulation speed $0.5 < v_{av} \leq 1.0$ m·s^{-1} the uniformity of the thermal field increases 2.7–3.3 times with the same temperature parameters.

The conducted researches make it possible to determine the variability of the temperature field of a chamber throughout drying period according to the actual measurements of the air circulation velocity in the initial period, which is not difficult.

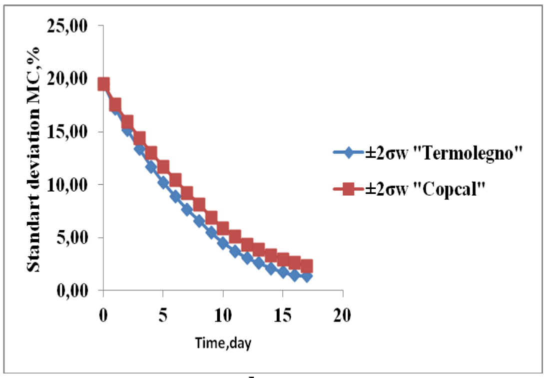
Figures 1 and 2 as the example represent the results of calculating the standard deviation of the current MC of pine and oak sawn timber with a thickness of 50 mm with a different actual dispersion of the initial MC during drying in chambers of different manufactures: «Termolegno» (loading volume 50 m^3, axial fans № 8 – 5 pc, engine power 3 kW, average actual air speed V_{av} = 0.85 m·s^{-1}, variation coefficient of air circulation speed V_v = 31.6%), «Nardi» (loading volume 70 m^3, axial fans № 8 – 6 pc, engine power 3 kW, average actual air speed V_{av} = 0.41 m·s^{-1}, variation coefficient of air circulation speed V_v = 25.5%), «Copcal» (loading volume 50 m^3, axial fans № 6 – 4 pc, engine power 1.5 kW, average actual air speed V_{av} = 0.47m·s^{-1}, variation coefficient of air circulation speed V_v = 72.1%).

The variation in the schedule parameters (temperature, humidity, circulation speed of air and its range) for the calculation was made in accordance with the experimental data obtained in determining the dispersion of the thermal and aerodynamic fields of the chambers. It can be seen that the chambers “Termolegno” and “Nardi”, which have more even distribution of the drying agent circulation velocity over the stack, are more preferable, however when the sawn timber is dried in with a wide dispersion of initial MC, the quality of the drying decreases.

It should be noted that the degree of influence of the unevenness of the distribution of the drying agent's parameters over the stack is manifested to a greater extent with a smaller dispersion of the initial MC of the sawn timber supplied for drying.



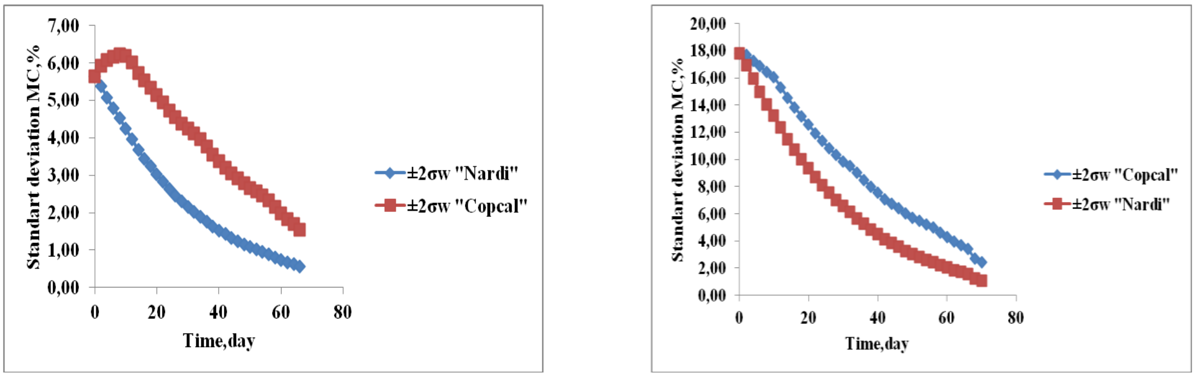
a



b

Fig. 1 Calculated curves of the standard deviation of the current MC of pine sawn timber during drying from: a – initial MC W_i = 42.3% to final MC W_f = 9.6% with initial MC dispersion d_w = 24.1, b - initial MC W_i = 47.0% to final MC W_f = 8.0% with initial MC dispersion d_w = 94.9.

A large dispersion of the initial MC increases the expected distribution of the final MC of sawn timber (PANG and WIBER 1998), even in chambers with a uniform aerodynamic field. This again confirms the need (WATANABE *et al.* 2013) for sorting sawn timber according to the initial MC.



a b

Fig. 2 Calculated curves of the standard deviation of the current MC of oak sawn timber during drying: a - from initial MC W_i = 54.9% to final MC W_f = 10.9% with initial MC dispersion d_w = 31.8, b - from initial MC W_i = 60.5% to final MC W_f = 9.0% with initial MC dispersion d_w = 79.4

Tab. 2 Results of the determination of the sawn timber final MC dispersion.

Wood species	Chamber	Actual saw timber initial MC,%	Actual saw timber initial MC dispersion	Actual saw timber final MC dispersion	Calculated saw timber final MC dispersion
Pine	«Termolegno»	42.0	24.1	0.26	0.21
	«Copcal»	42.0	24.1	-	1.31
	«Termolegno»	47.0	94.9	1.89	1.93
	«Copcal»	47.0	94.9	-	2.30
Oak	«Nardi»	54.9	31.8	0.60	0.62
	«Copcal»	54.9	31.8	-	2.39
	«Nardi»	60.5	79.4	1.51	1.51
	«Copcal»	60.5	79.4	-	3.29

The effect of the distribution of the aerodynamic fields of the chamber on the quality of drying depends not only how well the drying schedule is reproduced in the stack (Table1), but also on the applied processing schedule. The drying schedules recommended in the literature differ in terms of the temperature level, the humidity of the drying agent and the rate of moisture migration from the dried material determined by the drying gradient.

The analysis of the drying schedules prevalent at Ukrainian enterprises (1- (SELUHIN 1936), 2 - (SERGOVSKIY and RASEV 1987), 3 - (CHIVIDINI 2001), 4 - (COPCAL 1995), 5 - T3-C1 for oak, T3-B3 for pine (DENIG *et al.* 2000), 6-T2-B1-for oak, T7-B2 for pine (DENIG *et al.* 2000)) of pine and oak sawn timber showed that they all have the same trend in variation of the temperature and humidity of the drying agent throughout the drying process – Tab.3. The only difference is the proposed number of variations in the current parameters, i.e. steps.

In accordance with the above procedure, the expected dispersion of final MC W_f = 8% of pine and oak sawn timber 50 mm thick was calculated when dried in chambers with different distribution of the drying agent over the stack. The drying schedules were used, the parameters are shown in Table 3.

The national standard for determining the quality of drying DSTU 4921: 2008 regulates the magnitude of the variance of the final moisture for the first category of quality of drying $\pm 2\sigma_{W_f} = \pm 1{,}0\%$ and $\pm 2\sigma_{W_f} = \pm 1{,}5\%$ for the second category of quality drying.

Tab. 3 Parameters of the drying schedules used for calculating (W, % - saw timber current MC ; t, °C - temperature of the drying agent ; φ, % - humidity of the drying agent).

W,%	Schedule 1		Schedule 2		Schedule 3		Schedule 4		Schedule 5		Schedule 6	
	t,°C	φ,%	t,°C	φ,%	t,°C	φ,%	t,°C	φ,%	t,°C	φ,%	t,°C	φ,%
	Pine saw timbers, 50 mm											
> 40									43	83	54	90
40-35	49	80	52	84	55	72	60	81	43	83	54	90
35-30	52	70	55	72	55	72	63	65	43	78	54	84
30-25	53	60	55	72	63	50	67	65	49	70	60	81
25-20	59	44	55	72	70	45	67	50	54	52	66	67
20-15	61	39	70	33	70	40	72	35	60	32	71	42
< 15	63	33	70	33	75	25	75	25	71	25	71	25
Oak saw timbers,50 mm												
> 40	46	80							43	94	38	87
40-35	49	75	43	89					43	94	38	87
35-30	51	70	47	83	40	86	50	72	43	83	43	80
30-25	57	55	47	83	45	80	51	60	49	70	43	58
25-20	60	45	49	79	50	64	54	45	54	43	49	40
20-15	63	30	53	64	55	46	57	32	60	20	54	16
< 15	63	30	61	38	63	30	60	28	71	26	66	23

From the results of the calculation given in Table 4 and 5, it can be seen that it is possible to dry pine and oak sawn timber with a small dispersal of initial moisture in a chamber with the best aerodynamic parameters by any of the schedules considered. It can be expected that the quality of drying will correspond to the first or second quality categories. In this case, the determining factor in selection the schedule can be the minimum duration of the process. In the "Copcal" chamber, high quality of drying in the second category can provide the two gentlest schedules with a considerable processing time.

Tab.4. Results of calculations of the expected dispersal of the final MC $\pm 2\sigma_{W_f}$ of pine sawn timber 50 mm thick dried by different schedules in chambers of different manufacturers.

Initial moisture content W_i %	Initial MC dispersion d_{Wi}	Drying schedules					
		1	2	3	4	5	6
42.3	24.1	Chamber «Termolegno»					
		± 1.5 9*	± 1.5 10	± 1.4 15	± 1.4 10	± 1.0 18	± 1.2 17
		Chamber «Copcal»					
		± 3.0 9*	± 2.7 10	± 2.5 15	± 2.6 10	± 1.9 18	± 2.0 17
47.0	94.9	Chamber «Termolegno»					
		± 1.9 11*	± 1.8 11	± 1.6 16	± 1.7 12	± 1.4 19	± 1.5 18
		Chamber «Copcal»					
		± 3.3 11*	± 3.1 11	± 3.0 16	± 3.2 12	± 2.6 19	± 2.9 18
* time, day							

Tab. 5. Results of calculations of the expected dispersal of the final MC $\pm 2\sigma_{W_f}$ of oak sawn timber 50 mm thick, when dried by different schedules in chambers of different manufacturers.

Initial moisture content W_i %	Initial MC dispersion d_{Wi}	Drying schedules					
		1	2	3	4	5	6
54.9	31.8	Chamber «Nardi»					
		± 1.0 68*	± 1.5 65	± 1.4 66	± 1.5 65	± 1.3 57	± 1.1 64
		Chamber «Copcal»					
		± 2.0 68*	± 2.2 65	± 2.0 66	± 2.3 65	± 2.4 57	± 2.2 64
60.5	79.4	Chamber «Nardi»					
		± 1.2 70*	± 1.4 68	± 1.4 67	± 1.5 66	± 1.5 60	± 1.3 68
		Chamber «Copcal»					
		± 2.0 70*	± 2.2 68	± 2.3 67	± 2.5 66	± 2.3 60	± 2.0 68
* time, day							

If there is a wide dispersal of the initial moisture content of sawn timber, only two schedules can provide a high quality of drying in the "Termolegno" and "Nardi" chambers with the longest drying time. In a chamber with poor aerodynamics, obtaining sawn timber according to the second quality category is questionable.

CONCLUSIONS

A method for selecting the drying schedule is proposed. It allows to select a rational schedule that will provide an optimal result, both in the quality of the dried saw timber and in the duration before the process is carried out.

An analysis of the results of calculating the variation in the final MC in the batch of material showed that the dispersion of the sawn timber initial MC has the greatest influence. High unevenness of the chamber's thermal field also contributes to an increase of the final MC dispersion. To obtain a batch of dried material with a uniform distribution of the final MC, it is necessary to take into account the ability of the chamber to distribute the drying agent evenly over the stack – a considerable spread of the air temperature leads to increase the process duration and cost. In order to avoid this it is necessary to estimate the quality of drying by the dispersion of the final moisture in the stack, before drying, in convectional chambers of different manufactures and to choose the schedule that will provide it.

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ACKNOWLEDGEMENTS

This work was supported by the Ukrainian Ministry of Education and Science under Program No 2201040 "The research, scientific and technological development, works for the state target programs for public order, training of scientific personnel, financial support scientific infrastructure, scientific press, scientific objects, which are national treasures, support of the State Fund for Fundamental Research". The authors are grateful to Ministry of Education and Science of Ukrainian for financial support of this study.
This work was supported by the grant agency VEGA under the project No. 1/0626/16.

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