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MODEL PREDICTIVE CONTROL OF CONVECTIVE DRYING PROCESS OF LUMBER

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ABSTRACT

A programmable control system for the convective drying process of lumber in chambers is developed, based on specially designed drying algorithm, which allows for computing the set-point values for the temperature and the relative humidity of the heating and drying air as a function of the wood species, lumber thickness and the initial and desired final wood moisture content.

The system allows for carrying out model predictive automatic control, by means of which, after the operator enters the data on wood species and thickness of the lumber, as well as the initial moisture content and the desired final value of the moisture content, the programmable controller in the system calculates the current values for the temperature and the relative humidity of the processing air medium, and also the duration of the separate stages of the drying process, and carries out an automatic realization of the computed parameters.

An application of the developed system for predictive automatic control of the convective drying process of pine lumber with thicknesses of 32 mm and 76 mm is given and visualized.

Key words: convective drying process, lumber, automatic control, programmable controller

1. INTRODUCTION

Drying of wood is one of the basic technological operations of wood processing.

For achieving the desired quality of the wood, the lumber needs to be dried in a controlled environment using carefully monitored temperature and humidity levels, in order to avoid over-drying or under-drying. This is critical because it allows the wood to dry to the correct moisture content for its ultimate intended use, thereby enabling the wood to maintain stability and dimension. Wood that is over dried or under dried will warp or shrink and will not have the correct moisture content for its intended use (Nikolov and Videlov 1987, Shubin 1990, Trebula and Klement 2002, Videlov 2003).

The automated control systems for convective drying of lumber in chambers available on the market (e.g. produced by the firms Bollmann, Brunner, Hildebrand, Incomac, Incoplan, Ketres, Lignomat, Nardi, Mühlböck, Secal, Secea, Vanichek, etc.) are complicated and expensive for the small woodworking companies. Based on first-hand long time experience in the area of technology, equipment and control of hydro-thermal processing of wood materials, on the one hand, and in the development of microprocessor controllers, on the other hand, a team of scientists and Delta Instrument Ltd., Sofia designed and put into practice a series of algorithms and programmable logic controllers (PLCs) for automated convective drying of lumber, applicable also in very small chambers.

The aim of this paper is to present the results from the development of a control system for the convective drying of lumber in chambers, based on new drying algorithm and control functions, which are embedded in PLC, characterized by high functionality, easy servicing and low costs. The system ensures fulfilling of all quality requirements of the standards for dried wood materials.

2. MATERIAL AND METODS

2.1. Design of the Control System for Lumber Drying

The control system is based on personally developed drying algorithms, on moisture and temperature measurements of the drying air, and on set-points computation and programmable control. The algorithm along with some logic functions is embedded in specially designed programmable logic controller (PLC), which is used for the automatic control of the convective drying process of lumber.

The controller, shown in Fig. 1, is designed to measure the temperature T and the relative humidity RH of the air in the chamber, to compute the set-point values of T and RH, and to control the whole lumber drying process. The temperature T and the relative humidity RH are measured by a probe, which is produced by the Swiss Firm ROTRONIC. Two miniature sensors are mounted on its tip – one a resistance thermometer Pt-100, and another – a high-temperature capacitive sensor for RH.

Figure 1. *Programmable controller for computation, measurement and automatic control of T and RH, produced by Delta Instrument Ltd. Sofia*

The programmable controller, at the operator's option, can operate in the following three modes:

- Stabilizing control – the operator periodically enters the set-point values for the temperature SP-T and for the relative humidity SP-RH of the air processing medium and the controller keeps the measured variables close to their set-points. This type of control is used in drying rare wood species, absent from the controller menu, or when testing the operation of the actuators of the control system of the drying process;
- Programmable control – after the operator enters data for the wood species, the thickness of the lumber, the initial wood moisture content U_{beg} and the desired final moisture content U_{final}, the controller computes SP-T, SP-RH and the duration L of the separate stages of the drying process according to the drying algorithm, and carries out the automatic control;
- Monitoring control – the controller computes the parameters of the drying process and carries out the entire control of the drying process as a function of the current value for the wood moisture content U_{avg} of the lumber. The values for U_{avg} are received as current signals of 4 ÷ 20 mA from the analog output of a measuring programmable controller, which is not considered in this paper.

The controller computes the values for SP-T and SP-RH and continuously controls the drying process till the desired final moisture content U_{final} is reached, accounting for the current values for U_{avg} and the data entered by the operator that specifies the wood species and the lumber thickness.

The controller in Fig. 1 performs the following functions:

- measurement and visualization of T and RH of the drying agent – the air in the chamber;
- visualization of U_{avg} of the wood;
- calculation of the values of SP-T and SP-RH during the initial (InHTT), intermediate (ImHTT) and final (FHTT) hydro-thermal treatment of wood materials subjected to drying;
- automatic warming up of the drying chamber and the wood materials in it at the beginning of the process without letting inside moistening fluid. Warming up of the chamber continues till a specified temperature in it is reached, thus avoiding the undesired condensation of the moistening fluid on the cold materials and on the chamber walls;
- automatic ON-OFF or PID control of T and RH by continuously comparing the set-points for the controlled variables computed by the controller, and their current measured values. The control of T and RH is accomplished by changing the inflow of heating agent into the chamber, moistening fluid and cool air, and the outflow of humid air from it;
- automatic switching on and reversing the rotation of the fans in the chamber;
- automatic switching off the drying when reaching a specified final value for U_{final} of the lumber, and sound signalization of the end of the drying process.

2.2. Algorithm for Computation of Set-Points SP-T and SP-RH

The algorithm for computation of SP-T and SP-RH is developed and explained in details in (Deliiski 2002, 2008) after a profound analysis of:

- the available literature and Internet data about the recommended and used in practice modes for drying of lumber of various wood species (Nikolov and Videlov 1987, Shubin 1990, Videlov 2003);
- the functional facilities of the existing computer-integrated systems for automatic control of the convective drying process of lumber;
- the long-years research and engineering experience of the authors in this area.

A database in form of a table for the basic mode of drying in the controller software is filled in after entering corresponding password for each wood species. The mode parameters include the basic values for SP-T, SP-RH and L of the various stages of the process of drying as a function of the current value for the wood moisture content U of the lumber (Table 1).

Table 1. *Basic values for: set-point for temperature SP-T_{iB} and for relative humidity SP-RH_{iB} in the chamber; duration of the separate stages ST-L_{iB} at i = 2 ö 9 for each wood species from the controller's database*

Drying stage / **Parameter**	**1** Initial HTT (InHTT)	**2** U>45%	**3** 45≥U >35%	**4** 35≥U >25%	**5** 25≥U >20%	**6** Intermediate HTT (ImHTT)	**7** 20≥U >19%	**8** 19≥U >11%	**9** 11≥U ≥6%	**10** Final HTT (FHTT)
Air Temperature T, °C		T_{2B}	T_{3B}	T_{4B}	T_{5B}		T_{7B}	T_{8B}	T_{9B}	
Relative Humidity of the Air RH, %		RH_{2B}	RH_{3B}	RH_{4B}	RH_{5B}		RH_{7B}	RH_{8B}	RH_{9B}	
Duration of the Drying Stage L, min		L_{2B}= f(U_{beg})	L_{3B}	L_{4B}	L_{5B}		L_{7B}	L_{8B}	L_{9B}	

The initial (InHTT), the intermediate (ImHTT) and the final (FHTT) hydro-thermal treatment of the wood materials comprise separate stages of the process of drying in the algorithm, that correspond to change of U in the ranges, shown in the first line of Table 1.

The controller uses the data from Table 1 as well as the operator's input for the thickness d (in mm) of the drying materials, U_{beg} and U_{final} to compute SP-T, SP-RH and L for the different stages of the drying process, and records them in the so called operational table (Table 2). The operational table contains the values for SP-T and SP-RH, which should be reached by the end of each of the stages, as well as values for SP-L for each stage in case of programmable control.

The controller computes the values for SP-T_{iW}, SP-RH_{iW} and SP-L_{iW} to fill in operational Table 2, considering their corresponding values SP-T_{iB}, SP-RH_{iB} and SP-L_{iB} in the basic Table 1 according to 13 equations, which are given in (Deliiski 2008).

The subscript "i" denotes the number of the column in Table 2 with the values for SP-T, SP-RH and SP-L, $i = 1 \div 10$; T_{beg} is the temperature of the drying medium, which corresponds to the specified value for U_{beg} and from which the drying process starts.

During individualization of each drying regime, the controller carries out linear interpolation of the values for SP-T, SP-RH and SP-L in each two adjacent columns of Table 2. The controller software imposes restrictions on the values for d, U_{final}, U_{beg}, entered by the operator, and offers an option whether to be switched on or not the InHTT in the drying regime. Depending on U_{beg} and U_{final}, the number of the columns in Table 2 can vary from 1 to 10.

Table 3 gives the computed and used by the controller in the practice change in SP-T, SP-RH, SP-L, and EMC during the automatic control of convective drying process of pine lumber with d = 60 mm, U_{beg} = 55%, and U_{final} = 6%. The total duration of the drying process is equal to 377 h.

Table 2. *Operational values for SP-T_{iw}, SP-RH_{iw} and SP-L_{iw} at i = 1 ö 10, computed and used by the controller during the automatic control of the drying of given: wood species, d, U_{beg}, and U_{final}*

Drying stage / **Parameter**	**1** Initial HTT (InHTT)	**2** U>45%	**3** 45≥U >35%	**4** 35≥U >25%	**5** 25≥U >20%	**6** Intermediate HTT (ImHTT)	**7** 20≥U >19%	**8** 19≥U >11%	**9** 11≥U ≥6%	**10** Final HTT (FHTT)
Air Temperature T, °C	T_{1w}= =f(U_{beg})	T_{2w}	T_{3w}	T_{4w}	T_{5w}	T_{6w}= =f(T_{5w})	T_{7w}	T_{8w}	T_{9w}	T_{10w}= =f(U_{final})
Relative Humidity of the Air RH, %	RH_{1w}= f(RH_{2w})	RH_{2w}	RH_{3w}	RH_{4w}	RH_{5w}	RH_{6w}= =f(RH_{5w})	RH_{7w}	RH_{8w}	RH_{9w}	RH_{10w}= =f(RH_{9w})
Duration of the Drying Stage L, min	L_{1w}= =f(d,T_{beg})	L_{2w}= =f(U_{beg})	L_{3w}	L_{4w}	L_{5w}	L_{6w}= =f(d)	L_{7w}	L_{8w}	L_{9w}	L_{10w}=f(d)

Table 3. *Change of the values for SP-T, SP-RH, SP-L, and EMC, computed and used by the controller during the automatic control of the drying of pine lumber with d = 60 mm, U_{beg} =55%, and U_{final} = 6%*

Drying stage / **Parameter**	**1** Initial HTT (InHTT)	**2** U>45%	**3** 45≥U >35%	**4** 35≥U >25%	**5** 25≥U >20%	**6** Intermediate HTT (ImHTT)	**7** 20≥U >19%	**8** 19≥U >11%	**9** 11≥U ≥6%	**10** Final HTT (FHTT)
Air Temperature T, °C	65	60	63	69	73	73	74	79	81	81
Relative Humidity of the Air RH, %	92	82	80	70	57	74	54	33	18	70
Equilibrium Moisture Content (EMC), %	18.0	14.0	13.0	10.0	7.6	10.7	7.1	4.2	2.3	9.1
Duration of the Drying Stage L, min	360	1 680	2 220	3 420	2 640	240	240	5 940	5 460	420
Duration of the Drying Stage L, h	6	28	37	57	44	4	4	99	91	7

3. RESULTS AND DISCUSSION

The equations given in Deliiski (2008), as well as a number of logic conditions, developed on software language C++ and embedded in the controller software, comprise an algorithm for optimized model predictive automatic control (Hadjiski 2003) of the convective drying process of lumber in chambers.

The operation of the algorithm is illustrated by means of an example shown in Fig. 2, where the values for SP-T and SP-RH computed by the controller are given while drying pine lumber with thicknesses d = 32 mm and d = 76 mm. There a low-temperature drying is considered when the heating medium (agent) in the chamber is hot water instead of steam.

In the process of wood drying the controller displays continuously the current values for T, RH, U, SP-T and SP-RH. Optional indication can be requested via the controller's buttons and keys for:

- the wood species of the lumber in the chamber;
- the lumber thickness d;
- the initial wood moisture content U_{beg};
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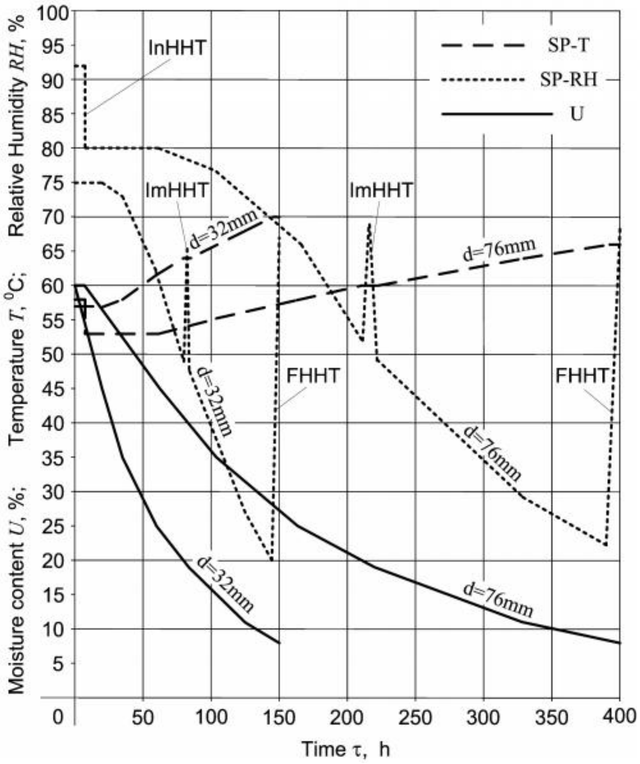

Figure 2. *SP-T and SP-RH profiles as a functions of U and τ while drying pine lumber with d=32 mm and d=76 mm*

- the final wood moisture content U_{final};
- the computed whole duration of the drying process, and also the durations of the separate stages of this process;
- the direction of the rotation of the fans in the chamber;
- the time left till the end of the fans' rotation or before the end of the pause between the turning of the direction of the rotation;
- the time from the start of the process;
- the time left to the end of the process;
- the computed values for all parameters from Table 2;
- the current type of control;
- the current day time and date.

4. CONCLUSIONS

The developed control system is implemented in several plants in Bulgaria. The system proves the effectiveness of the embedded control functions for carrying out the algorithm for the convective drying of lumber of various wood species with different thicknesses and different initial and final moisture content. It carries out automatic convective drying process along with thermal treatment of wood materials according to the requirements of International Standard for Phytosanitary Measures ISPM 15 and with envisaged RS connection to upper level supervisory controller.

This individualization of the drying regimes according to the parameters of each consignment of wood materials ensures optimization of the quality and minimization of the energy costs of the whole process.

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