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STATISTICAL ANALYSIS OF SIMULATED WOOD DRYING SCHEDULES AS REGARDS DRYING TIME REDUCTION IN AN EXPERIMENTAL KILN

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Abstract:
A new configuration of an experimental drying kiln requires tests in what regards the determination of an optimized drying schedule. To draw up the most advantageous drying schedule involves a lot of experimental effort. In order to reduce this effort we have proposed in this paper a statistical method that we have employed to analyze a number of 64 combinations of velocity, dry-bulb temperature and relative humidity, as drying schedule input values, applied to wood drying in an experimental kiln, regarding their influence upon drying time. We used the experimental design, where the experiments were replaced by simulation. The analysis of the data consisted in testing if there are any main effects or two-factor interactions or a three-factor interaction. A conclusion of this analysis is that the low velocity values have less influence upon the drying time, but the temperature has a main effect upon it.

Key words: *laboratory drying kiln; spruce, drying simulation; design of experiments; three-factor experiment.*

INTRODUCTION

Convective drying of wood boards is an important phase of the wood products manufacturing process. The optimization of this process is required to enhance its efficiency, in terms of energy consumption and process time, without the deterioration of the product quality, for example by strong heterogeneous drying or excessive thermal gradient. In this regard the influence of the air flow related parameters (velocity, temperature and relative humidity) on the wood boards is to be investigated. Several papers report investigations from the perspective of the optimization of the drying process, which are mentioned hereinafter. A parametric study provides the first step towards modeling of the drying process in an industrial kiln by investigating the main factors impacting the drying process, such as the influence of air speed, flow temperature, turbulence intensity, drying conditions (Defraeye *et al.* 2012). The drying process modeling presupposes that the velocity and temperature fields develop simultaneously and they cannot be decoupled from the heat and mass transfer. The design optimization of a drying chamber by achieving higher heat and mass transfer rates and a uniform drying consists in the prevention of the development of unfavorable aerodynamic phenomena during the operation of the kiln (Lamnatou *et al.* 2010). Convective heat and mass transfer from porous materials involves transport both in air and porous material, being a conjugate transport problem. In this respect, the air and the porous material properties are of account in the drying process modeling (Defraeye *et al.* 2012). From the previous considerations, the convective wood drying process cannot be separated from the drying agent properties and the relationship between wood properties (species, density, thickness, initial and final moisture content) and air properties (dry-bulb and wet-bulb temperatures, velocity and relative humidity) is specified by the drying schedule. The development of an optimized drying schedule aimed to enhance specific characteristics of the drying quality is the endeavor of drying professionals and a lot of research is dedicated to this issue by using different numerical and experimental analysis methods (Gorvad and Arganbright 1979, Nassif 1983, Carlsson and Esping 1997, Frühwald 2007, Martinović *et al.* 2001, Rämänen *et al.* 2012, Goujot *et al.* 2012).

In order to obtain drying products that involve small drying times and low energy consumption, but also fulfill the desired quality requirements, more research is needed to understand the relationship between drying parameters and drying time.

OBJECTIVES

The aim of this paper was to achieve the most advantageous drying schedule for a laboratory drying kiln from a set of 64 combinations of velocity, dry-bulb temperature and relative humidity, as drying schedule input values, as regards the reduction of the drying time. The study was carried out on a controlled climate air duct with closed circuit, used as an experimental kiln. The full factorial design 3×4 was used to analyze statistically the drying results obtained from simulation.

METHOD, MATERIALS AND EQUIPMENT

Laboratory drying kiln

For laboratory experimental purpose, the industrial wood drying kiln is designed as a controlled air duct (wind tunnel), as indicated by (Molnar 2007). An experimental kiln is installed at the Laboratory of heat and mass transfer of Transilvania University of Brasov that was described exhaustively in (Şova *et al*. 2012). It consists in a controlled climate air duct of rectangular section (145×175mm) with closed circuit, fitted with a rectangular test section (250×300×1500mm) provided with a sealed tight door. One wood sample is placed within the kiln on a device conceived for both sample support and vertical motion and for continuous weighing. The laboratory kiln is the scale model of the full-size industrial drying kiln equipment. By applying the principles of similarity, that establish the conditions under which the laboratory research can be applied to similar, real processes, for both, the industrial kiln and the laboratory kiln, the required air velocity for the test section of the laboratory kiln has been determined for constant air temperature (60^{o}C) and the corresponding velocity in the industrial drying kiln (3m/s). It was obtained a velocity of 0.4m/s, due to the dimensions of the test section which are large, compared to the dimensions of the air flow channel in the drying kiln that was simulated in the wind tunnel (Şova *et al*. 2012).

Drying simulation

We used in the paper the TORKSIM computer program for the drying process simulation (TRATEK 2008). The input data refer to information about timber (species, density, thickness, moisture content etc), air velocity between board layers in kiln stack, time- or moisture content based drying schedule. The resulting output data are, for example, wood moisture content, moisture gradient, wood temperature, drying time, stress development, energy consumption, drying costs (Salin 2007).

Considering the laboratory kiln and the velocity obtained by similarity, the drying schedules were conceived based on fixed parameters: velocity, dry-bulb temperature and relative humidity (Câmpean and Marinescu 2000, Trübswetter 2006). The values used for the drying simulation and the symbol assignments are indicated in Table 1.

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Table 1

Drying schedule parameters

Velocity [m/s]	Dry-bulb temperature [^oC]	Relative humidity [%]
V_1: 0.5	T_1: 50	F_1: 20
V_2: 0.6	T_2: 60	F_2: 25
V_3: 0.7	T_3: 70	F_3: 30
V_4: 0.8	T_4: 80	F_4: 35

The wood sample placed in the laboratory drying kiln has small dimensions: 240×240×20mm, which are appropriate to the cross-section wind tunnel dimensions. In this paper we selected for simulation the properties of a spruce (*Picea Abies*) sample with the thickness of 20mm and initial moisture content of 30%. The drying was conducted at 10% target moisture content. The wood properties remain constant during simulation.

We used in simulation only time based drying schedules and obtained as results for further statistical analysis, the drying time values.

Design of Experiments

The Design of Experiments is a method used to determine simultaneously the individual and interactive effects of a set of factors upon the output results (http://www.home.agilent.com/upload/cmc_upload/All/DesignOfExperimentsTutorial.pdf?&cc=RO&lc=eng).

For the achievement of a drying schedule that can be applied to the laboratory drying kiln, leading to the least drying time, we used the three-factor experiment, in this case the full 3×4 factorial experiment. We designed 64 drying experiments (treatments) by combining three parameters of the drying schedule: velocity, dry-bulb temperature and relative humidity. Since the randomized block design (RBD) is appropriate to our purpose, we grouped the combinations in two blocks (r=2) of the same shape, each of p=64 units. The units of the blocks are the drying time values, being the results of the drying simulation. We used as blocking factors two moisture content values that are in the proximity of the target moisture content (values close to 10%). Within the blocks the variance among units is up to 35h and among blocks it is very small (1h). We assigned randomly the treatments (combinations) to the units of the blocks. Each treatment occurs only once in each block. For this purpose we used a table of random numbers. A separate randomization was used for each block.

The analysis of the resulting data consists in estimating and testing if there are any main effects or two-factor interactions or if there is a three-factor interaction. For this purpose we have firstly constructed block totals, two-way and three-way tables of factor totals, as basis for calculations in the analysis of variance, according to the procedure described by (Petersen1985).

RESULTS AND DISCUSSION

The analysis refers to the influence of the drying schedules parameters upon the drying time. According to the significance tests, the three-factor interaction (V×T×F) is significant at 5% level, meaning that none of the factors acts independently, the two-factor interactions (V×T) and (T×F) are significant at 1% level, the interaction (V×F) is not significant and all of the factors V, T and F have main effects, being significant at 1% level. The most significant factor is the temperature, whereas the least significant is the velocity. The results of the treatments designed to test the effect of velocity, temperature and relative humidity of air on the drying time are summarized in Tables 2, 3 and 4.

In Table 2 it can be seen a slight difference of drying times in respect to the air velocity, the tendency being not clear in what regards uniform increase or decrease. In case of all velocities, the drying times increase with relative humidity increasing and decrease with temperature increasing. The data in Table 3 indicate large differences among drying times with temperature increase, the tendency being to decrease very much. The differences between velocities are not consistent for a certain temperature value.

Regarding Table 4, the data show the tendency of drying time to increase with relative humidity increase, the differences being larger at lower temperatures than at higher temperatures. Again, there is a very obvious tendency of drying times decrease with temperature increase.

A conclusion of this analysis is that the low velocity values do not influence very much the drying time below 30% wood moisture content, but the temperature has a main effect upon it. It can be recommended as the most advantageous time-based drying schedule for the laboratory drying kiln the combination $V_4 \times T_4 \times F_1$ (0.8m/s, 80^{o}C, 20%).

The drying times obtained by simulation are based on the heat and mass transfer equations (Salin 1999). As compared to the simulation method, the drying time can be empirically estimated for both drying

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periods, above and below the fibre saturation point. Trübswetter (2006) indicates for the second drying period, the relation:

$$t_2 = \ln\frac{MC_{FSP}}{EMC}\left(\frac{d}{25}\right)^n f_F\, f_W \left(\frac{150-T_2}{T_2}\right)^{1.5} \frac{3}{DG} f_{HT} \text{ [h]} \qquad (1)$$

MC_{FSP} – fibre saturation point related moisture content, in %
EMC – equilibrium moisture content (target moisture content), in %
d – wood board thickness, in mm
n – exponent depending on the wood thickness,
f_F – correction coefficient depending on wood shape,
f_W – correction coefficient depending on wood type,
T_2 – drying temperature, in ^oC,
DG – drying gradient,
f_{HT} – correction coefficient depending on kiln running time.

Table 2
Mean drying times resulted from 4×4×4 combinations of velocity, temperature and relative humidity values

Velocity	Temperature	Relative humidity			
		F_1	F_2	F_3	F_4
V_1	T_1	29.5	32.5	35.5	39.5
	T_2	19.5	25.5	27.5	30.5
	T_3	16.5	17.5	18.5	20.5
	T_4	11.5	12.5	13.5	14.5
V_2	T_1	33.5	36.5	40.5	44.5
	T_2	22.5	23.5	26.5	28.5
	T_3	15.5	16.5	17.5	19.5
	T_4	10.5	11.5	12.5	13.5
V_3	T_1	32.5	35.5	38.5	43.5
	T_2	21.5	22.5	24.5	27.5
	T_3	14.5	15.5	16.5	12.5
	T_4	10.5	10.5	11.5	12.5
V_4	T_1	31.5	34.5	37.5	41.5
	T_2	20.5	22.5	24.5	26.5
	T_3	13.5	14.5	16.5	17.4
	T_4	9.5	10.5	11.5	12.5

Standard error = 0.4978 (three-factor interaction)

Table 3
Mean drying times resulted from velocity and temperature interaction

Velocity	Temperature			
	T_1	T_2	T_3	T_4
V_1	34.25	25.75	18.25	13
V_2	38.75	25.25	17.25	12
V_3	37.5	24	16.25	11.25
V_4	36.25	23.5	15.5	11
Mean	36.687	24.625	16.812	11.812

Standard error = 0.2489 (two-factor interaction)

Table 4
Mean drying times resulted from temperature and relative humidity interaction

Temperature	Relative humidity			
	F_1	F_2	F_3	F_4
T_1	31.75	34.75	38	42.25
T_2	21	23.5	25.75	28.25
T_3	15	16	17.25	19
T_4	10.5	11.25	12.25	13.25
Mean	19.562	21.375	23.312	25.687

Standard error = 0.2489 (two-factor interaction)

Considering the four temperature values used for the drying simulation of the 20mm thick spruce sample, the correction coefficients estimated at n=1, f_F=1, f_W=19, f_{HT}=1 and the temperature-depending mean drying gradients of 3.845 (50^{o}C), 4.412 (60^{o}C), 5.176 (70^{o}C) and 6.033 (80^{o}C) provided by TORKSIM software, we have calculated the drying times and compared them graphically with those obtained from simulation. The results are shown in Fig. 1 and 2.

Fig. 1 and 2 indicate the correlation of the drying time with temperature for different velocity and relative humidity values, respectively and the comparison with the drying time calculated with relation (1) proposed by Trübswetter, which is not directly depending on velocity and relative humidity values.

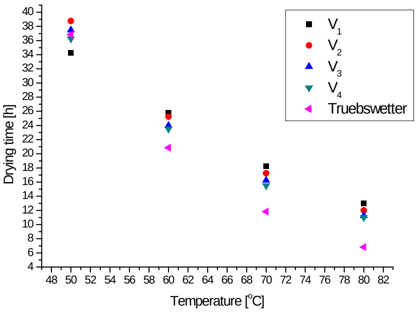

Fig. 1
Mean drying times resulted from velocity and temperature interaction.

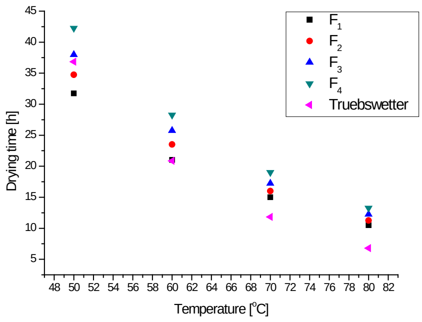

Fig. 2
Mean drying times resulted from temperature and relative humidity interaction.

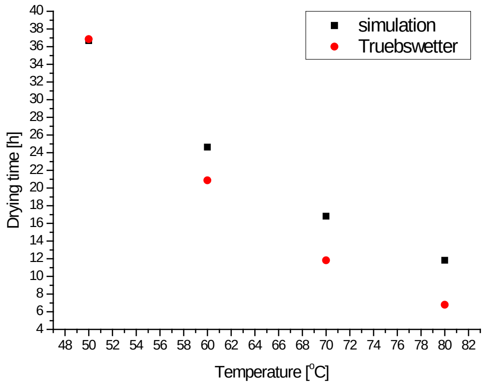

Fig. 3
Mean drying time versus temperature.

The mean drying times resulted from both, velocity and temperature interaction and temperature and relative humidity interaction, are equal at each temperature and they were represented in Fig. 3 comparatively to the drying times resulted from the application of Trübswetter equation. It can be seen a good agreement between the results, especially at lower temperatures. At higher temperatures, the drying times resulted from Trübswetter equation are smaller.

CONCLUSIONS

The methodology we have proposed can give a good reason to be used in case of new experimental drying kilns and/or drying products or exploratory drying processes, when the most advantageous drying schedule must be selected from a number of variants. Since the drying results can be obtained by simulation of a large number of factor combinations and the outcomes processed by using a multifactor experiment, the experimental work can be reduced, the presence and magnitude of factor interactions can be estimated and recommendations over a large variety of conditions can be outlined.

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