EFFECTS OF AIR PARAMETERS ON DRYING TIME AND ENERGY CONSUMPTION

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Abstract. In the present work a numerical simulation model of the convective drying process for a single board sample within an experimental wind tunnel was used. Since it is difficult to obtain the exact solutions of the differential equations of heat and mass transfer applied to the drying process, numerical simulation provides important outcomes for process description. A number of 64 different drying schedules were simulated. They were obtained from the combination of three air parameters, namely temperature (50-80 ^{o}C), velocity (0.5-0.8 m/s) and relative humidity (20-35%). The simulation results were drying time and energy consumption. By using a multiple regression model the relationship between the factor settings and responses was acquired.
Keywords: convective drying; numerical simulation; multiple regression analysis.

1. INTRODUCTION

Wood conventional timber drying is the process in which the heat transfer from the warm air to wood and the mass transfer from wood to air are encountered. This process is one of the most important because it enhances wood mechanical and technological properties and ensures the protection of the wood against insect and fungal attack. The drying process aims at a compromise among high quality, short residence time and low energy usage. Quality and residence time have been usually prioritized before the energy usage [1]. But the wood convective drying efficiency is estimated in all terms: drying time, energy consumption, drying cost and product quality and it depends significantly on the air flow related parameters, like velocity, temperature and relative humidity.

Therefore, one of the main challenges in wood drying is choosing an optimal drying schedule. The optimal drying schedule means the values of temperature, relative humidity and air velocity for which the best quality, shortest drying time and lowest energy consumption are achieved. A numerical simulation can be beneficial in choosing the optimal drying schedule by predicting drying variables, such as final moisture content, very quickly and accurately, without running a kiln. Given sets of predicted output drying variables for different input drying parameters makes it easier to choose the most optimal drying schedule [2].

There are several reports on different simulation models for conventional timber drying, all based on coupled heat and mass transfer equations [3, 4], [5]. A very practical simulation model for a single board conventional drying was developed by Salin [6] which resulted in a computer program. It can be used for drying schedule optimization and process improvement. The model has been verified against many full scale tests.

New or modified drying methods and dryers were also proposed for drying effectiveness improvement in aspects regarding energy saving, drying time shortening and quality of the dried products [7, 8]. Most of simulation models are validated by experiments on full scale driers. But, some of the experiments are carried out on pilot-scale kilns or different laboratory driers, such as tunnel laboratory driers [9, 10], custom-made laboratory kiln [11], experimental electrical oven [8] and climate chamber [12].

Statistical techniques are appropriate methods for the evaluation of different properties on the drying outcomes. On one hand, the multivariate data (principal component regression) analysis is applied to develop a regression model for investigating the wood properties that influence the final moisture content and the measure of this influence [13]. On the other hand, wood characteristics and drying schedule parameters are used as independent variables and a number of drying results (such as defects) as dependent variables in different multivariate regression analyses [8].

The objective of this research was to investigate how temperature, relative humidity and velocity of air in the drying process of spruce, simulated in an experimental kiln, affect the drying time and energy

consumption, two out of the three major factors through which the drying efficiency is measured.

2. MATERIALS AND METHODS

2.1. Drying simulation

A wood drying simulation model is based on Fourier's heat transfer equation (1) and Fick's mass transfer equation (2):

$$\frac{\partial T}{\partial t} = \nabla(\alpha \nabla T) \quad (1)$$

$$\frac{\partial u}{\partial t} = \nabla(D \nabla u) \quad (2)$$

where: T is temperature, t is time, $\alpha$is thermal diffusivity, u is wood moisture content, D is diffusion coefficient, ∇ is the gradient operator.

It is difficult to obtain exact solutions of the differential heat and mass transfer equations applied to the wood drying process, due to many process variables (the thermal diffusivity and diffusion coefficient depend on wood species, three principal directions of heat and mass transfer, moisture content, temperature, external boundary conditions etc.), therefore numerical modeling gives important information about the process. Nowadays models are much based on balance equations for energy and moisture [14] that lead to the analogy between heat and mass transfer:

$$\frac{h}{h_m} = \rho c_p \quad (3)$$

where: h and h_m are transfer coefficients for heat and mass, respectively. But, experimental results indicated a deviation from the analogy; the real mass transfer coefficient is much lower than expected from the analogy [14]. Therefore, a correction factor is included in the drying simulation model, dependent on surface moisture content and temperature [6].

The wood drying simulation model (TORKSIM) we used in the paper [15] has been tested against 28 full scale measurements and the measured and simulated final moisture content resulted in a 1.4% standard deviation [6]. The TORKSIM computer program is based on information regarding wood properties, drying schedule and kiln model and the results consist in drying time, energy consumption and drying costs calculation and quality aspects.

Our simulation input data refer to:

- wood species: spruce (*Picea Abies*)
- board thickness: 20 mm
- wood initial moisture content: 30% (falling rate drying period)
- wood target moisture content: 10%
- drying schedule: the time based drying schedules used in the drying simulation were created on fixed parameters: velocity, dry-bulb temperature and relative humidity of air [16]. The values and the symbol assignments are indicated in Table 1.

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

We designed 64 drying schedules by combining the values of the three parameters: velocity, dry-bulb temperature and relative humidity.

- kiln model: the simulation was carried out for a single board drying in a controlled laboratory tunnel, which is the scale model of the full-size industrial drying kiln equipment. The climatic conditions remained constant throughout the drying simulation.

2.2. Statistical analysis

A preliminary evaluation of the simulation results (drying time and energy consumption) was done with univariate analysis. Temperature, relative humidity and velocity, variable factors of the drying schedules, were plotted against drying time and energy consumption, the responses. The relationships between factor settings and responses were evaluated with the multiple quadratic regression model. All 64 drying schedules were used for drying time and energy consumption evaluation. The responses were approximated by a quadratic polynomial model (response surface modeling design). The regression analysis was applied to estimate the regression coefficients in a model that relates the factors (x_1, x_2, x_3), their interaction (x_1x_2, x_1x_3 and x_2x_3) and quadratic terms (x_1^2, x_2^2 and x_3^2) to a response y. The models for the two responses were calculated individually by using the software MODDE 9.1.1 [17] for construction and analysis of experimental designs and response surface plotting. The software was also used for statistical evaluation of the models.

Quadratic and interaction terms that were not significantly different from zero, with 95% confidence, were excluded from the models.

3. RESULTS AND DISCUSSION

3.1. Univariate analysis

The univariate analysis (Fig. 1) shows that both, drying time and energy consumption decrease with temperature increase. The variation of velocity and relative humidity had a minor influence on drying time and energy consumption. A slight decrease of energy consumption and increase of drying time with relative humidity increase can be observed.

A correlation between drying time and energy consumption was identified, i.e. the energy consumption increases very much at long drying times, where the points dispersion is notable (Fig. 2). For low drying times, the energy consumption is nearly the same.

3.2. Multivariate analysis of drying time

Non-significant model terms were deleted and the regression coefficients showed that temperature and relative humidity were the two dominating factors. Drying time decreased with increasing temperature and decreasing relative humidity (Fig. 3).

The influence of velocity and factors interaction were significant but of minor importance. The model accuracy was appreciated by the high R^2 and Q^2 values, 0.99 and 0.985, respectively (Table 2).

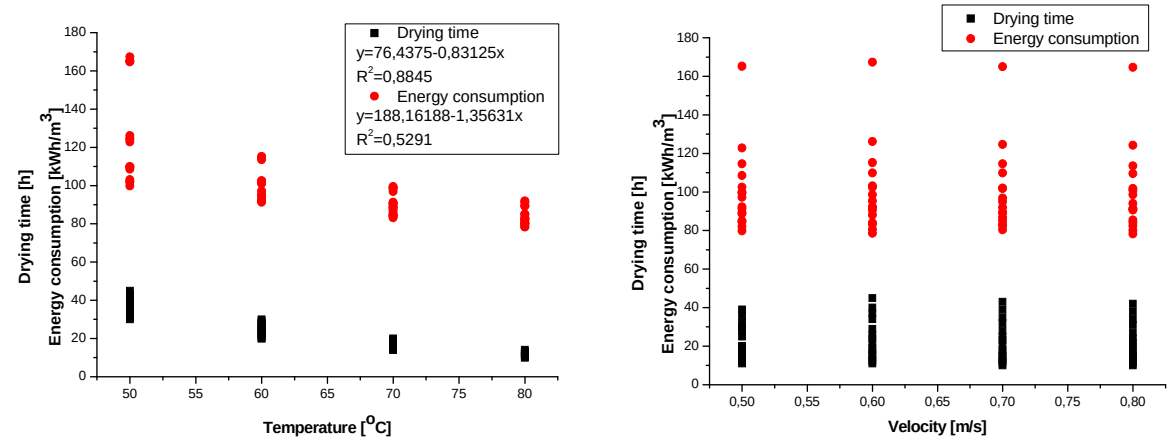


Fig. 1. Influence of temperature, velocity and relative humidity on drying time and energy consumption.

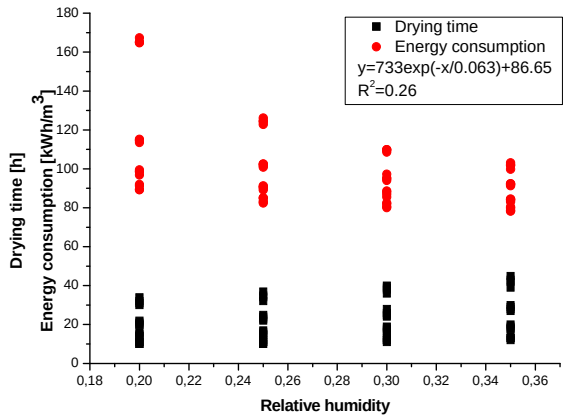
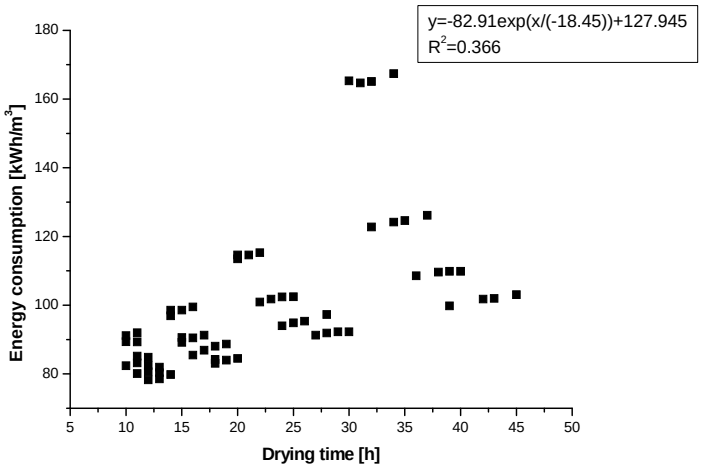


Fig. 2. Correlation between drying time and energy consumption.



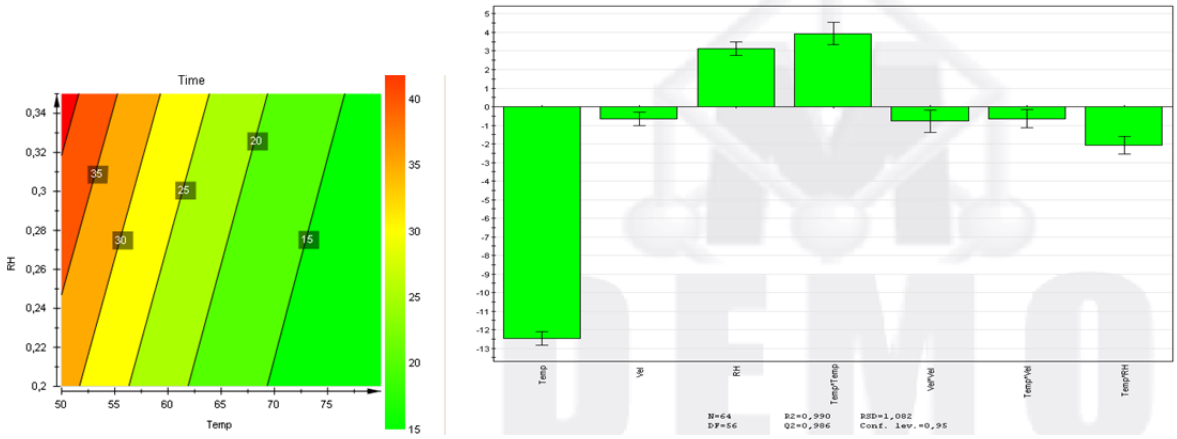


Fig. 3. Response surface plot for drying time (boxed figures, hours) at different temperature and relative humidity values at 0.65m/s velocity (left) and regression coefficients with 95% confidence interval (right).

Table 2.

Regression modeling statistics

Response	Constant	Temp	Vel	RH	$Temp^2$	Vel^2	RH^2	Temp×Vel	Temp×RH	R^2	Q^2
Drying time	20.49	–12.47	–0.65	3.11	3.94	–0.77	ns	–0.64	–2.07	0.99	0.985
Energy consumption	90.54	–20.34	ns	–13.63	10.18	ns	7.27	ns	12.14	0.943	0.903

ns – not significant.

3.3. Multivariate analysis of energy consumption

The multiple regression analysis of energy consumption resulted in a similar model to that of drying time, with a good fit according to the regression coefficients (Fig. 4). Thus, the energy consumption decreased with increasing temperature and relative humidity. Again, the temperature and relative humidity had important influence. Of importance were also the quadratic terms and the factors interaction.

Both models were validated by high R^2 values and they had good predictive capabilities according to cross validation (high Q^2 values), (Table 2). Most of the responses could be explained, but an unexpected result was the minor influence of velocity. The influence of the velocity was significant only for the drying time, even if its contribution was unimportant (Figs. 3 and 4). A reason for the result could be the low velocity values which were adopted according to the similarity conditions applied to the laboratory kiln. The test section of the laboratory kiln is larger than the air flow channel from the industrial kiln that was simulated in the wind tunnel.

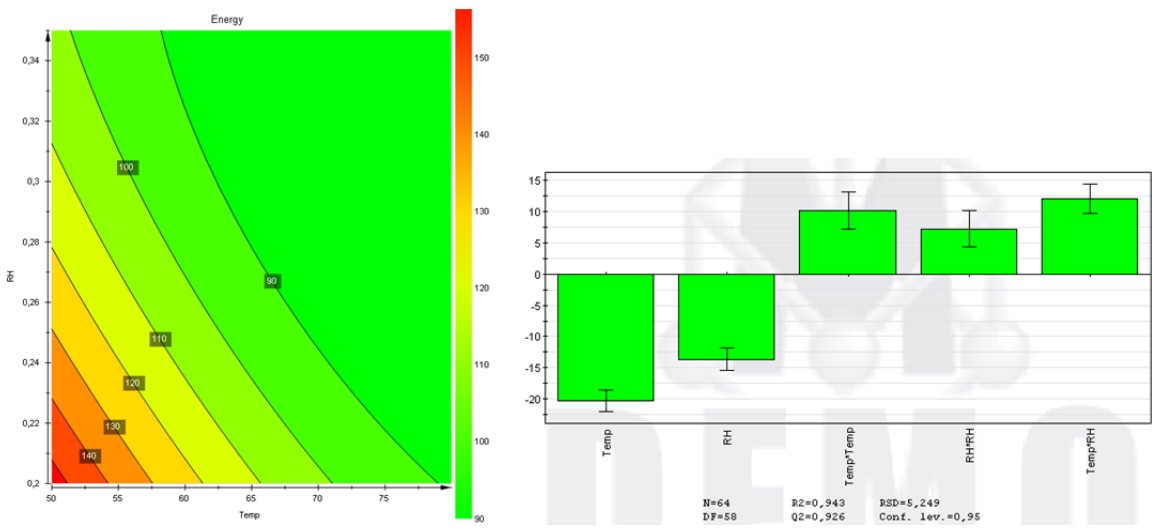


Fig. 4. Response surface plot for energy consumption (boxed figures, kW/m^3) at different temperature and relative humidity values at 0.65m/s velocity (left) and regression coefficients with 95% confidence interval (right).

The results shown in Figs. 1, 3 and 4 raised an important question: should the drying process be run at high or low relative humidity? Both univariate and multivariate analyses show, especially at low temperature values, a different behaviour of drying time and energy consumption when the relative humidity increases (the regression coefficients of the relative humidity factor in the two models are positive and negative, respectively). It can be observed that at higher temperatures than 65°C, the drying time and energy consumption are low, regardless the relative humidity values. Since, both drying time and energy consumption decrease with temperature increase, the drying should be run at high temperature and lower relative humidity, considering also the falling rate drying period. In this manner, the wood drying quality would not be negatively influenced.

4. CONCLUSIONS

In the present study, within the range of variables we have used, the following conclusions can be drawn:

1. Drying time (10-50 h) and energy consumption (80-170 kWh/m^3) were obtained by wood drying simulation with 64 different drying schedules. The results accuracy is high since the model was validated by many full scale tests.
2. Drying schedule parameters are correlated and their interaction influence drying time and energy consumption.
3. High temperature is the most important variable to decrease drying time and energy consumption.
4. At high temperature (above 65°C), the relative humidity can take any value, without increasing drying time and energy consumption. But, high temperature and low relative humidity can assure during the falling rate drying period a good wood drying quality.
5. The low velocity values have minor importance on drying time and energy consumption.
6. A correlation was found between drying time and energy consumption.
7. The precision of the quadratic regression models (response surface modeling design) was proved by high R^2 and Q^2 values.

The study presented the importance of the main parameters of the drying agent in a limited range. It doesn't cover all possible variations in the wood sample and the process. In future research, the results obtained on the experimental drying kiln should be compared with those obtained on the actual kiln. The study can be extended furthermore with a multivariate analysis of the stress development inside the wood board during drying. In this way all aspects of drying efficiency would be covered.

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