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THE INFLUENCE OF FAN SPEED REDUCTION ON AIRFLOW UNIFORMITY IN TIMBER STACK DURING KILN DRYING

Jerzy Majka
Poznań University of Life Sciences, Faculty of Wood Technology
Poznań, Poland

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ABSTRACT

The relation between fan speed reduction and airflow uniformity in a stack during kiln drying of timber was established. The results obtained from selected drying quality parameters support the hypothesis on the negative influence of excessive fan speed reduction as related to the decrease of air velocity spread, but also causes an increased differentiation of drying conditions in the stack. It is primarily due to air velocity reduction below the level ensuring the required drying conditions. The results of the performed analyses may be used to develop principles of fan speed reduction which account for a uniform airflow in the stack for a given option of fan speed.

KEYWORDS: Air velocity spread, drying quality, frequency inverter.

INTRODUCTION

The need for air velocity control during timber convective drying results, among other things, from a reduction of electricity consumption used for driving fans as well as the requirements of uniform drying of wood with an acceptable intensity providing high quality of the product, i.e. dry timber. Air velocity influences timber drying intensity only in the initial stage of drying, i.e. when the moisture content decrease above the fiber saturation point (Nakajima et al. 1990, Simpson 1997). An acceptable intensity of drying during the initial stage may be locally exceeded due to the spread of air velocity in a kiln. The timber drying process with an acceptable intensity is limited to the stack zones, which are characterized by the required air velocity. Therefore, not only a reduction of air velocity, but also the limitation of air velocity spread in the initial stage of drying are factors guaranteeing the proper drying intensity and increasing drying uniformity, as well as providing optimum conditions of water evaporation from the wood surface. Air velocity control in timber kiln dryers is possible due to the reduction of fan speed by a frequency inverter.

Investigations on the application of frequency inverters for air velocity control in timber kiln dryers focused primarily on optimization of electricity consumption for fans. It was found that a reduction of frequency of electricity from 50 to 20 Hz is proportional to air velocity flowing through the stack (Nakajima et al. 1990). It was also observed that electricity consumption was reduced from 40 to 60 % for drying processes starting from the green state to the final moisture content of 10 %. Riley and Haslett (1996) showed that the air velocity reduction in the final stage of radiate pine drying caused the decrease of electricity consumption of 67 %. The other effect of air velocity reduction in the final stage of drying is the reduction of steam consumption used for controlling the required relative humidity of air (Haufa el al. 1987, Salin 2004). There is practically no information on the possible use of fan speed control in improving airflow through the stack in order to enhance airflow uniformity. According to Nakajima et al. (1990), the reduction of fan speed improves the characteristics of airflow through the stack and uniformity of timber drying. It was stated on the basis the increase of statistical parameters of airflow uniformity (i.e. air velocity spread and the coefficient of variation COV). The increase in values of these parameters was found for the reduction of fan speed. The observations of Nakajima et al. (1990) may be confirmed by later investigations by Majka et al. (2005). It was found that a reduction of fan speed to 75 and 50 % of the nominal value caused a reduction in the variation of the final moisture content of oak and pine timber. However, the reduction of fan speed was applied only in the final stage of drying.

In earlier studies the problem of airflow uniformity was not considered as a criterion in the reduction of fan speed. The main goal of fan speed control is reduction air velocity in the stack. An additional effect of air velocity reduction is the decrease of air velocity spread (Majka et al. 2005). However, there is no information on the other consequences of fan speed reduction, i.e. a possible influence on airflow uniformity as well as the rate of evaporation, especially in the initial drying phase. Moreover, under some conditions air velocity reduction below some critical level may even cause an increased variation of drying conditions (e.g. in some hardwood species). Variation of drying conditions may be estimated with the assumption that actual air drying parameters (temperature, relative humidity) depend on airflow uniformity in the stack. Airflow non-uniformity is also responsible for two different drying zones in the stack. The first zone corresponds to air parameters consistent with the drying schedule (it is observed for the zones of the stack, in which air velocity is required by the assumptions). The other zone corresponds to air parameters not consistent with the assumed values. As it was already shown by Nakajima et al. (1990), the estimation of drying conditions with statistical parameters of airflow uniformity may lead to false conclusions. In the case of low air velocity in the stack the estimation of airflow in a kiln using statistical parameters is not complete. Therefore, it significantly limits a reliable analysis of the control of fan speed in context of airflow uniformity and quality of timber drying especially in the initial phase of drying in some hardwood species. The objective of the study was to determine the relation between air velocity in a stack and fan speed and to identify the effect of air velocity spread and drying conditions in a stack on selected estimators of drying quality. An additional objective was to determine rules of fan speed control with the use of a frequency inverter.

MATERIAL AND METHODS

The investigations of airflow through the stack were made in a single tracked batch kiln (Fig. 1). Airflow was forced by two fans. The power of each fan was 1.5 kW. The total output of fans was 20000 $m^3.h^{-1}$ for the nominal speed (NS) of 1405 rpm. The kiln had a system consisting of a microprocessor controlled range frequency inverter (Siemens MICROMASTER 420) to control the speed of three phase AC motors of fans. The system was used to change fan speed and measure electricity consumption with an internal energy consumption meter during the operation of fans. The stack consisted of 1800 green oak wood strips (the initial moisture content was about 60 %). The dimensions of the strip were 500 x 90 x 30 mm, corresponding to length, width and thickness, respectively. The strips were placed on stickers of 20 mm in thickness. The total dimensions of the stack were 3000 x 1200 x 1300 mm in length, width and height, respectively (Fig. 1).

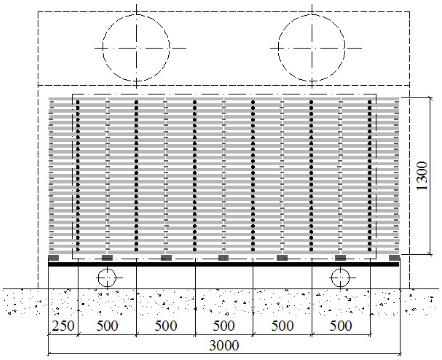

Fig. 1: Vertical cross-section through a single tracked batch kiln (black dots – air velocity measurement positions in outlet face of the stack, dash-dot line – boundary of the measurement plane).

Oak timber was selected, as it is a hard-to-dry species especially in the initial phase of drying. In that phase oak timber requires mild drying conditions, as well as a uniform and reduced airflow through the stack. The requirements may be satisfied when fan speed is reduced. The range of fan speed reduction was determined taking into account:

a) results of previous investigations by Widłak (2001) – the practical range of fan speed reduction was limited to 30 % nominal value,

b) the requirement of uniform airflow with a reduced air velocity in the oak timber stack.

In order to perform a detailed analysis of airflow in the stack 12 options of fan speed were selected (Tab. 1).

Tab. 1: Selected fan speed percentage of the nominal value corresponding electricity frequency.

Fan speed (%)	90	80	70	60	54	50	46	42	38	34	30	26
Electricity frequency (Hz)	45	40	35	30	27	25	23	21	19	17	15	13

In order to characterize airflow through the stack air velocity measurements were taken in 156 locations in the plane perpendicular to the flow direction in the outlet face of the stack. The measurements were made for the selected fan speed levels (Tab. 1). Air velocity was measured with a MPA 10 microprocessor controlled hot wire anemometer. The anemometer compensated for changes in the temperature and pressure of ambient air. The anemometer sensor was placed in each fillet space between stacked strips. The measurement position was always in the middle between two stickers. Velocity was measured before the onset of the drying process immediately after the kiln had been loaded. The temperature during the measurements was ca 20°C. The door and vents of the kiln were closed during the measurements.

Average air velocity through the stack for selected fan speeds was supplemented by airflow uniformity indexes, i.e. air velocity spread and the coefficient of variation (COV). Different drying conditions were estimated with the assumption that actual air drying parameters (temperature, relative humidity) depend on airflow uniformity in the stack. Airflow non-uniformity is also responsible for two different drying zones in the stack. The zones correspond to a) air parameters consistent with the drying schedule (it is observed for the zones of the stack, in which air velocity is the same as that required by the assumptions), and b) air parameters not consistent with the assumed values. Therefore, the total flow area can be determined as follows:

$$A = \sum A_a + \sum A_b + \sum A_c \qquad (\mathrm{m}^2)$$

where: A_a – the zone with a too slow air velocity range,
A_b – the zone with the required air velocity range,
A_c – the zone with a too fast air velocity range.

Airflow uniformity through the stack was measured by the proportion of the zone with air velocity required during kiln drying of oak timber. For that purpose the measurement plane was defined in the outlet face of stack. The boundary of the plane was established by the extreme positions of air velocity measurements (Fig. 1). The measurement plane was 3.25 m^2, which is 85 % of the total area of the stack. Additionally airflow uniformity in the measurement plane was illustrated by 2D contour plots. The plots were constructed with the collected air velocity measurements and its positions in the boundary of the plane. The contour plots are presented for 3 ranges of air velocity;

a) $v < 1.0\ \mathrm{m.s^{-1}}$- too slow air velocity range,
b) $1.0 < v < 2.0\ \mathrm{m.s^{-1}}$- required air velocity range,
c) $v > 2.0\ \mathrm{m.s^{-1}}$- too fast air velocity range.

The limits of the velocity ranges were determined according to the following criteria:

a) in case of air velocity below 1.0 $\mathrm{m.s^{-1}}$ turbulent flow between timber layers, indispensable for proper heat and mass transfer during convective drying (Salin 1996), may not be provided,
b) in the case of hard-to-dry wood species (e.g. oak) air velocity should not exceed 2.0 $\mathrm{m.s^{-1}}$ (Die Schnittholztrocknung 1987, Denig et al. 2000),
c) air velocity above 2.0 $\mathrm{m.s^{-1}}$ may result in exceeding the acceptable limit of intensity, which may cause a deterioration of drying quality especially in the initial phase of drying, i.e. for moisture content above the fiber saturation point.

Each 2D contour plot was converted into a bitmap in order to calculate contents of the zones defined by equation. Contents made it possible to determine airflow uniformity for different options of fan speed. The content of the zones of the required velocity range of 1.0-2.0 $\mathrm{m.s^{-1}}$ was assumed as a basic measure of airflow uniformity.

The obtained contour plots were used to select the optimal option of fan speed, for which air velocity was within the range of 1.0-2.0 $\mathrm{m.s^{-1}}$, as well as to find the highest airflow uniformity. The optimum option of the fan speed was applied in the whole drying process. The drying schedule used in drying is presented in Tab. 2.

Tab. 2: Drying schedule of 30 mm oak timber (Cividini 2000).

Phase of drying	Moisture content MC (%)	Dry-bulb temperature t (°C)	Wet-bulb depression Δt (K)	Equilibrium moisture content EMC (%)
Heating	>40	40	2	18
Drying*	>40	40	2	18
	40-20	40...45	2...7	18...10.5
	20-6	45...65	8...24	10...4
Equalizing	-	60	20	5
Conditioning	-	60	20	9

*Target moisture content 6 %

In order to determine the relation between air velocity in the stack and non-uniformity of drying conditions in the stack, drying quality was estimated using the variation of moisture content and moisture gradient in the timber cross-section. Moisture content of timber after drying was determined using the oven-dry method (according to EN 13183-1, 2004). The material for determining the final moisture content was sampled after conditioning and cooling of the kiln. The samples were taken from those zones of the stack, in which different air velocities were observed.

RESULTS AND DISCUSSION

Electricity consumption by fans as depending on fan speed is presented in Fig. 2. The results of air velocity measurements are shown in Fig. 3. The obtained results confirm the earlier observations of Widłak (2001), who found a linear relation between mean air velocity in the stack and the reduction of fan speed. The linear relation was approximated in the present study and shown in Fig. 3. Statistical parameters of airflow are presented in Tab. 3. The performed analysis of the obtained parameters showed that the reduction of fan speed is accompanied by a reduction of air velocity spread in the stack. Such a relationship was not reported and quantified in ealier studies on airflow in batch kilns for timber drying. It was found that the ratio of the lowest and highest values of fan speed was 0.289. It was also found that the ratio of average air velocities for the lowest and the highest fan speed was 0.294 and it was nearly identical to the ratio of the spread of air velocity, which was 0.291.

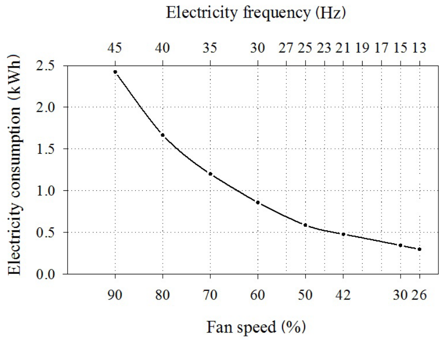

Fig. 2: Electricity consumption depending on fan speed percentage of the nominal value.

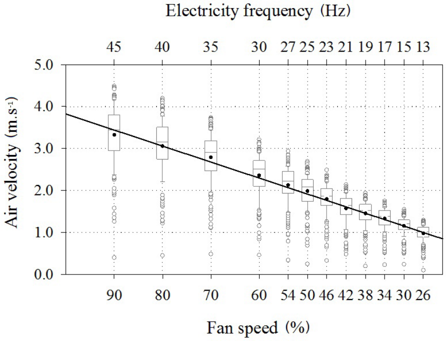

Fig. 3: Average air velocity (black circles) and air velocity spread (whisker plot) in the outlet face in the stack depending on fan speed percentage of the nominal value.

Tab. 3: Description statistics of the airflow in outlet face of the stack as well as contents of zones with air velocity ranges.

Fan speed	**Air velocity (m.s^{-1})**			**Air velocity spread. (m.s^{-1})**	**SD**	**COV**	**Contents of zones with air velocity ranges (%)**		
(%)	**Min**	**Average**	**Max**			**(%)**	**< 1.0 m.s^{-1} (too slow)**	**1.0-2.0 m.s^{-1} (required)**	**> 2.0 m.s^{-1} (too fast)**
90	0.40	3.33	4.49	4.09	0.71	21.3	-	3.53	96.46
80	0.45	3.06	4.20	3.75	0.68	22.1	-	8.38	91.62
70	0.48	2.79	3.74	3.26	0.60	21.6	-	10.63	89.37
60	0.46	2.36	3.21	2.75	0.53	22.5	0.37	18.86	80.77
54	0.34	2.13	2.94	2.60	0.45	21.2	0.41	24.20	75.39
50	0.25	1.98	2.69	2.44	0.42	20.9	1.11	33.48	65.41
46	0.33	1.79	2.49	2.16	0.38	21.2	3.56	63.95	32.49
42	0.48	1.57	2.14	1.66	0.34	21.8	7.99	91.74	0.27
38	0.20	1.45	1.94	1.74	0.30	20.9	8.61	91.39	-
34	0.23	1.33	1.75	1.52	0.27	20.4	11.06	88.94	-
30	0.24	1.15	1.55	1.31	0.22	18.8	16.59	83.41	-
26	0.10	0.98	1.29	1.19	0.19	19.7	39.94	60.06	-

SD – standard deviation, COV – coefficient of variation (100*SD/Average)

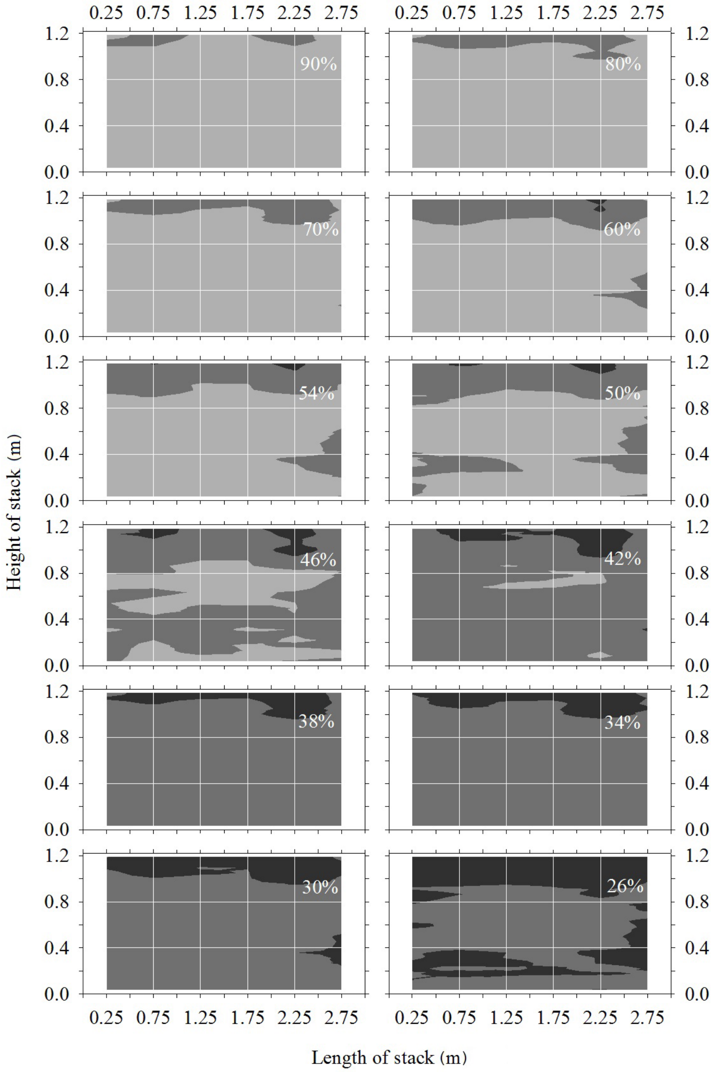

Fig. 4: Airflow uniformity for selected fan speed percentage of the nominal value (black area - air velocity below 1.0 m.s^{-1}, dark gray area – air velocity in range 1.0-2.0 m.s^{-1}, light gray area – air velocity above 2.0 m.s^{-1} .

The observation of air velocity spread showed that the reduction of fan speed may favorably influence airflow uniformity and equalize drying conditions. However, similar values of the coefficient of variation (COV) presented in Tab. 3 may suggest that airflow uniformity does not depend on fan speed. The inconsistency of these observations forced us to conclude that the estimation of airflow uniformity cannot be based on statistical parameters of air velocity spread only. Therefore, the results of air velocity measurements and positions of measurements were

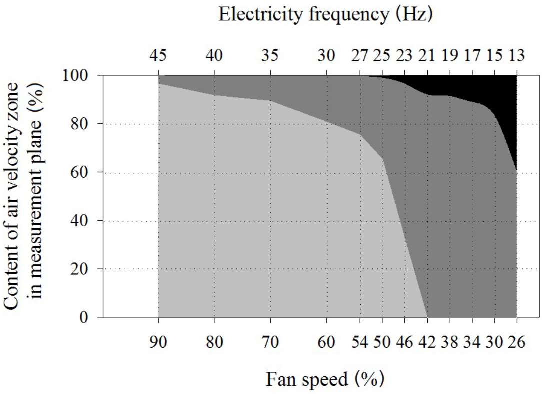

Fig. 5: Contents of air velocity zones in the outlet face of the stack depending on fan speed percentage of the nominal value (black area - air velocity below 1.0 m.s^{-1}*, dark gray area - air velocity in range 1.0-2.0 m.s*$^{-1}$*, light gray area - air velocity above 2.0 m.s*$^{-1}$*).*

used to construct 2D contour plots (Fig. 4). The contour plots were used to illustrate air velocity spread in the stack. A simple comparison of the 2D contour plots shows that airflow through the stack is characterized by diversified zones of velocity and thus diversified drying conditions. The contour plots also show a dislocation of the zones and the change in their content as a function of fan speed. Tab. 3 shows the results of the digital analysis of the contour plots, i.e. the contents of air velocity zones. The reduction of fan speed caused changes in the contents of zones of the required air velocity, which was assumed as a basic parameter of airflow uniformity (Tab. 3). However, such defined airflow uniformity depends on fan speed in a more complex way than it could be shown by the statistical analysis of air velocity measurements. It was found that for each fan speed option higher than 50 % nominal value airflow was not recognized as acceptable. For the highest value of fan speed (90 % of the nominal value) only 3.5 % of the total measurement plane indicated the required range of air velocity (Fig. 5). Airflow in the stack could be considered as uniform when fan speed was reduced to 46 % of the nominal value. In that case the zone of the required air velocity range was 64.0 % of the total plane of measurements. However, as much as 32.5 % of the total measurement plane still indicated air velocity exceeding the acceptable range. The best uniformity of airflow (the content of the zone of the required air velocity range as high as 91.7 %) was obtained after the reduction of fan speed amounting to 38 % of the nominal value. A further reduction of fan speed resulted in decrease of velocity spread (Tab. 3) and electricity consumption for driving fans (Fig. 2). However, the content of zones in which air velocity was below 1.0 m.s^{-1} was observed to increase, i.e. drying conditions were incorrect. For the lowest fan speed investigated in the present study the content of the zone with air velocity below 1.0 m.s^{-1} was almost 40 % of the total measurement plane (Fig. 5).

The obtained results of wood moisture content after drying showed that oak strips located in the stack zone with air velocity below 1.0 m.s^{-1} (i.e. the zone with an insufficient drying intensity) were characterized by too high final moisture content. Moreover, the variation of final moisture content was twice the variation observed for oak strips from the zone with the required air velocity (Tab. 4).

Tab. 4: Final moisture content of oak strips located in two different air velocity zones in the stack (according to EN 13183-1, 2004).

Air velocity zone	**Number of replications**	**Moisture content MC (%)**			**Moisture content variation**	**SD**	**COV (%)**
		Min	**Average**	**Max**			
< 1.0 (too slow)	24	6.5	8.8	16.9	10.4	2.39	27.0
1.0-2.0 (required)	48	6.2	7.6	11.1	4.9	1.02	13.4

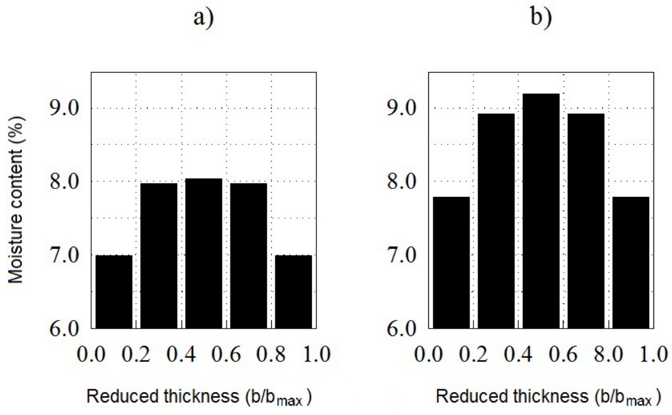

Fig. 6: Moisture content gradient after drying on cross-sections of oak strips located in a) stack zone with the required air velocity range (1.0-2.0 m.s^{-1}) and b) stack zone with to slow air velocity range(below 1.0 m.s^{-1}) range (below 1.0 m.s^{-1}).

The observed moisture content gradient at the cross-section was higher for strips located in the zone with an insufficient drying intensity (Fig. 6b). The performed estimation of drying quality confirmed the hypothesis on the negative influence of fan speed reduction on the uniformity of drying conditions in the stack.

CONCLUSIONS

1. It was observed that mean air velocity and air velocity spread decreased with a linear reduction of fan speed and/or electricity frequency.
2. The digital analysis of the contour plots showed that airflow through the stack is characterized by the formation of zones with different air velocities. The reduction of fan speed caused dislocations of the zones and changes in the zone contents. Therefore, the uniformity of airflow in the stack depends on fan speed.
3. The obtained results of selected drying quality parameters support the hypothesis on the negative influence of an excessive reduction of fan speed as related to the reduction of air velocity spread, but also causing an increase in the differentiation of drying conditions in the stack. It is primarily due to the air velocity reduction below the level ensuring the required drying conditions.

4. Statistical estimators of air velocity spread have limitations in the evaluation of the differentiation in drying conditions within the stack.
5. The contour plots may significantly improve the analysis of airflow in the stack and supplement the statistical estimation of air velocity measurements.

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JERZY MAJKA
POZNAŃ UNIVERSITY OF LIFE SCIENCES
FACULTY OF WOOD TECHNOLOGY
WOJSKA POLSKIEGO 28
60-637 POZNAŃ
POLAND
Corresponding author: jmajka@au.poznan.pl