Climate control in vacuum dryers for convective heat transfer

Part 1: Demands on climate control

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Abstract The European Drying Group (EDG) proposal on a wood drying quality standard defines demands on final moisture content variation of the dried wood. The final moisture content variation will depend on material parameters as well as the production process and the wood will always show a “natural” moisture content variation after drying. Thus the drying process has to be defined well enough to allow for the natural moisture content variation in order to fulfil the demands of the drying standards. As the average equilibrium moisture content of the wood in a vacuum drying kiln with pure steam atmosphere is determined by the pressure and the temperature, the demands on the climate control system to fulfil the demands of the drying standard can be calculated with regard to the natural moisture content variation of the wood. In the first part of this contribution the demands on climate control in vacuum dryers are calculated based on the EDG-standard and the natural moisture content variation. In the second part of the contribution the demands on climate control are compared with climate and moisture content measurements from industrial production in vacuum kilns. Critical factors in kiln design and climate control system design necessary to maintain a controlled drying climate are listed.

Climate control to reach a defined final moisture content

A well controlled drying climate throughout the wood batch is crucial in order to minimise drying defects at the same time as maintaining a high drying capacity. Variations in drying climate within the kiln will lead to corresponding variations in the resulting drying quality as well as an increased final Moisture Content (MC) variation.

As the vulnerability to degrade during drying depends on several factors such as wood species, dimension, moisture content and treatment prior to drying, the demands on climate control in order to avoid drying defects can vary considerably between kilns at different production facilities. However, the demands on climate control in order to reach a well defined final MC will be less variable as this will be

Received 20 April 2000

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dependent on the connection between the climate and the Equilibrium Moisture Content (EMC) for the wood species to be dried together with the natural MC variation. A drying kiln that should deliver wood of a certain wood species with a well defined MC must be able to maintain the climate within certain limits independently of the characteristics of the production facility, as will be shown below.

The demands on climate control in a drying kiln can thus be defined by the demands on final MC variation of a certain species.

Demands on final wood moisture content variation

The European Drying Group (EDG) recommendation of 1994 defines three quality classes; Standard (S), Quality (Q) and Exclusive (E). Table 1 shows the allowable MC variation in the three proposed quality classes [Welling 1996].

Regarding the wood batch as an unlimited number of wood pieces, the MC limits above can be used to calculate the corresponding maximum allowed standard deviation of the MC. With the average MC exactly on the target MC, 90% of the wood pieces will be within ± 1.64 MC standard deviation. The maximum allowed standard deviation will accordingly in the E class be $s = 1.0/1.64 = 0.6\%$ at 10% target MC and $s = 1.8/1.64 = 1.1\%$ at 18% target MC.

Natural moisture content variation of wood

Wood will always show a MC variation even after prolonged storage in a fixed climate. This “natural” MC variation varies with species and is dependent on several material parameters such as chemical composition, structure and density [Chafe 1991]. The natural MC variation increases with the average MC level. See Table 2.

Although each of the values in Table 2 represents a fairly limited number of wood pieces measured at a single or a few separate occasions, the values above indicate the approximate level of the natural moisture variation of the wood species.

The values of Scots Pine are chosen to calculate the natural MC variation at different MC levels in the following sections of the article, expressed as the standard deviation:

$$s_{\text{natural}} = 0.033 \cdot MC_{\text{average}}$$

(1)

Possible drying climates and corresponding EMC

The theoretically possible drying climates of a vacuum kiln are defined by the saturation curve as the steam pressure can never increase above the saturation pressure. In addition to this there are technical and practical limits presented by

Table 1. Allowable MC variation according to the 1994 EDG-proposal. $MC_{1/3}$ refers to MC measured by means of resistance at 1/3 of the wood thickness. [Welling 1996]

Drying	90% of all $MC_{1/3}$ readings must be within the limits	Allowable range of $MC_{1/3}$ if MC_{target} is:		
		10%	14%	18%
S (standard)	$MC_{\text{targ}} \pm MC_{\text{targ}} \times 0.3$	7.0–13.0	9.8–18.2	12.6–23.4
Q (quality)	$MC_{\text{targ}} \pm MC_{\text{targ}} \times 0.2$	8.0–12.0	11.2–16.8	14.4–21.6
E (exclusive)	$MC_{\text{targ}} \pm MC_{\text{targ}} \times 0.1$	9.0–11.0	12.6–15.4	16.2–19.8

Table 2. Natural MC variation of four wood species

Wood species	Standard deviation at approximate MC-level					Source
	4%	6%	10%	12%	18%	
Norwegian Spruce (<i>Picea Abies</i>)	–	0.1	–	0.2	0.3	[Esping 1992]
Scots Pine (<i>Pinus Silvestris</i>)	–	0.2	–	0.4	0.6	[Esping 1992]
Oak (<i>Quercus</i> Robur)	–	0.3	–	–	–	[Jönsson 1998]
Tasm. Mountain Ash (<i>Eucalyptus</i> Regnans)	0.3	–	0.4	–	0.6	[Calculated from Chafe 1991]

the vacuum kiln design and the drying process. The fan motors usually limit the maximum temperature to 80°C. The low density and resulting low heat capacity of the steam at low pressures makes it impractical to dry wood at extremely low pressures. Although pressures below 5 kPa are used during the prevacuum phase, few kilns are operated at absolute pressures below 10 kPa during the drying phase. This sets the limits for the drying climates that normally can be used, as shown in Fig. 1.

The relative humidity or relative vapour pressure is defined by the ratio between the partial steam pressure and the saturation pressure of the steam. In a vacuum dryer with a pure steam atmosphere, the partial steam pressure is equal to the absolute pressure. Thus the relative vapour pressure of the steam is determined by the absolute pressure and the temperature.

As the saturation pressure increases with temperature, the relative pressure will decrease if the temperature is raised at a fixed pressure. Figure 2 shows relative pressures within the pressure and temperature ranges that normally are used in a vacuum drying kiln.

Fig. 1. Theoretically possible and normally used drying climates in a vacuum kiln

Fig. 2. Relative steam pressure at various temperatures and absolute pressures in pure steam. Drying climates normally not available dotted. Calculated from Steam Tables [Grigull et al. 1990]

Effect of temperature changes on EMC

The EMC of wood depends mainly on the relative humidity and the temperature. In a vacuum kiln, an increase of the temperature at a fixed pressure will lead to a decrease of the EMC in two ways:

- 1) a decrease of the EMC due to the reduced relative vapour pressure as shown above as well as
- 2) a decrease of the EMC due to the increased temperature at that specific relative pressure.

Due to this combined effect even a small change in temperature will lead to significant changes in EMC in the temperature and pressure ranges present in vacuum kilns.

EMC values of Sitka Spruce at different temperatures and relative humidities from [Esping 1992] are used in the following to calculate EMC- values at various climates. The relative vapour pressure at various pressures and temperatures have been calculated from Steam Tables [Grigull et al 1990]. A curve fit of the EMC values to the temperature at each different pressure have been made by means of Matlab in the form of:

$$EMC = a - b \cdot e^{\left(\frac{c}{d \cdot \text{Temperature}}\right)} \quad (2)$$

The components a, b, c and d above are purely based on the curve fit and do not represent any specific physical properties. The calculated EMC values at various pressures and temperatures are shown in Fig. 3.

The figure above clearly illustrates that the temperature control of the drying climate is crucial in order to maintain a controlled EMC. This will be the case especially at higher target MC levels and higher pressure levels where even a very small change in temperature will lead to great changes in EMC. The effect of

Fig. 3. The influence of temperature variations on EMC of Sitka Spruce in pure steam calculated at fixed absolute pressures. EMC values outside of normal drying climates dotted

temperature variations is significant also at lower MC levels, at a fixed pressure of 20 kPa and a temperature increase from 64°C to 66°C the EMC would drop 3%.

Without a strict temperature control, the kiln will only be able to reach a low MC variation at very low average MC of the wood.

Effect of pressure changes on EMC

The effect of pressure changes on the EMC are calculated in a similar method as the temperature. Figure 4 shows the resulting EMC at different pressures at fixed temperatures.

The effect of pressure changes on EMC are great at low temperatures and high target MC levels, but reduced at temperatures normally used in vacuum kilns.

Demands on absolute climate control

This paper is based on the assumption that the wood drying process can be controlled by the EMC of the climate surrounding the wood. The actual MC of the wood surface will then be dependent on the short term average of the climate.

To reach a specific EMC, the temperature and the relative humidity of the atmosphere surrounding the wood have to be controlled. The climate control must thus incorporate the steam pressure and the steam temperature.

An absolute minimum in demands on the climate control in a kiln is to maintain the EMC within the MC limits of the desired moisture class. The climate must in reality be controlled better than this in order to actually reach the desired final MC variation, due to the natural MC variation of the wood.

The total MC standard deviation is obtained by adding the standard deviation due to the natural MC variation and the standard deviation due to variations in the drying climate quadratically, as they can be expected to be independent from each other. With an allowed total standard deviation in the E-class of 1.8%/1.64 = 1.1% at 18% target MC and a standard deviation for pinewood of 0.6% due to the natural MC variation according to [1], the allowed variation in EMC of the climate can be expressed as:

Fig. 4. The influence of pressure variations on EMC of Sitka Spruce in pure steam at fixed temperatures. EMC values outside of normal drying climates dotted [calculated from Esping 1992]

$$s_{\text{EMC}} = \sqrt{s_{\text{total}}^2 - s_{\text{natural}}^2} = \sqrt{1.1^2 - 0.6^2} = 0.92\% \tag{3}$$

Thus, in order to dry Pinewood according to the E-class to 18% target MC, a drying kiln must be able to maintain the EMC within 18% $\pm$ 1.64*0.92%, or explicit within 16.49%–19.51%.

Demands on temperature control

The acceptable temperature variations within the kiln are calculated by means of the formulas from the curve fit. At 10 kPa absolute pressure, the EMC range 16.49%–19.51% would allow for a total temperature variation throughout the entire kiln between 47.7°C and 49.2°C or $\pm$ 0.75°C from the set temperature, see Fig. 3.

The acceptable temperature variations at different target MC levels are then calculated in similar fashion for S, Q and E drying class at 10 kPa and 30 kPa absolute pressure. Figure 5 shows the calculated temperature ranges in order to fulfil the demands in the S, Q and E drying classes.

Although the values obtained above not should be interpreted as absolute values, Figure 5 clearly illustrates the narrow temperature ranges that the vacuum kiln needs to operate within in order to achieve wood with a controlled MC. Table 3 shows the maximum acceptable temperature deviation from the set temperature in order to fulfil the demands of EDG drying classes S, Q and E at fixed pressures obtained P = 10 kPa and P = 30 kPa.

As the demands on temperature control increase with higher target MC levels, the demands on temperature control will be defined by the acceptable temperature deviation at the maximum MC level at which a specific MC class will be used.

As the higher drying classes mainly are intended to be used at lower MC levels, the demands for the E- class will hardly be applied at for instance 18% target MC. In order to adapt to this, the demands on the temperature control are

Fig. 5. Acceptable temperature ranges to reach EDG drying classes S, Q and E calculated at 10 kPa and 30 kPa absolute pressure. To reach the S class the temperature should be maintained within the dotted lines, Q class within the dashed lines and E within the solid lines

Table 3. Maximum acceptable deviation from set temperature to reach EDG classes S, Q and E at different target MC levels and fixed pressures 10 kPa and 30 kPa

Drying class/ pressure (kPa)	Maximum deviation from set temperature at target MC level (°C)			
	6%	10%	14%	18%
S/10	7.6	4.3	3.4	2.9
S/30	7.2	3.6	2.9	2.5
Q/10	4.5	2.7	2.1	1.8
Q/30	4.1	2.2	1.8	1.6
E/10	1.9	1.1	0.9	0.8
E/30	1.7	1.0	0.8	0.7

calculated at 12% for Exclusive Class (E), 16% for Quality Class (Q) and 18% for Standard Class (S). Table 4 shows the maximum acceptable deviation from set temperature for each drying class at fixed pressures.

Demands on pressure control

Since the pressure is easier to control with high precision than the temperature, every effort should be made to control the pressure with the maximum accuracy in order to allow for greater temperature variations. A well designed pressure control system should be capable of maintaining the pressure on the pressure side of the stack within ± 0.2 kPa of the set pressure at low pressures and $\pm 1\%$ of the set pressure at higher pressures.

Acceptable pressure ranges at fixed temperatures in order to fulfil the EDG standard are calculated in a similar fashion as the temperature ranges. Figure 6 shows pressure limits at 60°C and 80°C for the S, Q and E classes.

Table 4. Maximum acceptable deviation from set temperature for EDG classes S, Q and E at expected target MC ranges and fixed pressures 10 kPa and 30 kPa

Drying class	Target MC (%)	Maximum acceptable deviance from set temperature (°C)	
		P = 10 kPa	P = 30 kPa
S (Standard)	<18	2.9	2.5
Q (Quality)	<16	1.9	1.7
E (Exclusive)	<12	1.0	0.8

Fig. 6. Pressure limits in order to reach EDG drying classes S, Q and E at fixed temperatures 60°C and 80°C. The pressure should be kept within the limits of the solid lines in order to reach E class, within the dashed lines to reach Q class and dotted lines to reach S class

As the effect of pressure changes on the EMC is reduced at higher temperatures as well as low target MC, the demands on the pressure control can be defined by the lowest temperature used and 18% target MC. At 60°C temperature and 18% target MC the acceptable pressure variations for the E class would be ± 0.475 kPa. However, as the higher drying classes Q and E only are applicable to low target MC, the acceptable pressure variations are in reality greatly extended. Table 5 shows acceptable pressure variations to reach S, Q and E class at fixed temperatures.

With a pressure control system capable of maintaining the pressure within $\pm 1\%$ of the set pressure, the effect of pressure variations on the EMC level can be neglected in comparison to the effect of temperature variations.

Discussion

This contribution is based on a combination of EMC values originally published in 1931, measurements of MC variation of various species and the demands on final MC variation suggested by the EDG drying group.

The basis for the EMC curves in Fig. 3 can be traced to original measurements made by W.K. Loughborough, published by Hawley in 1931 [Esping 1997]. There

Table 5. Maximum acceptable deviation from set pressure for EDG drying class S, Q and E at fixed temperatures 60°C and 80°C

Drying class	Target MC (%)	Maximum acceptable deviation from set pressure (kPa)	
		60°C	80°C
S (Standard)	<18	2.0	out of range
Q (Quality)	<16	1.6	3.0
E (Exclusive)	<12	0.8	1.5

are uncertainties about the number of measurements and the accuracy of the measurements as the original material no longer can be traced [Ressel 1999]. The EMC values are also measured on Sitka Spruce and it can be expected that other wood species will show different EMC- values. This will have the effect that the EMC- curves hardly are suitable for determining the specific EMC in a certain climate.

However, the general shape of the EMC curves of various wood species can be expected to be close to the published EMC- curves, and the effect of changes in the surrounding climate of the wood can be calculated. Thus the EMC- curves can be used to determine the accuracy in climate control needed to maintain the EMC variation within certain limits.

The natural MC variation of wood after prolonged storage in a certain climate sets the practical limit for the MC variation which is possible to reach. Although the calculations in this contribution are based on a fairly limited number of measurements, the data suggests a natural MC variation with a standard deviation of approximately 0.6% at the 18% MC level.

The natural MC variation above is approximately half the acceptable MC variation of the Exclusive Class but only one fourth of the acceptable variation in the Quality Class. This indicate that the natural MC variation for the wood species in Table 2 only will have a significant effect on the demands on climate control in the Exclusive Class.

The demands on climate control in this contribution are based on the demands on final MC variation in the EDG proposal. This has been chosen as the EDG proposal is the basis for an European CEN- standardisation procedure concerning drying quality of wood. Although the demands on final MC variation differs in other drying standards, the three different quality levels of the EDG proposal cover the range from very high to fairly low quality demands. The EDG proposal can be considered as an acceptable basis for calculations of the demands on climate control.

Conclusions

The demands on EMC control in vacuum dryers calculated from the allowed MC variation in the EDG standard and the natural MC variation of wood defines the demands on pressure and temperature control.

The crucial factor in order to reach a controlled drying climate is to maintain the set temperature throughout the entire kiln.

The pressure needs to be controlled within +/-1% of the set pressure and the temperature within +/-0.8°C of the set temperature throughout the entire kiln in order to reach the EDG E- class at 12% target MC.

The need to control the climate within the limits above leads to the need for a strictly controlled climate throughout the entire drying kiln load in order to ensure an adequate drying quality and a high drying capacity.

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