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UPON THE DRYING OF FROZEN SPRUCE TIMBER

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Abstract:

The article presents the results regarding the influence of different freezing conditions upon the drying behaviour of spruce wood (Picea abies L.) in terms of drying time, quality aspects and energy consumptions.

Differently frozen spruce samples were kiln-dried together with unfrozen, green control samples in a conventional kiln, within the same batch.

The moisture content and temperature of the samples was monitored throughout the whole drying process and thus the thawing rate and the drying speed were established. After the drying process was finalised and all samples reached the target moisture content of 12%, the drying quality was evaluated.

Based on the results regarding the drying time, the involved energy consumptions for each situation were calculated and then compared.

The results clearly show that the freezing affects both the drying time and the drying quality.

Key words: *drying; frozen wood; spruce; freezing rate; thawing rate; drying time; energy consumptions; drying quality.*

INTRODUCTION

Drying timber is a necessary operation at the beginning of any woodworking process. Its duration and accuracy determine decisively the cost and quality of the finished product in which the dry raw material is embedded. Therefore, there exists a constant concern of specialists and researchers to improve the drying process in terms of time reduction, energy reduction, and especially quality improvement (Hopper and Toennisson 1980, Esping 1982, Garrahan 1983, Salin 2004, McCurdy 2006, Elustondo and Oliveira 2006, 2007, McCurdy and Pang 2007, Perré *et al.* 2007).

The drying process becomes more complicated in case of frozen wood, because the heating-up phase is accompanied in this case by a phase transformation of the moisture inside wood (solid ice into liquid water). This phenomenon has consequences upon the drying time - which is elongated by the thawing time, upon the energy consumption - which is increased by the consumption necessary for melting the ice, and also upon the drying quality, as freezing and thawing generate, in some situations, considerable internal stresses inside wood (Ilic 1995, Szmutku *et al.* 2011a, 2011b, 2011c).

Most literature information related to the topic of frozen wood refers to the heating of frozen logs (Korala and Kivimaa 1947, Kübler 1964, Chudinov 1968, Feihl 1972, Steinhagen 1977, 1978, 1980, 1987, 1989) or using freezing as a pre-treatment for reducing shrinkage and collapse (Kübler 1962, Kelsey 1963, Erickson *et al*. 1968). Vasquez (1997) studied the influence of some pre-treatment methods (sonic, boiling and steaming) after 4-9 weeks of storage in frozen state, and then the drying behaviour of Pacific Madrone species.

However, regarding the conventional drying of frozen wood, reference literature provides only few information (Marinescu 1980, Cividini 2001), stating mainly that the temperature during the heating-up phase should be kept lower (at ca. 30ºC) than usual.

The results obtained after vacuum freeze-drying experiments performed by Erickson (1968) showed that the freezing temperature has a significant influence upon shrinkage: with lower temperatures, shrinkage decreases.

Campean *et al.* (2008, 2009) performed experimental studies with fir, spruce, pine, larch, alder and lime samples and showed that after a single cycle of freezing (at temperatures of -15 ... -30°C) and thawing (at +1°C), green wood can eliminate over 10% of its free water, depending on the species, initial moisture content and temperature and freezing time.

Experimental studies performed by Szmutku *et al.* (2013) regarding the temperature variation inside spruce wood during the freezing and thawing processes shows that the thawing time and the thawing rate are significantly influenced by the freezing rate. The results show an increase by 13-17% of the heating (thawing) time in case of slowly frozen samples (by -1°C/h) compared to rapidly (by -10°C/h) frozen samples.

OBJECTIVE

The main objective of the experimental study presented within this paper was to determine the influence of different freezing conditions upon the drying behaviour of spruce wood, in terms of drying time, drying quality and energy consumptions involved. Two freezing conditions were chosen so as to simulate real conditions which may appear in industrial practice: long-term freezing, by storing the timber in an open yard for 3 winter months and short-term freezing, by freezing wood slowly down to -25ºC, then maintaining it just for 3 days in frozen state.

MATERIAL, METHOD AND EQUIPMENT

The material used within the experimental research consisted of spruce (*Picea abies* L.) timber boards, with an average initial moisture content of 40%, sized at 2000x150x24mm. A total of 6 control samples were introduced in a 2m^3 stack (Fig. 1).

Two of the control samples were previously frozen slowly, by a freezing rate of -1ºC/h down to -25ºC and then maintained at this temperature for 3 days in a FEUTRON type 3423-16 climate chamber.

Other two control samples were previously kept for 3 winter months in an open yard, exposed to natural temperature variations (Fig. 2). The extreme temperatures during this period were +7ºC, respectively -15ºC and the average was -4,5ºC. The maximum difference between the day and night values was 16ºC and the average was 6ºC.

Other two control samples were introduced unfrozen into the drier. A SEBA SDW type PRO-DRY kiln chamber was used in the experiment. The drying schedule applied is presented in Table 2.

In each control sample, a 10mm long V2A moisture content sensor and a digital 1-wire type DS18S20 temperature sensor were introduced, in order to measure continuously the moisture content and temperature inside wood during the drying process. Based on these measurements, the drying diagram, the moisture content decrease graph and the temperature variation graph were drawn. Also, the thawing rate and the drying speed were calculated according to the relations:

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$$\text{Thawing rate} = \frac{\Delta T}{D_1} \ [^{o}C/min] \qquad (1)$$

where:

ΔT is the difference between the initial and final temperature of wood during thawing, ºC;
D_1 – thawing time, minutes.

$$\text{Drying speed} = \frac{\Delta MC}{D_2} \ [\%/h] \qquad (2)$$

where:

ΔMC is the difference between the initial and final moisture content of wood during drying, %;
D_2 – drying time, hours.

Fig. 1
Wood stacks with control samples.

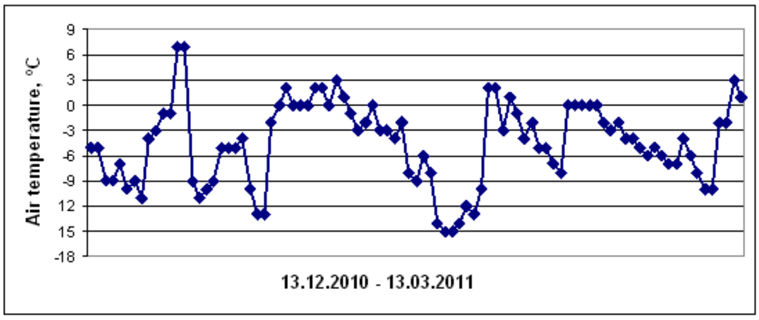

Fig. 2
Temperature variations during the three months of outdoor exposure of the samples.

Table 2

The applied drying schedule

Phase	Temperature, °C	Equilibrium moisture content, %	Duration
Initial heating (and thawing)	50	15	2h
Actual drying	50	15	Until average 30% mc is reached
	60	13	U=30 – 20%
	52	10	U=20 – 15%
	55	7	U=15 – 10%
Conditioning	55	10	10h
Cooling	20	-	2h

After the drying process was finalised and all samples reached the target moisture content of 12%, the drying quality was evaluated by core moisture content measurements on 10 samples of each assortment, by means of a resistive moisture-meter type BROOKHUIS - in order to establish the uniformity of the final moisture content, by the casehardening test performed according to ENV 14464:2002 on 3 samples from each assortment – in order to establish the casehardening degree, by naked-eye observation of all samples - in order to establish the gravity and frequency of surface fissures and by cross-cutting 3 samples from each assortment – in order to establish if any internal fissures occurred.

EVALUATION OF ENERGY CONSUMPTIONS INVOLVED

The heat consumption during the drying process is given by four major components: the amount necessary to warm-up wood and kiln walls (Q_1), the amount necessary to evaporate water from wood (Q_2), the amount which is necessary to compensate for the heat losses through the kiln construction elements (Q_3) and the amount which is necessary to cover the vent losses (Q_4). These four thermal energy components were calculated according to equations (3)-(6), as provided by reference literature (Marinescu 1982, Trübswetter 2006, Elustondo and Oliveira 2006, Ananias *et al.* 2012).

When drying frozen timber, one more heat consumption has to be considered: the heat amount necessary to melt the ice (Q_5). The amount of water which freezes inside wood can be approximated as (MC_i-15) (Marinescu 1982), where MC_i is the initial moisture content of wood. This assumption is based on the fact that only liquid water freezes and that the amount of liquid water in wood is composed of the free water and a part of the bound water – namely the one considered as being bound by capillary condensation, which is around 15%. The heat consumption necessary for melting the ice inside wood was calculated according to equation (7) (Marinescu 1982).

- **Heat consumption for warming-up wood and kiln:**

$$Q_1 = \rho_u \cdot c_p \cdot (T_1 - T_0) + \frac{\rho_{Al} \cdot V_{Al} \cdot c_{pAl} \cdot (T_1 - T_e)}{V} \quad \text{[kJ/m}^3\text{]} \tag{3}$$

where:

ρ_u is the green wood density, kg/m^3;
c_p - specific heat of wood, kJ/kg.ºC;
T_1 - temperature inside kiln during the heating phase, ºC;
T_0 - initial temperature of wood, ºC;
ρ_{Al} - aluminum density (kiln walls), kg/m^3;
V_{Al} – walls volume, m^3;
$c_{p,Al}$ - specific heat of aluminum (kiln walls), kJ/kg.ºC;
T_e - outside temperature, ºC;
V – wood volume within one batch, m^3.

- **Heat consumption for water evaporation:**

$$Q_2 = \rho_0 \cdot \Delta MC \cdot \Delta h \quad \text{[kJ/m}^3\text{]} \tag{4}$$

where:

ρ_0 is the oven-dry density of wood, kg/m^3;
ΔMC - difference between initial and final moisture content of wood, kg/kg;
Δh - latent heat for evaporation, kJ/kg.

- **Heat consumption to cover heat losses through kiln walls, ceiling and floor:**

$$Q_3 = \frac{(A_{Al} \cdot U_{Al} + A_c \cdot U_c) \cdot \Delta T \cdot \tau}{V} \quad \text{[kJ/m}^3\text{]} \tag{5}$$

where:

A_{Al} is the heat transfer area of walls and ceiling, m^2;
U_{Al} - heat transfer coefficient for walls and ceiling, kW/m^2.ºC;
A_c - heat transfer area of concrete floor, m^2;
U_c - heat transfer coefficient for concrete floor, kW/m^2, ºC;
ΔT- difference between inside and outside temperature, ºC;
τ - time, s;
V - wood volume, m^3.

● **Heat consumption to cover the vent losses:**

$$Q_4 = \frac{E}{M_v} SG_g \frac{MC_i - MC_f}{100} \quad [\text{kJ/m}^3] \tag{6}$$

where:

E is the energy loss per weight of vented water, kJ/kg;
M_v – mass of vented water, kg;
SG_g - specific gravity of wood, kg/m^3;
MC_i - initial moisture content of wood, %;
MC_f - final moisture content of wood, %.

● **Heat consumption to melt the ice inside and thaw wood:**

$$Q_5 = \rho_t \cdot SG_g \cdot \frac{MC_i - 30}{100} \quad [\text{kJ/m}^3] \tag{7}$$

where:

ρ_t is the latent heat for melting ice, kJ/kg;
SG_g - conventional wood density, kg/m^3;
MC_i - initial moisture content of wood, %.

The electric energy consumption (*P*) during drying is given by equation (8):

● **Electric power consumption:**

$$P = \frac{P_1 \cdot n_{fans} \cdot \tau}{V} \quad [\text{kJ/m}^3] \tag{8}$$

where:

P_1 is the fan power, kJ/s;
n_{fans} - number of fans, pcs;
τ - drying time, h;
V - wood volume, m^3.

Finally, the total energy consumption necessary for the drying of 1m^3 of timber was calculated by summing up the six components for the case of drying frozen wood (equation 9), and without Q_5 for the case of drying non-frozen wood.

● **Total energy consumption in case of drying frozen wood:**

$$Total\_energy = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + P \quad [\text{kJ/m}^3] \tag{9}$$

where:

Q_1 is the thermal energy consumption for heating-up wood and the kiln walls, kJ/m^3;
Q_2 - thermal energy consumption for water evaporation, kJ/m^3;
Q_3 - thermal energy consumption for covering the heat losses through the kiln construction elements, kJ/m^3;
Q_4 – thermal energy consumption for covering vent losses, kJ/m^3;
Q_5 - thermal energy consumption for melting the ice inside wood, kJ/m^3;
P - electrical energy consumption, kJ/m^3.

RESULTS AND DISCUSSIONS

Fig. 3 shows the drying diagram with the values recorded for the three main drying parameters (average moisture content, temperature and equilibrium moisture content), during the drying of 24mm thick spruce timber with an average initial moisture content of 43%.

Fig. 4 shows the moisture content variation curves and Fig. 5 shows the temperature variation curves inside wood, recorded for the six monitored wood samples throughout the process.

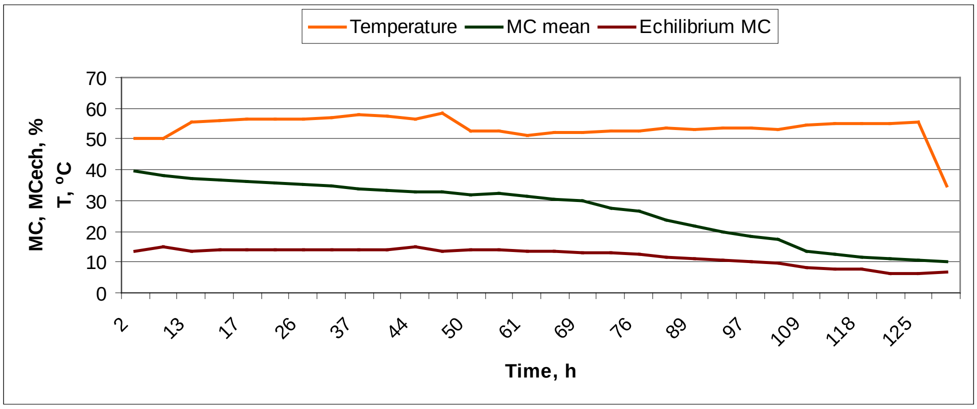

Fig. 3.
The drying diagram.

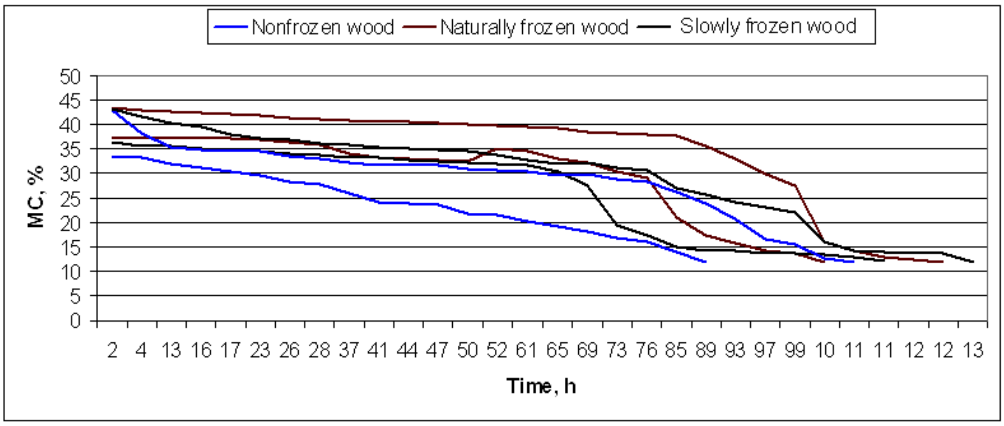

Fig. 4
Variation of moisture content inside the six monitored wood samples during the drying process.

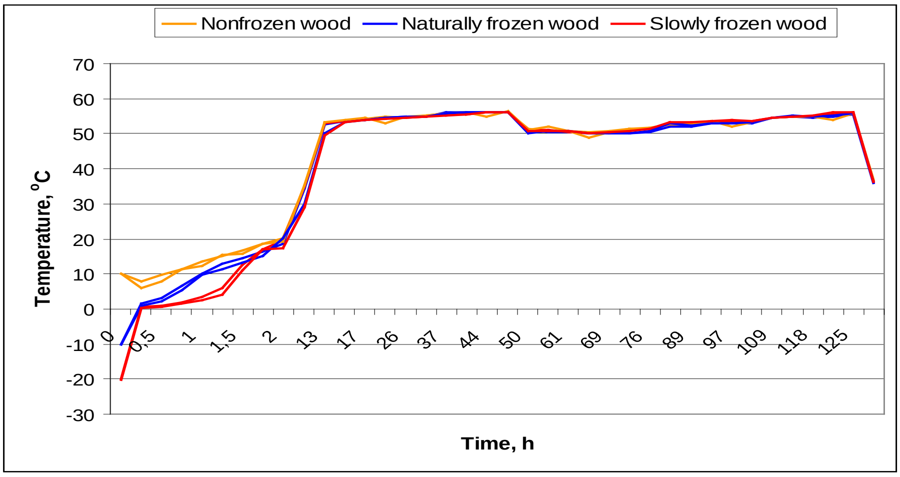

Fig. 5
Variation of temperature inside the three monitored wood samples during the drying process.

Drying Time

The average drying times of the three wood assortments are given in Table 3.

Table 3

The average drying times

Wood sample	Initial moisture content MC_i, %	Initial temperature T_0, °C	Drying time τ, h
Non-frozen wood	43,2	10	115
Long-term frozen wood (after 3 winter months of open yard exposure)	43,6	-10	125
Short-term frozen wood (frozen slowly by -1ºC/h down to -25ºC, then maintained for 3 days in frozen state)	43,4	-20	135

It can be noticed that the freezing affects significantly the drying time, which is by 8% longer in case of the long-term frozen wood, and respectively by 15% higher in case of the short-term frozen wood. The difference between the two freezing situations must be given by the freezing temperature (-25°C for the artificial short-term freezing, compared to max. -15°C in the case of the natural freezing), which seems to have greater influence upon the drying time than the time of exposure to freezing conditions.

The thawing time was 2h for both frozen samples to reach the same temperature as the non-frozen sample, but starting from different initial temperatures (Table 3). It was noticed that the thawing rate was higher in the case of the long-term frozen samples (Table 4).

The drying dynamics was also affected by freezing (Table 4). The same hierarchy is maintained: the fastest dried the non-frozen samples, followed by the long-term frozen ones and last, the short-term frozen ones, which means a delay by 7% and 14% respectively, in the case of the long-term frozen samples and the short-term frozen ones, compared to the non-frozen wood.

Table 4

The thawing rate and drying speed of the six monitored wood samples

Assortment/Number of sample	Thawing rate °C/min	Drying speed within the moisture content decrease interval from 40% to 12% %/h
Non-frozen 1	-	0.25
Non-frozen 2	-	0.28
Long-term frozen (naturally) 1	1.16	0.23
Long-term frozen (naturally) 2	1.13	0.26
Short-term frozen (artificially) 1	0.76	0.20
Short-term frozen (artificially) 1	0.74	0.24

Drying Quality

The quality control at the end of the drying process revealed a good uniformity of the final moisture content in the non-frozen samples (the measurement results did not differ by more than 0,5%), while with the frozen samples, the final moisture content measured inside wood was more uneven: the difference reached 1,7% in the case of the naturally frozen wood and 1,8% in the case of the artificially frozen wood.

The casehardening values followed the same pattern, with lowest values for the non-frozen samples (0,5-1mm), slightly higher values for the long-term frozen samples (1-2mm) and the highest values for the short-term frozen samples (2-5mm). This result clearly indicates that the short-term freezing condition was tougher for wood. This may be attributed to the lower negative temperature (-25°C for the artificial short-term freezing, compared to max.-15°C in the case of the natural freezing). We can also assume that the average freezing rate under the natural conditions was sometimes higher than 1ºC/h, which means that the artificially frozen samples were frozen slower. The freezing rate is important because it determines the size of the ice crystals: the lower the freezing rate, the larger the ice crystals are (Kopstad and Elgsaeter 1982). This would also explain the larger time required by the artificially frozen samples to thaw and to dry.

No surface checks and no internal fissures were recorded in any of the examined situations.

Energy Consumption

Based on the values obtained for the drying time, the heat and power consumptions for each of the three situations were calculated (Table 5).

Table 5

Heat and power consumptions involved by the drying of frozen and unfrozen spruce timber

Wood sample	Q_1, MJ/m^3	Q_2, MJ/m^3	Q_3, MJ/m^3	Q_4, MJ/m^3	Q_5, MJ/m^3	*Total heat consumption* MJ/m^3	*P*, MJ/m^3	Total energy, MJ/m^3
Non-frozen wood	64	301	206	47	0	618	621	1239
Long-term (naturally) frozen wood	98	301	420	79	17	915	675	1590
Short-term frozen wood	113	301	484	83	17	998	729	1727

CONCLUSIONS

The study revealed that water freezing inside wood has a significant influence upon the drying behaviour of spruce wood: the drying time is increased by ca. 15% when drying frozen wood and the final moisture content is more uneven.

The thawing time, the drying time and also the drying quality are affected by the conditions under which the freezing occurred. The negative temperature value has a greater importance in this view than the time of exposure to the negative temperature.

Along with the drying time, the required energy consumption also increases: drying wood from frozen state takes up to 34% more energy than from non-frozen state. This is mainly due to the additional quantity of heat required, which is up to 1.5 times higher in winter than under average climatic conditions.

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