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Temperature distribution in beech wood during vacuum drying

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Abstract: *Temperature distribution in beech wood during vacuum drying.* The temperature distribution and changes in humidity in beech wood in the form of friezes during drying in a vacuum were analysed. The intensity of the occurring phenomena of desorption and the volumetric flow of moisture through the anatomical structures of the wood, depending on the absolute pressure and the temperature of the process, was determined. It was found that the fastest temperature increase took place in the subsurface layers directly adjacent to the heating plates. The introduction of conditioning between the drying phases made it possible to even out the humidity and temperature distribution in the entire element. On the basis of the analysis of changes taking place between the volumes of the three components of wood, it was found that the volume of moisture in the form of vapor removed in the initial phase of drying is over 20 times greater than the volume of voids in wood structures, and in the following phases it decreases to 0.27. The average volume of vapour removed from 1 m^3 of wood at the temperature of 55℃ is 13.9 m^3/h, decreasing in the following phases to 9.1 m^3/h at the drying temperature of 60℃ and then 3.1 m^3/h at the temperature of 65℃. The drying rates for these phases reach the value of 0.15%/h, 0.17%/h and 0.075%/h, respectively. Direct measurements of wood moisture, made during the experimental course of the drying process at an absolute pressure of 150 hPa, follow the equivalent moisture, determined on the basis of the Hailwood-Horrobin model, taking into account the appropriate calculation factors.

Keywords: Vacuum drying, wood equivalent moisture, drying phases, beech wood

INTRODUCTION

Drying wood in a vacuum allows the use of lower temperatures compared to conventional conditions, the reduction of drying time and the preservation of colour and high-quality material. (Riechers et al. 1941, Hildebrand 1970, Gerhards 1986 Koumoutsakos et al. 2001, Dobrowolska et al. 2018).

Drying in a vacuum causes a different movement of moisture in the wood compared to drying under normal pressure. The movement of moisture in the wood takes place through the transport of liquid under the influence of capillary and surface forces and steam migration in the pores, as a result of the influence of the partial pressure difference (Simpson 1991, Chen 1997). In a vacuum, when the temperature of the wood approaches its boiling point, the resulting steam causes an increase in the pressure difference, increasing the mass of the moisture given off by the material (Waananen et al. 1993, Siau, 1984, Avramidis et al. 1992, Zwick et al. 2000, Mottonen, 2006). At the beginning of the drying process, boiling occurs mainly on the cross-sectional surfaces which move towards the centre of the element, leaving the boiling area behind. As the moisture is removed, the pressure drops and boiling takes place in deeper and deeper internal layers that spread along the wood structures (Chen, 1997, Waananen et al. 1993, Chen et al. 2001).

The intensity of the process at reduced pressure depends on the amount of heat supplied and the morphological features of the wood (Chen et al. 2001).

In contact drying in a vacuum, energy is supplied mainly by conduction, then the heat and mass fluxes have the same direction. The intensity of moisture movement in wood (Voigt et al. 1940, Chen, 1997) depends primarily on the total pressure difference, occurring both in the phase of moisture movement in liquid and gas form. During this process, the temperature of the material is lower, the greater the distance of a given layer from the surface in contact with the heating surface. As the moisture decreases, the boundary of the evaporation zone moves towards the heated surface of the material. Due to the decreasing temperature difference between the heated surface of the material and the evaporation surface, the drying process slows down. On the surface of the material, the drying speed depends on the size of the temperature gradient inside the material. After heating the wood to the required temperature, the absolute pressure generated in the drying chamber remains constant for a specified duration of the process. As the moisture evaporates, the relative humidity increases inside the wood structures, causing them to cool down at the same time. Lowering the temperature increases the equivalent moisture of wood and slows down the drying process (Chen, 1997). The drying time in vacuum is 20% to 50% shorter than the process carried out at normal pressure (Fohr et al. 1995, Simpson, 1987). It has been shown that the drying rate can be from 0.32%/h to 2.2%/h, while maintaining high quality material (Chen, Lamb 2001, 2004, 2007).

The process of drying wood in a vacuum according to Skaar (1972), is associated with changes taking place in three volumetric phases (without taking into account shrinkage): wood substance, liquid in the form of free water and gaseous substance, which is a mixture of air and water vapor. Changing the proportion between these three phases makes it possible to assess the intensity of the decrease in wood moisture during the vacuum drying process (Chen, 1997).

Many different theories have arisen to characterize the phenomena of wood sorption, occurring under atmospheric pressure (Simpson 1991). Taking into account the effect of reduced ambient pressure on the EMC wood equivalent humidity was made possible using the Hailwood-Horrobin (1946) model in conjunction with the coefficients calculated by Simpson et al. (1971, 1973) and Liu et al (2010). In this way, determining the EMC of wood has become important in the analyses of the process of reducing wood moisture under negative pressure (Chen, 1997, U. S. FPL, 1955).

The aim of the study was to evaluate the efficiency of the drying process in a vacuum contact dryer. The process was carried out according to an experimental scheme, assuming obtaining dried elements in the form of beech friezes with uniform humidity. The analysis of the process was carried out by measuring the temperature distribution and changes in humidity in the dried elements. The intensity of the occurring phenomenon of desorption and the volumetric flow of moisture through the anatomical structures of the wood, depending on the absolute pressure and temperature of the process, was also determined.

MATERIAL AND METHODS

The research material was friezes with dimensions of 710 mm × 76 mm × 76 mm, which were cut from beech timber at the temperature of 90°C for 12 hours. As a result of this process, a pinkish-salmon colour was obtained across the entire cross-section of the element. The wood density was 695 kg/m^3 (V=4.8%), and its initial moisture content was 60% (V=5.2%).

The drying process was carried out in an industrial contact vacuum dryer.

For temperature measurement during the process, drying was prepared in a special part of the material batch. The numbers of measurement points are arranged along the length of the element, in accordance with the longitudinal direction of the fibres. Measurement points 1, 2, 3, 5 were marked in the axis of the element, points 1 and 5 respectively at a distance of 50 mm from the fronts, point 2 at 200 mm from the left face and point 3 in the middle of the length of the element. The measurements were supplemented with two points 4 and 6, located in line with point 5. Both points were placed 5 mm from the top and bottom edges (Fig. 1). Holes 40 mm deep and with a diameter corresponding to the dimensions of 6 temperature sensors were made at all points (Fig. 2). The signal transmitted from the sensors was read continuously by a temperature recorder and recorded on a paper tape.

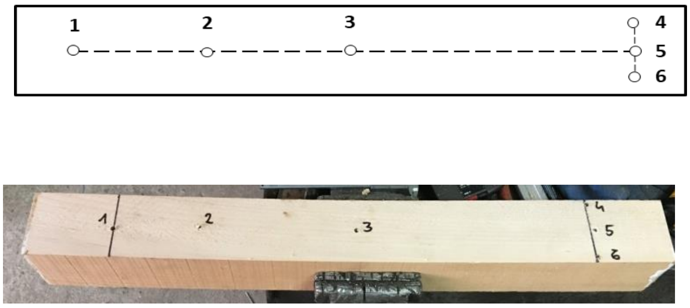


Figure 1. An element in the form of a beech frieze with designated places for measuring the temperature of the wood during the drying process

During the drying process, the moisture content in the friezes placed in the dried part of the material was also measured using measuring probes connected to a Tanel K2 hygrometer.

Figure 2. Beech frieze with sensors for temperature measurement

The drying process was divided into 5 phases. The parameters of their course are presented in Table 1. The drying process was carried out in accordance with a specific scheme consisting of 5 phases, including interfacial conditioning, and 3 phases after the first period of the drying process.

The process started with heating the material by gradually increasing the temperature of the dryer shelves from 40℃ to 55℃ with the condensers turned off. The actual drying phase was carried out with a negative pressure of 0.075 MPa to 0.085 MPa. In the first part of this process, drying from initial humidity to approx. 23% humidity took place, which lasted 177 hours. This part of the process was preceded by a 12-hour conditioning phase with a shelf temperature of 65°C, with the condensers off. The next interval, from 23% to 10% of the change in wood humidity, took place within 76 hours, with the shelf temperature equal to 60℃. The last phase of the process, including the change in wood humidity from 10% to 7%, was carried out at the temperature of 65℃ and lasted 40 hours.

Table 1. Beech wood drying process parameters

Drying process phase	Time (h)	The temperature of heating shelves (°C)	Condensers surface temperature (°C)	Under pressure (MPa)
1. Heating the material	18	40	Turned off	Lack
	7	45		
	5	50		
2. Drying: W ≥ 23%	177	55	42	0.075÷0.085
3. Conditioning	12	65	Turned off	0.075÷0.085
4. Drying 23% ÷ 10%	76	60	42	0.075÷0.085
5. Drying 10% ÷ 7%	40	65	42	0.075÷0.085

During the drying process in a vacuum, changes in the volume of wood (V) consisting of (without shrinkage) the volume of: wood substance (V_w), free water (V_m) and a mixture of air and water vapor (V_w), were calculated for wood humidity of 60%, 23%, 10% and 7% according to the following equations (Skaar 1972).

$$V = V_w + V_a + V_m$$

The contribution of wood substance (v_w) in the volume of moist wood is (Skaar 1972):

$$v_w = \frac{V_w}{V} = \frac{W_w \cdot d^{-1}}{W_w \cdot (G \cdot d_m)^{-1}} = \frac{G \cdot d_m}{d}$$

Then the proportion of free water (v_m) is equal to:

$$v_m = \frac{W_m \cdot d_m^{-1}}{W_w \cdot (G \cdot d_m)^{-1}} = \frac{G \cdot MC}{100}$$

and the contribution of the gas phase (v_a):

$$v_a = 1 - G \cdot \left(0{,}667 + \frac{MC}{100}\right)$$

In the equations:
W_w i W_m – denote the weight of wood and moisture, respectively,
G – wood density (kg/m^3)
d_m – water density (kg/m^3)
MC – wood moisture (%)
d – the density of wood substance (1500 kg/m^3)

Volumetric changes of wood components occurring during subsequent stages of the drying process will allow to determine the dynamics of moisture movement in the wood. The EM humidity of the wood, changing under vacuum drying conditions, was determined on the basis of the Hailwood-Horrobin model (1946). The calculation formulas take into account the coefficients established by Simpson (1973) and Chen (1997).

$$MC = \left(\frac{K_1 \cdot K_2 \cdot h}{1 + K_1 \cdot K_2 \cdot h} + \frac{K_2 \cdot h}{1 - K_2 \cdot h}\right) \cdot \frac{1800}{W} \quad (\%)$$
$$K_1 = 4.737 + 0.04773 \cdot t - 0.00050123 \cdot t^2$$
$$K_2 = 0.70594 + 0.001698 \cdot t - 0.0000055534 \cdot t^2$$
$$W = 223.385 + 0.6942 \cdot t - 0.018533 \cdot t^2$$

Wherein:
MC – wood moisture (%)
h – ratio of absolute pressure to vapor saturation pressure at a given temperature,
t – temperature (°C).

The calculated equilibrium moisture content of wood will be compared with the moisture achieved at a certain temperature and negative pressure during the drying process of beech friezes.

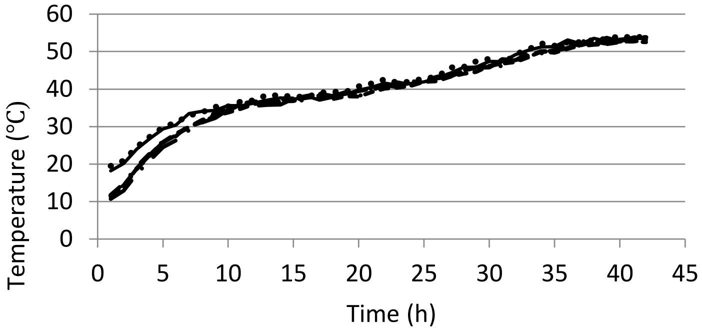
RESULTS AND DISCUSSION

The performed vacuum drying process, in accordance with the planned parameters, included five phases: heating the material, two phases of reducing the humidity in the range from 70% to 23% and from 23% to 10%, separated by the conditioning phase, and the final phase to obtain the desired humidity of 7%.

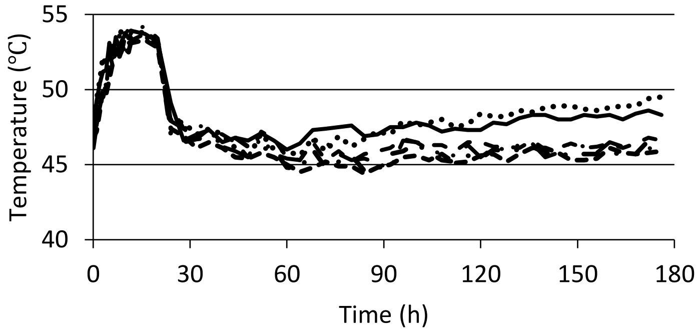
Temperature measurement by means of thermocouples took place at points located along the axis, i.e., 1, 2, 3, 5 and 4 and 6, located at the surface of the element. During the heating (Fig. 3 A) in the first hours of the process, the intensity of the temperature increase measured at the surface, i.e., in points 4 and 6, was higher than the others by about 10 K. The lowest temperature value was recorded in the point 2 away from the forehead by 200 mm and 3 at the centre of the element. After 14 h of heating, the temperatures at all points were similar, reaching an average value of about 37°C with fluctuations not exceeding ± 1.2 K. At the end of the heating phase, the temperature of the element was 52°C ± 1.5 K. The variation in wood moisture was ± 3.0 percentage points in relation to average moisture of 62.0% ± 1.5% (Fig. 10). The average temperature in the second phase with the assumed drying temperature of 55°C and the change in humidity from the initial to 23% (Fig. 3 B) was 48°C. After 12 hours of this cycle, a sharp drop in temperature by 10 K was observed at each of the measurement points, which resulted from the evaporation of moisture mainly from the border layers of wood (Chen, 1997, Kaczmarek, 2010). A phenomenon of a similar nature was also observed in the fourth and fifth phases of the process. In the final part of the 2nd phase, the temperature distribution in the wood was even, and the maximum difference between the measurements was ± 1.0 K, lasting up to 177 hours of the drying process, and the average wood humidity was 26.0% ± 1.0% (Fig. 4). The next stage of the process–conditioning was introduced in order to remove the stresses created in the wood during the removal of moisture in the second phase of drying. Due to the temperature increase of the heating shelves to 65°C, the element temperature increased at each of the measuring points. With the condensers turned off, the wood moisture content first increased by a few percentage points, and then after 8 h the wood moisture content decreased to an average of about 25.0% ± 1.0% (Fig. 4). In the fourth phase, in the range of change in wood moisture content from 23% to 10% and a heating shelf temperature of 60°C (Fig. 3 C), there was a temperature drop of about 8 K between the hours of 8 and 16.

Then the wood humidity decreased from 21% to 15% and the temperature increased, reaching the heating shelves near the end of the process. The differences between the temperature measurements during this phase of the process were in the range of ± 1.5 K, and at the end they did not exceed ± 0.5 K. The mean final humidity was 9.8% ± 0.5% (Fig. 4).

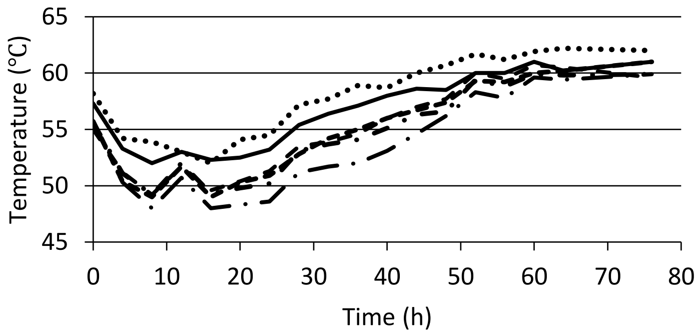
A – 1st Phase



B – 2nd Phase



C – 4th Phase



D – 5th Phase

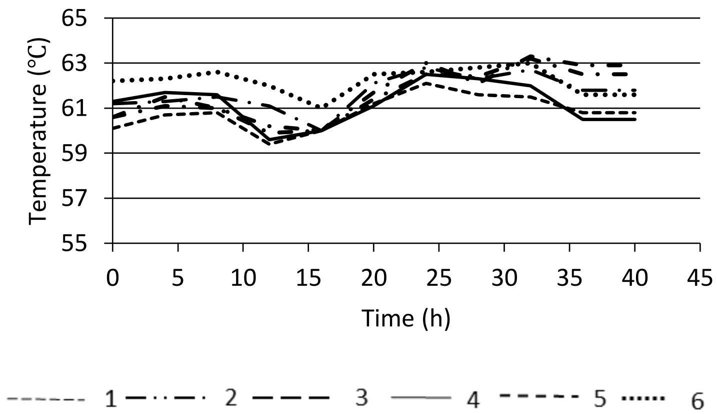


Figure 3. Temperature distribution in 6 measuring points in 4 phases during vacuum drying at a vacuum of 850 ÷ 750 hPa

In the last, fifth (Fig. 3 D) drying phase, an average final moisture content of 7.1% was obtained (Fig. 4). The wood temperature increased to 65℃, stabilizing at the temperature of the heating shelves. At the 12th hour of the process, there was a 5 K drop in temperature, mainly in the internal measuring points, where the humidity dropped to 8.5%. The temperature distribution in the final part of the 5th phase of drying was uniform, with the maximum difference between the measured values equal to ± 1.2 K.

The similar observations were presented by Krzysik et al. (1970) and Gajewska et al. (2010) while drying pine beams, as well as Chen (1997), who analysed the vacuum drying time of sawn timber with different cross-sections of red oak wood.

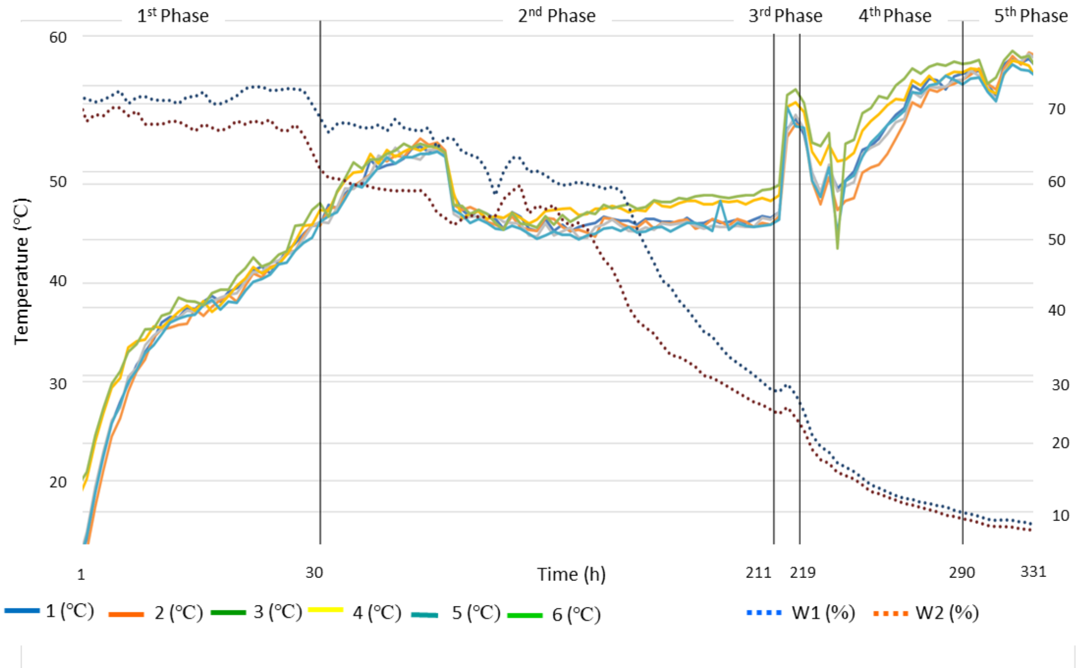


Figure 4. Temperature distribution in 6 measuring points and the course of changes in wood humidity in five stages of vacuum drying at a vacuum of 850 ÷ 750 hPa

Figure 5 shows the changes between the volumes of the three components of wood: wood substance, free water and air during vacuum drying. The conducted analyses show that with a constant volumetric share of the wood substance with the decrease in the moisture content of the wood MC, the share of spaces filled with air and steam increases.

When drying wood in a vacuum, the internal pressure in its structures is higher than the pressure in the drying chamber. Moisture removal occurs as a result of the volumetric steam flow through the wood caused by the total pressure difference. Along with the decrease in wood humidity from 60% to 7%, the volume fraction of the moisture content decreases and the volume fraction of voids in the wood structures increases. At 60% wood moisture, the moisture fraction was 0.417 and the pores 0.12 (Fig. 5).

It can be assumed that for a humidity of 60%, in the volume of 1 m^3 of beech wood, there were 0.417 m^3 of moisture, 0.464 m^3 of wood substance and 0.120 m^3 of voids. If the shrinkage value is not taken into account, then with a humidity drop from 60% to 23%, the mass of the drained water will be 257 kg/m^3 (Tab. 2). At a drying temperature of 55°C (the first part of the process) and with a specific volume of saturated steam of 9.578 m^3/kg, the volume of the generated steam will be 2462 m^3.

Then the volume of evaporating moisture is greater than the volume of voids in the internal structures of the wood. In the further part of the drying process at the temperature of 60°C, the volume of moisture removed is nearly twice as large, and at 65°C it decreases to 0.27 in relation to the volume of air in the porous structure of the wood. In the consecutive time intervals for the reduction of humidity, the average volume of vapor removed, related to 1 m^3 of wood, in the first part of the process (55°C) is 13.9 m^3/h, in the second (60°C) 9.1 m^3/h and in the last (65°C) 3.1 m^3/h (Tab. 2).

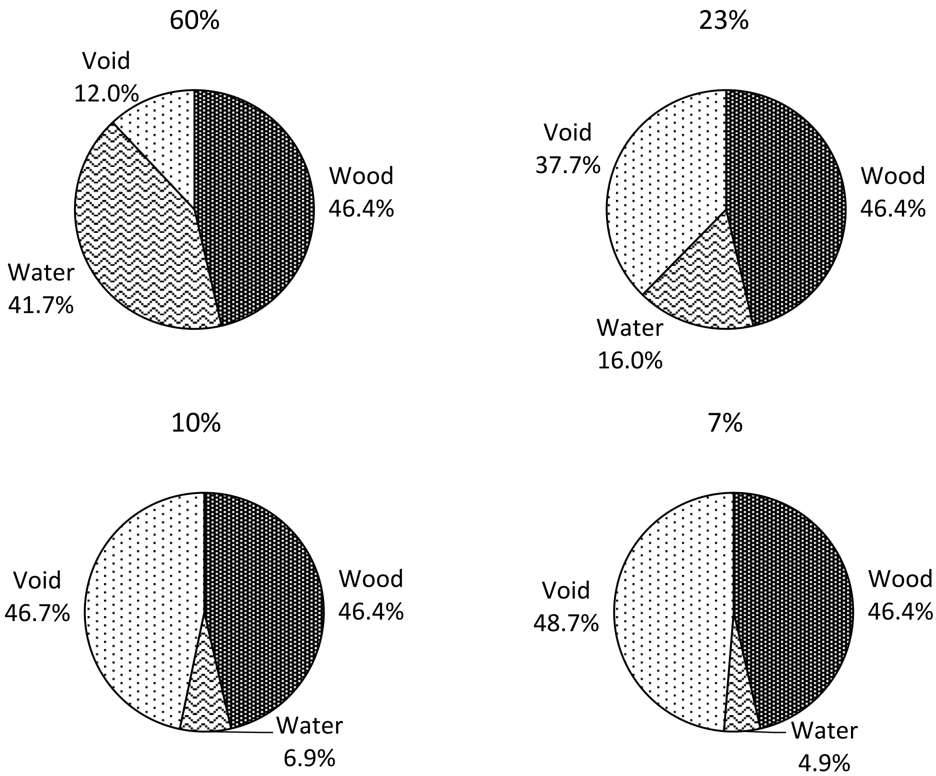


Figure 5. The percentage by volume of three phases in beech wood at humidity: 60%, 23%, 10% and 7%

Table 2. The mass of moisture removed and volume of steam removed during the beech drying process

Change in wood moisture (%)	The mass of moisture removed from the wood (kg/m^3)	The specific volume of steam (m^3/kg)	Drying time (h)	The volume of removed steam (m^3/h)
60 – 23	257	9.578*	177	13.9
23 – 10	90	7.678*	76	9.1
10 – 7	40	6.201*	40	3.1

*) The International Association for the Properties of Water and Steam - IAPWS

Figure 1 and Table 3 show the results of calculations of the change in beech wood humidity at negative pressure ranging from 750 hPa to 850 hPa, determined on the basis of the Hailwood-Horrobin model (1946) supplemented with coefficients by Simpson et al. (1971, 1973) and Liu et al (2010). The estimated wood moisture for a vacuum of 750 hPa in the temperature range from 60°C to 70°C drops from 54% to 13% (Fig. 6). Equivalent humidity of wood dried at a negative pressure of 850 hPa at a temperature of 55°C is 21.2%, at a temperature of 60°C it reaches a value of 12.9%, and at 65°C it drops to 8.5% (Fig. 7).

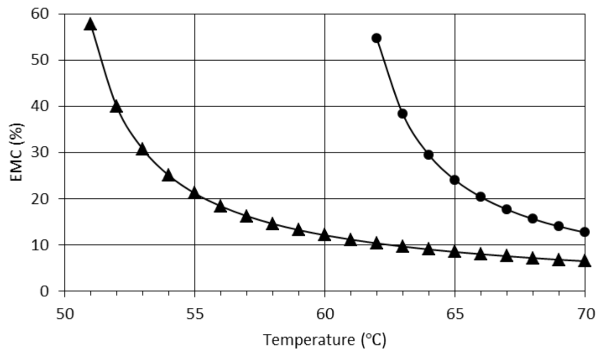


Figure 6. The hygroscopic equilibrium of wood depending on the temperature at a drying vacuum of 850 hPa (▲) and 750 hPa (●)

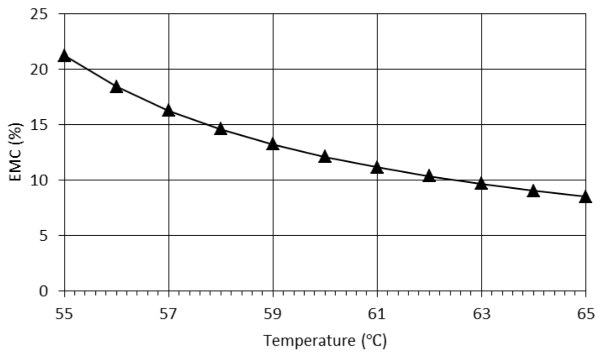


Figure 7. The hygroscopic equilibrium of wood depending on the temperature in the range from 55°C to 65°C at a negative pressure of 850 hPa (▲)

Table 3. The values of calculation coefficients in the Hailwood-Horrobin (1946) model of wood desorption at an absolute pressure of 150 hPa in the temperature range from 55°C to 65°C

t (°C)	Coefficients for formula				EMC (%)
	h	K_1	K_2	W	
55	0.953	5.846	0.783	318	21.2
56	0.908	5.838	0.784	320	18.4
57	0.866	5.829	0.785	323	16.3
58	0.826	5.819	0.786	326	14.6
59	0.789	5.808	0.787	329	13.2
60	0.753	5.796	0.788	332	12.1
61	0.719	5.783	0.789	335	11.2
62	0.687	5.770	0.790	338	10.4
63	0.656	5.755	0.791	341	9.7
64	0.627	5.739	0.792	344	9.0
65	0.600	5.722	0.793	347	8.5

Further comparisons between the theoretical changes in humidity and those measured under the conditions of the actual drying process show that in the second phase, the volume of moisture decreased with a simultaneous increase in the volume filled with steam and air by nearly 26 percentage points (Fig. 5). In practice, in this phase there was a high volatility of the wood giving up moisture, expressed as a volume of vapor removed of 13.9 m^3/h and a change in humidity of 35 percentage points (Fig. 4). At a drying temperature of 55°C and an absolute pressure of 150 hPa, the calculated equivalent wood moisture content was 21.1% (Tab. 3, Fig. 7). In the experimental drying process for these parameters, the beech wood humidity after

177 hours of the process time followed the equivalent humidity, reaching the value of 26.5% ± 1.5%.

On the basis of the weight and volume of the moisture evaporated from the wood, the drying rate was set at 0.15 %/h. The introduction of conditioning after this stage of drying (3^{rd} phase) allowed for the equalization of humidity in the entire element to 25.5% ± 1.5%, confirmed by temperature differences of ± 0.5 K between points located along the length and width of the element.

In the 4^{th} drying phase, carried out at 60°C, with a humidity drop of a further 10 percentage points, with a theoretically determined vapor removal volume of 9.1 m^3/h, the drainage rate increased to 0.17 %/h. The design EMC moisture content was 12.1%, and the wood moisture content at the end of this phase was 11.0% ± 0.4%.

The last stage of the process was characterized by a change in humidity by 3 percentage points. The volume of steam removed was 3.1 m^3/h with a humidity drop of 0.075 %/h. In this case, the theoretical equivalent moisture was 8.5%.

Theoretical calculations concerning the equivalent moisture content of wood (Fig. 6 and 7) as well as the intensity of evaporated moisture (Tab. 2, Fig. 5) follow or coincide with the moisture measurements carried out during the experimental course of the drying process of beech wood (Fig. 4) in the form of friezes at a vacuum of 850 ÷ 750 hPa.

CONCLUSIONS

Based on the conducted research and analyses, it was found:

1. The temperature distribution measured at 6 points during the vacuum drying of elements in the form of beech friezes showed:

- The fastest temperature increase in the surface layers directly adjacent to the heating plates.
- In each of the three drying phases, i.e., 2, 4 and 5, there was a significant temperature drop in all 6 measuring points, caused by the evaporation of moisture from the dried material.
- The introduction of the 3^{rd} phase of conditioning after the 2^{nd} phase, during which there was a decrease in humidity by nearly 35 percentage points. It was possible to even out the humidity and temperature distribution in the entire element.
- Both in the 4th and 5th phases, the wood moisture content was steadily decreased, which was confirmed by slight temperature differences, ranging from ± 0.5 K to ± 1.2 K.

2. Based on the analysis of changes occurring between the volumes of the three components of wood: wood substance, free water and air, it was established that the volume of moisture in the form of vapor removed in the initial phase of drying is over 20 times greater than the volume of voids in wood structures. In subsequent phases, the volume of moisture removed decreased by 2 and 0.27 times in relation to the volume of air in the porous structure of the wood.

3. During the decrease in humidity during the second phase, the average volume of vapor removed from 1 m^3 of wood at 55°C temperature is 13.9 m^3/h, decreasing in subsequent phases to 9.1 m^3/h at a drying temperature of 60°C and then 3.1 m^3/h at 65°C. The drying rates for these phases reach the value of 0.15%/h, 0.17%/h and 0.075%/h, respectively.

4. The direct measurements of beech wood moisture made during the experimental course of the vacuum drying process at an absolute pressure of 150 hPa followed the equivalent

wood moisture content determined theoretically on the basis of the Hailwood-Horrobin model, taking into account the appropriate conversion factors.

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Streszczenie: *Rozkład temperatury w drewnie bukowym podczas suszenia próżniowego*. Przeanalizowano rozkład temperatury i zmiany wilgotności w drewnie bukowym w postaci fryzów, podczas suszenia w próżni. Ustalono intensywność zachodzących zjawisk desorpcji oraz objętościowego przepływu wilgoci przez struktury anatomiczne drewna, w zależności od ciśnienia bezwzględnego i temperatury przebiegu procesu. Stwierdzono, że najszybszy wzrost temperatury miał miejsce w warstwach przypowierzchniowych bezpośrednio przylegających do płyt grzejnych. Wprowadzenie kondycjonowania między fazami suszenia pozwoliło na wyrównanie wilgotności oraz rozkładu temperatury w całym elemencie. Na podstawie analizy zmian mających miejsce między objętościami trzech składników drewna stwierdzono, że objętość wilgoci w postaci pary usuwanej w początkowej fazie suszenia jest przeszło 20 razy większa od objętości wolnych przestrzeni w strukturach drewna, a w następnych fazach maleje do 0.27. Średnia objętość usuwanej pary z 1 m^3 drewna w temperaturze 55°C wynosi 13,9 m^3/h, ulegając w kolejnych fazach obniżeniu do 9.1 m^3/h przy temperaturze suszenia 60°C a następnie 3.1 m^3/h w temperaturze 65°C. Szybkości suszenia dla tych faz osiąga wartość odpowiednio 0.15%/h, 0.17%/h i 0.075%/h. Bezpośrednie pomiary wilgotności drewna dokonane podczas eksperymentalnego przebiegu procesu suszenia przy ciśnieniu bezwzględnym równym 150 hPa, nadążają za wilgotnością równoważną, ustaloną na podstawie modelu Hailwooda-Horrobina z uwzględnieniem odpowiednich współczynników obliczeniowych.

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