

SATURATED WATER STEAM CONSUMPTION STANDARD FOR THE PROCESS OF STEAMING BEECH WOOD WHILE ELIMINATING DIFFERENCES IN THE COLOR OF SAPWOOD AND FALSE HEARTWOOD

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ABSTRACT

The article presents the normative values of the consumption of saturated water steam for steaming beech lumber with false heartwood wood of thickness $h = 40$ mm by a volume of 16 m^3 in pressure autoclave AZ 240 for the purpose of eliminating color differences between sapwood and false heartwood by steaming modes I. and II. The norm of water steam consumption for the steaming process of beech wood using mode I, uniting the wood to a light brown color, is $m_{\text{H}_2\text{O-I}} = 2637.6$ kg. Normative heat consumption for the process of steam mode II. to dark brown-gray color is $m_{\text{H}_2\text{O-II}} = 3051.9$ kg.

The discontinuous process of steaming wood in an autoclave is characterized by uneven consumption of saturated water steam, the largest consumption is at the beginning of the technological process when heating the steamed wood and the autoclave. In the heating phase, in the most demanding mode of steam consumption, mode II, $m_{\text{H}_2\text{O}} = 856.4 \text{ kg}\cdot\text{h}^{-1}$ steam is consumed. After heating, the consumption of saturated steam drops significantly to $m_{\text{H}_2\text{O}} = 6.1 \text{ kg}\cdot\text{h}^{-1}$. The practical benefit of specifying the consumption of saturated water steam in the process of steaming wood in a steam autoclave is when planning the production of heat in the heat source – the boiler room of the plant and the capacity load of the waste water treatment plant.

Key words: beech wood, sapwood color, false heartwood color, steaming of wood, consumption of saturated water steam

INTRODUCTION

The wood *Fagus sylvatica* L. belongs to the scattered-porous, coreless woods with the possibility of forming a false heartwood. Some older trees have wood of a different color in the center of the trunk, referred to as false heartwood. The color of beech wood in the zone of sapwood and mature wood is light whitish-grey, or white pink Nečesaný (1959), Makovíny (2010), Dzurenda – Dudiak (2022) and in the zone false heartwood is brown-red color Nečesaný (1959), Dzurenda – Dudiak (2023). Dzurenda (2023) numerically documented the visual color differences between the color of beech sapwood and wood with false heartwood through the values on the coordinates of the color space CIE $L^*a^*b^*$ and the total color difference ΔE^* . The wood color is white with lightness $L^* = 79.2 \pm 2.4$ and values on the chromatic coordinates $a^* = 8.3 \pm 1.6$, $b^* = 19.1 \pm 1.8$. The color of the false heartwood is described by the following values: $L^* = 65.8 \pm 3.8$, $a^* = 11.6 \pm 1.9$, $b^* = 19.5 \pm 1.5$. The color difference between the color of the wood of the false heartwood and the color of the sapwood, expressed through the total color difference, is $\Delta E^* = 18.1$. Within the categorization of color difference, the value total color difference $\Delta E^* = 18.1$ belongs to the category of significantly different colors. The difference in the color of the wood of the false heartwood from the color of the sapwood is the reason for the removal of sawmill assortments with a share of wood of the false heartwood from the production of bent furniture, sports tools and partly construction and carpentry products.

Steaming of wood is a technological process in which wet wood is heated by the action of heat in the form of saturated moist air or saturated water steam and changes its physical, mechanical and chemical properties. Temporary physical-mechanical changes are used in the production of veneers, plywood, bent furniture, or pressed wood Nikolov *et al.* 1980; Sergovskij – Rasev 1987; Lawniczak 1995; Trebula 1996; Dzurenda – Deliiski (2019). Permanent chemical changes manifested, among other things, by a change in color, change the color of the wood to more or less distinct shades Deliiski (1991), Tolvaj *et al.* (2009), Dzurenda (2014), Milić *et al.* (2015), Geffert *et al.* (2017), Dzurenda – Dudiak (2022).

The aim of this paper is to determine the norm of saturated water steam consumption for steaming beech wood for a discontinuous heat consumer (steaming autoclave) in order to eliminate the differences between the colors of the sapwood and the false heartwood.

MATERIALS AND METHODS

On the basis of experimental research aimed at analyzing the influence of temperature and length of steaming on the unification of the color of beech sapwood and wood of false heartwood presented in the work of *Dzurenda – Dudiak (2024)*, 2 steaming modes of unification of the color of sapwood and false heartwood with different degrees of darkening of steamed beech wood were proposed wood in Fig. 1.



Figure 1: Wood color of unsteamed beech wood with false heartwood (native) and steamed beech sapwood with false heartwood by individual steaming modes after unification of color.

Due to the technological conditions of steaming, mode I. at the steaming temperature $t_I \approx 105 \text{ }^\circ\text{C}$, beech wood acquires a pale brown color with values on the coordinates of the color space: $L^* = 63.4 \pm 2.3$, $a^* = 13.0 \pm 1.4$; $b^* = 19.1 \pm 1.6$. Mode II. at the steaming temperature $t_{II} \approx 120 \text{ }^\circ\text{C}$, the color of the sapwood and the false heartwood becomes dark brown-gray color with values on the coordinates: $L^* = 57.5 \pm 2.0$; $a^* = 13.4 \pm 1.2$; $b^* = 18.8 \pm 1.5$.

The modes of steaming beech wood with saturated water steam in order to eliminate the differences between the color of the sapwood and the color of the wood of the false heartwood are shown in Fig. 2.

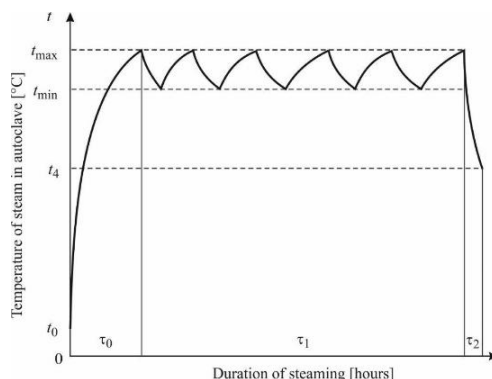


Figure 2: Mode of steaming beech wood with saturated water steam in order to eliminate the differences between the color of the sapwood and the false heartwood.

A breakdown of the technological conditions of steaming by individual modes of steaming beech wood in the form of $h = 40$ mm thick lumber to eliminate color differences between the color of sapwood and the color of wood with a false heartwood is presented in Table 1.

Table 1: Modes for steaming beech wood with saturated water steam

Modes	Saturated steam temperature [°C]			Steaming time [h]			Total time
	t_{max}	t_{min}	t_4	τ_0 heating	τ_1 steaming	τ_3 cooling	
Mode I	102.5	107.5	100	3.5	18.0	0.5	22.0
Mode II	117.5	122.5	100	3.5	9.0	0.5	13.0

The source of heat for the implementation of the technological process is the condensation heat of saturated water steam. One of the alternatives for determining its consumption is the heat consumption balance of the technological process in the steam autoclave. The heat losses of the steaming autoclave and heat consumption balances, among others, are discussed in the following works: Deliiski (2003), Dzurenda – Deliiski (2008), Dzurenda (2016), Dzurenda – Deliiski (2019). The heat consumption balance of the steaming autoclave and the individual heat consumption items of the balance are described by the equations:

$$Q_{ha} = Q_{hw} + Q_{hf} + Q_{hil} + Q_{he} + Q_{hfv} + Q_{hew} \text{ [kJ]} \tag{1}$$

- where: Q_{hw} – heat required for heating steamed wood, kJ;
- Q_{hf} – heat required to heat the structural material of the autoclave, kJ;
- Q_{hil} – heat required to heat the autoclave insulation, kJ;
- Q_{he} – heat loss from the surface of the thermal insulation of the pressure autoclave to the atmosphere, kJ;
- Q_{hfv} – heat loss of the pressure autoclave by the saturated water steam removed from the unfilled working space of the autoclave during its emptying, kJ;
- Q_{hew} – heat extracted by condensate from the pressure autoclave, kJ;

Individual heat consumption in the technological process of steaming wood is described by the equations:

Q_{hw} – heat required to heat steamed wood with moisture content $w > 30\%$:

$$Q_{hw} = V_D \left[\rho_R \left(1 + \frac{w}{100} \right) \right] \frac{c_D}{10^3} (t_4 - t_D) \text{ [kJ]} \quad (2)$$

where: V_D – volume of steamed wood in the pressure autoclave, m^3 ;

ρ_R – reduced wood density, $kg \cdot m^{-3}$;

w – absolute moisture content of steamed wood, %;

c_D – mean value of specific heat capacity of steamed wood, $kJ \cdot kg^{-1} \cdot K^{-1}$;

t_D – wood temperature at the beginning of the thermal process, $^{\circ}C$;

t_4 – temperature of saturated steam and autoclave body at the end of the technological process, $^{\circ}C$.

Q_{hf} – Heat required to heat the structural material of the autoclave:

$$Q_{hf} = m_A c_A [t_4 - t_A] \text{ [kJ]} \quad (3)$$

where: m_A – pressure autoclave body weight, kg ;

c_A – specific heat capacity of the pressure autoclave material, $kJ \cdot kg^{-1} \cdot K^{-1}$;

t_4 – temperature of saturated steam and autoclave body at the end of the technological process, $^{\circ}C$;

t_A – temperature of the pressure autoclave material at the beginning of the technological process, $^{\circ}C$;

Q_{hil} – Heat required to heat the autoclave insulation:

$$Q_{hil} = m_I c_I \left(\frac{(t_1 + t_2)}{2} - t_{Ai} \right) \text{ [kJ]} \quad (4)$$

where: m_I – mass of insulating material, kg

c_I – average value of the specific heat capacity of the insulating material $kJ \cdot kg^{-1} \cdot K^{-1}$;

t_1 – temperature of the body of the autoclave during the technological process, $^{\circ}C$;

t_2 – temperature on the outer surface of the autoclave insulation during technological process, $^{\circ}C$;

t_{Ai} – autoclave insulation temperature before heating, $^{\circ}C$.

Q_{he} – Heat loss from the surface of the thermal insulation of the pressure autoclave to the atmosphere:

$$Q_{he} = 3,6 \cdot \alpha_k \cdot [\pi(D + 2 \cdot h_i)L + \pi(D + 2 \cdot h_i)^2] \cdot (t_2 - t_0) \cdot (\tau_C - \tau_1) \text{ [kJ]} \quad (5)$$

where: α_k – heat transfer coefficient of the surface of the autoclave, $W \cdot m^2 \cdot K^{-1}$

D – diameter of pressure autoclave without insulation, m ;

h_i – thickness of the insulating layer of the pressure autoclave body, m ;

L – length of the cylindrical part of the pressure autoclave, m ;

t_2 – temperature on the outer surface of the autoclave insulation during technological process, $^{\circ}C$;

t_0 – temperature of the pressure autoclave material at the beginning of the technological process, °C;

τ_0 – heating time, h;

τ_1 – time 1 of the technological process phase, h.

Q_{hfv} – Heat loss of the pressure autoclave by the saturated water steam removed from the unfilled working space of the autoclave during its emptying:

$$Q_{hfv} = \left[\frac{\pi \cdot D^2}{4} \cdot L - V_D \right] \cdot \frac{h''}{v''} \text{ [kJ]} \quad (6)$$

where: D – pressure autoclave diameter without insulation, m;

L – length of the cylindrical part of the pressure autoclave, m;

V_D – volume of color-modified wood in the pressure autoclave, m³;

h'' – enthalpy of saturated steam in the autoclave at the end of the technological process, kJ.kg⁻¹;

v'' – specific volume of saturated steam in the autoclave at the end of the technological process m³.kg⁻¹.

Q_{hcw} – Heat loss of the pressure autoclave by the drained condensate at the end of the technological process:

$$Q_{hcw} = m_K (h' - h_{H_2O}) = \frac{Q_{hw} + Q_{hf} + Q_{hil} + Q_{hc}}{r} (h' - h_{H_2O}), \text{ [kJ]} \quad (7)$$

where: m_K – mass of condensed saturated steam during the technological process, kg;

h' – condensate enthalpy at the end of the technological process, kJ.kg⁻¹;

h_{H_2O} – enthalpy of water used to produce saturated steam; kJ. kg⁻¹.

Q_{hw} – heat required for heating colored modified wood, kJ;

Q_{hf} – heat required to heat the structural material of the autoclave;

Q_{hil} – heat required to heat the autoclave insulation, kJ;

Q_{hc} – heat required to cover heat losses from the surface of the pressure autoclave, kJ;

r – condensation heat of saturated steam used in the technological process; kJ. kg⁻¹.

The amount of saturated water steam consumed in the steaming process is quantified by a mathematical notation:

$$m_{H_2O}'' = \frac{Q_{ha}}{r} \text{ [kg]} \quad (8)$$

where: Q_{ha} – total heat consumption wood steaming process, kJ;

r – heat of condensation of saturated water steam used in the steaming process; kJ.kg⁻¹.

The steaming process of wood in a pressure autoclave is a typical discontinuous process characterized by uneven heat consumption. According to the work of Dzurenda – Deliiski (2010), the largest heat consumption is at the beginning of the technological process during the heating time, when the heat of the condensing water steam is used to heat the steamed wood and heat the autoclave. Subsequently, during the technological process, the heat of the condensing saturated steam is used to cover the heat losses of the autoclave. The consumption of saturated

steam during the heating of steamed wood and the autoclave τ_0 and the phase I. of the technological process τ_1 are described by equations (9) and (10):

$$m''_{H_2O-\tau_0} = \frac{Q_{hw}+Q_{hf}+Q_{hil}+Q_{hfv}+Q_{hcw}}{(h''-h')\cdot\tau_0}, [\text{kg}\cdot\text{h}^{-1}] \quad (9)$$

where: Q_{hw} – heat required for heating steamed wood, kJ;
 Q_{hf} – heat required to heat the structural material of the autoclave;
 Q_{hil} – heat required to heat the autoclave insulation, kJ;
 Q_{hc} – heat required to cover heat losses from the surface of the pressure autoclave, kJ;
 Q_{hfv} – heat extracted by saturated steam after opening the autoclave, kJ;
 h'' – enthalpy of saturated steam in the autoclave at the end of the technological process, $\text{kJ}\cdot\text{kg}^{-1}$;
 h' – condensate enthalpy at the end of the technological process, $\text{kJ}\cdot\text{kg}^{-1}$;
 τ_0 – heating time, h.

$$m''_{H_2O-\tau_1} = \frac{Q_{he}}{(h''-h')\cdot\tau_1}, [\text{kg}\cdot\text{h}^{-1}] \quad (10)$$

where: Q_{hc} – heat required to cover heat losses from the surface of the pressure autoclave, kJ;
 h'' – enthalpy of saturated steam in the autoclave at the end of the technological process, $\text{kJ}\cdot\text{kg}^{-1}$;
 h' – condensate enthalpy at the end of the technological process, $\text{kJ}\cdot\text{kg}^{-1}$;
 τ_1 – time phase I of the technological process, h.

RESULTS AND DISCUSSION

Heat consumption for individual steaming modes in Table 2 are performed for steaming 16 m^3 of beech lumber with a moisture content of $W_a \approx 60\%$, saturated water steam in an AZ 240 autoclave with a weight of $m_A = 12\,500 \text{ kg}$.

The individual items of heat consumption of the AZ 240 steaming autoclave in Table 2 quantify the heat consumption of the technological process for eliminating the color differences of beech sapwood and false heartwood. The largest heat consumption is the heat for heating with steamed wood $Q_{hw} \approx 69.2\%$. Heat consumption and heating of the structure of the steam autoclave and insulation is $(Q_{hf} + Q_{hil}) \approx 11\%$ and $Q_{hcw} \approx 15.7\%$ is consumed to cover the heat losses of the pressure autoclave in the form of drained condensate.

Table 2: Heat consumption of the steaming process of beech sapwood and the false heartwood in the AZ 240 autoclave

Title of heat consumption item	Symbol	Mode I		Mode II	
		[MJ]	[%]	[MJ]	[%]
Heat for heating thermally treated wood	Q_{hw}	4 026.48	68.1	4 726.20	70.4
Heat for heating the construction material of the autoclave	Q_{hf}	570.00	9.6	660.00	9.8
Heat for heating the autoclave insulation	Q_{hil}	82.62	1.4	95.66	1.4
Heat to cover the heat losses of the pressure autoclave	Q_{hc}	255.11	4.3	120.37	1.9
Heat loss of by the saturated water steam removed from the working space of the autoclave during its emptying	Q_{hfv}	54.94	0.9	54.94	0.8
Heat losses in the removed condensate at the end of the steaming process	Q_{hcw}	927.10	15.7	1 054.31	15.7
Total heat consumption for steaming wood in an autoclave	Q_{ha}	5 916.25	100.0	6 720.48	100.0

The fact that more than 2/3 of the supplied heat is directly used for the implementation of the technological process testifies to the high efficiency of heat use in the thermal process of color homogenization of wood in pressure autoclaves. The stated value is 3 times higher than the direct use of heat in wood steaming technologies implemented at atmospheric pressure in steam pits, chambers and bells Lawniczak (1995), Trebula (1996), Dzurenda – Deliiski (2019).

A comparison of the heat consumption of individual steaming modes shows that steaming mode II. has the largest heat consumption. Steaming process by mode II. although it is shorter by $\Delta\tau = 9$ h than mode I., but the increased temperature of saturated water steam from temperature $t_I = 105$ °C to temperature $t_{II} = 120$ °C, i.e. by $\Delta t = 15$ °C is reflected in an increase in heat consumption in the process of unifying the colors of sapwood and false heartwood from $Q_{ha} = 5 916.25$ MJ to $Q_{ha} = 6 720.48$ MJ i.e. by 13.6%.

Table 3 shows the consumption of saturated water steam for the steaming process based on heat consumption balances in the individual beech steaming modes with Tab. 2.

Table 3: Consumption of saturated water steam for steaming beech wood according to individual modes

Steam conditions		Mode I	Mode II
Consumption of saturated steam	kg	2637.6	3051.9

In Fig. 3 shows the consumption of saturated water steam during the process of steaming beech wood to a dark brown-gray color by mode II. for the heating phase and the unification phase of the wood colors by the steaming process according to equations (9) and (10).

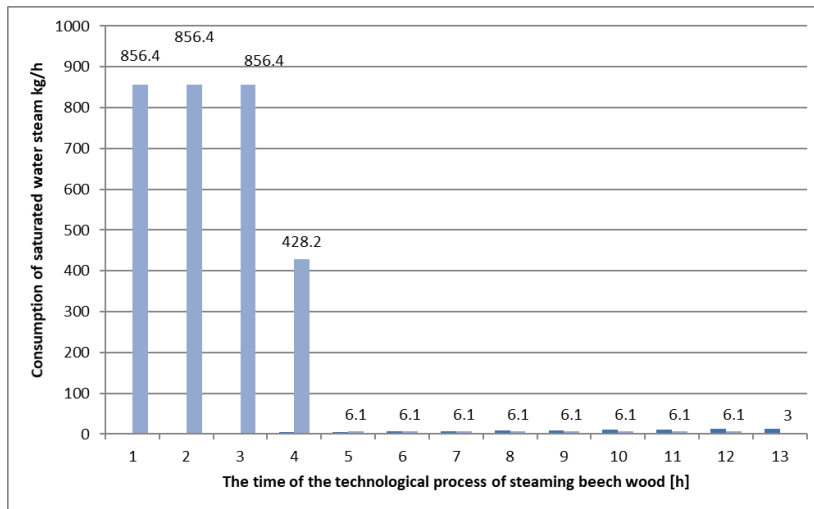


Figure 2: Dependence of the consumption of saturated water steam during the technological process steaming $V = 16 \text{ m}^3$ of beech lumber in pressure autoclave AP 240 mode II.

The presented results of the consumption of saturated water steam of the steaming autoclave AZ 240 when unifying the colors of beech sapwood and false heartwood specify the requirements for the heat source. At the beginning of the technological process in mode II, during heating τ_0 , the hourly consumption of saturated steam is $m_{\text{H}_2\text{O}} = 856.4 \text{ kg}\cdot\text{h}^{-1}$. During the wood color modification process itself, the hourly consumption of saturated water steam drops to $m_{\text{H}_2\text{O}} = 6.1 \text{ kg}\cdot\text{h}^{-1}$.

The specification of the consumption of saturated water steam during the steaming of wood in a steam autoclave is an important source of information for the planning of heat production in the thermal system of the plant.

Condensed water steam is contaminated during the technological process of wood steaming by products of hydrolysis and extraction from steamed wood Samešova *et al.* (2018). After the end of the technological process, it is not sent to the heat producer's boiler room, but to the wastewater treatment plant. The condensate balance is also a specification of the capacity requirements for wastewater treatment at the wastewater treatment plant.

CONCLUSION

The article presents the consumption of heat and saturated water steam in the process of steaming 16 m^3 of beech lumber with a moisture content of $W_a \approx 60\%$, in order to eliminate the differences between the color of the sapwood and the wood of the false heartwood in the pressure autoclave AZ 240.

Due to the technological conditions of steaming, mode I. at the steaming temperature $t_{\text{I}} \approx 105 \text{ }^\circ\text{C}$, beech wood acquires a pale brown color with values on the coordinates of the color space: $L^* = 63.4 \pm 2.3$, $a^* = 13.0 \pm 1.4$; $b^* = 19.1 \pm 1.6$. Mode II. at the steaming temperature $t_{\text{II}} \approx 120 \text{ }^\circ\text{C}$, the color of the sapwood and the false heartwood becomes dark brown-gray color with values on the coordinates: $L^* = 57.5 \pm 2.0$; $a^* = 13.4 \pm 1.2$; $b^* = 18.8 \pm 1.5$.

A comparison of the heat consumption of individual steaming modes shows that steaming mode II. has greater heat consumption. Steaming process by mode II. although it is shorter by

$\Delta\tau = 9$ h than mode I., but the increased temperature of saturated water steam from temperature $t_1 = 105$ °C to temperature $t_{II} = 120$ °C, i.e., by $\Delta t = 15$ °C is reflected in an increase in heat consumption in the process of unifying the colors of sapwood and false heartwood from $Q_{ha} = 5\,916.25$ MJ to $Q_{ha} = 6\,720.48$ MJ i.e., by 13.6%.

From the analyzes of the consumption of saturated water steam in the steaming process of 16 m^3 of beech wood in the pressure autoclave AZ 240, it follows that the autoclave consumes $m_{H_2O} = 3051.9$ kg of saturated water steam at a temperature of $t_{II} = 120 \pm 2.5$ °C during the technological process. At the time of maximum consumption, at the beginning of the technological process during heating, the hourly consumption of saturated water steam is $m_{H_2O} = 856.4$ kg.h⁻¹.

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