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HEAT BALANCES OF CONCRETE PITS WHEN STEAMING OR BOILING UNFROZEN LOGS

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ABSTRACT

An approach to calculating the heat balance of concrete pits during the steaming or boiling of unfrozen logs intended for the production of peeled veneer is presented. Using our non-stationary model, the heating times of beech logs with a diameter of 0.4 m, initial temperatures of 0, 10, and 20 °C, and humidity of 0.6 kg.kg^{-1} at an operating temperature in the pit of 80 °C were determined. Using the determined log heating times and our stationary model, the change in total energy required to perform the entire steaming or boiling process, as well as the energy needed for each of the individual components of the pit heat balance, was calculated. Computer simulations were performed for a concrete pit with overall dimensions of 7.4 × 2.8 × 2.5 m, a working volume of 20 m³, and a degree of filling with logs of 45%, 60%, and 75%. The total heat consumption for heating beech logs with a diameter of 0.4 m, an initial temperature tw0 = 10 °C, and a humidity of 0.6 kg·kg^{-1} at an operating temperature in the pit tm1 = 80 °C and a degree of filling f = 75% is equal to 114.7 kWh.m³ for log steaming and 152.7 kWh.m³ for log boiling. It was found that increasing the initial log temperature from 0 °C to 20 °C results in a decrease in the total energy consumption of the pit, from 122.8 to 106.3 kWh.m³ for the steaming process and from 159.7 to 145.4 kWh.m³ for the boiling process. Reducing the pit load from 75% to 45% would result in an increase in energy consumption in the pit from 114.7 to 157.0 kWh.m³ in the log steaming process and from 152.7 to 278.8 kWh/m³ in the log boiling process.

Keywords: pits; heat balance; steaming or boiling logs; plasticizing; veneer production.

INTRODUCTION

It is well known that steaming and boiling wood are technological processes in which wet wood materials are subjected to heating using saturated water steam or hot water, and their physical, mechanical and partly chemical properties change (Chudinov, 1968; Kollmann and Côté, 1984; Pervan, 2009; Niemz and Sonderegger, 2017).

The heat treatment of logs in steaming or boiling pits is carried out most often to plasticize the wood to reduce the cutting resistance during the formation of quality veneer (Lawniczak, 1995; Mahút *et al.,* 1998 Trebula and Klement, 2002; Deliiski, 2003, 2004; Videlov, 2003; Steinhagen, 2005; Deliiski and Dzurenda, 2010; Kavalov and Angelski, 2014; Klement *et al.,* 2021; Niemz *et al.,* 2023; Klement *et al.,* 2024).

The steaming and boiling processes of wood in pits are characterized by high energy consumption and low energy efficiency. The works (Sohor and Kadlec, 1990; Lawniczak, 1995; Dzurenda and Deliiski, 2019) state that in steaming pits, when heating wood for veneer production, the heat effectively used for heating the wood does not exceed 25 – 30% of the total heat consumed.

Publications devoted to determining the energy required to steam or boil wood materials in pits are scarce. Only in Dzurenda and Deliiski (2019), a mathematical model of the heat balance of the concrete pit (Fig. 1) was proposed when boiling unfrozen wooden prisms intended for veneer production. When studying with this model, the balance of the pit for the case of boiling in it 12 m^3 beech prisms with dimensions 0.4 × 0.25 × 1.2 m, moisture content of 0.8 $kg \cdot kg^{-1}$, the initial temperature of 10 °C at a water temperature of 80 °C until reaching a temperature in the center of the prisms of 70 °C, the total energy consumption of the pit of 630.13 $MJ \cdot m^{-3}$ was calculated. The following results were obtained for the individual components in the heat balance: 29.3% for heating the prisms, 31.1% for heating the pit construction, 35.4% for warming up the water, 3.2% for covering the heat losses, 1.0% for warming up of the pit metal radiator, which is powered by steam or hot water under increased pressure and provides indirect heating of boiling water in the pit. Using this model, the components of the energy required to heat the individual parts of the pit construction were calculated.

The aim of this work is to update the model presented in (Dzurenda and Deliiski, 2019) and, after its extension by a model for wood steaming in pits and to compare the heat balances of the same concrete pit for the cases of separate steaming or boiling of unfrozen wooden prisms intended for veneer production.

MATERIAL AND METHODS

Design features of the pit, in which the logs are subjected to steaming or boiling

The study was conducted on the heat balances of the pit shown in Fig. 1, which has the following dimensions: length Lp = 7.4 m, width Bp = 2.8 m, and depth Hp = 2.5 m.

The symbols, units, and values of all the parameters marked in Fig. 1 are given in Table 1. The pit is a concrete tank with steel reinforced walls and a steel armature at the bottom. The body of the tank is waterproofed against both the escape of hot water from the pit and the penetration of groundwater into the pit. The walls and the bottom of the pit are thermally insulated in order to reduce the density of the heat flow from the inside of the pit to the atmospheric air in the above-ground part of the pit walls and the heat flow to the soil in the part of the pit located in the ground.

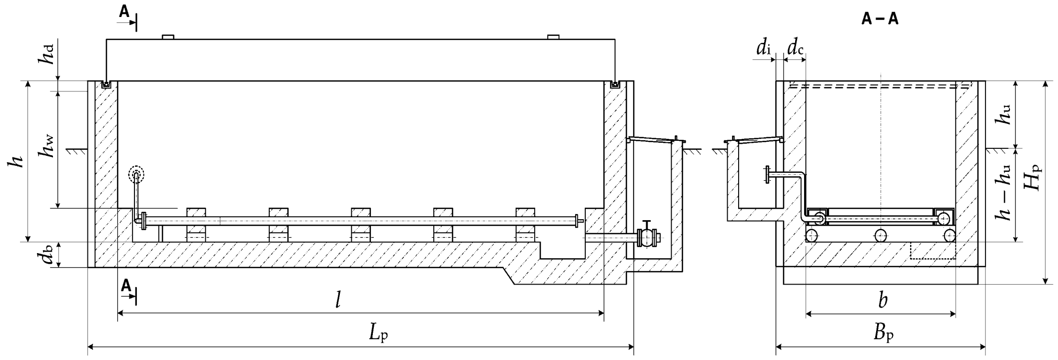


Fig. 1 Longitudinal and transverse section of the pit for steaming or boiling wood materials used during the computations of its heat balances.

Tab. 1 Main set parameters of the concrete pit used to solve the mathematical models.

Parameter	Symbol	Unit	Value
1. Length of the working volume of the pit	l	m	6.6
2. Width of the working volume of the pit	b	m	2.0
3. Depth of the working volume of the pit	h_w	m	1.52
4. Depth of the pit walls	h	m	2.0
5. Depth of the upper (above-ground) part of the pit	h_u	m	0.8
6. Working volume of the pit, equal to $l \cdot b \cdot h_w$	V_{pit}	m^{-3}	20
7. Thickness of the walls and bottom of the pit	d_c, d_b	m	0.3
8. Thickness of the insulating layer of the walls and steel lid	d_i, $d_{i\text{-lid}}$	m	0.1
9. Thickness of the steel sheets of the pit lid	d_{Fe}	m	0.004
10. Distance of the drainage channel from the pit edge	h_d	m	0.13
11. Density of the concrete walls and bottom of the pit	ρ_c	$kg \cdot m^{-3}$	2300
12. Density of the insulating layers of the pit walls and lid	ρ_i, $\rho_{i\text{-lid}}$	$kg \cdot m^{-3}$	350
13. Density of the steel sheets of the lid	ρ_{Fe}	$kg \cdot m^{-3}$	7850
14. Initial temperature of the pit walls and bottom	t_{cu0}, t_{cg0}	ºC	10
15. Initial temperature of the pit insulating layer and soil	t_{i0}, t_{s0}	ºC	10
16. Specific heat capacity of the concrete (average value)	c_c	$J \cdot kg^{-1} \cdot K^{-1}$	1134
17. Specific heat capacity of the pit insulation layers	c_i, $c_{i\text{-lid}}$	$J \cdot kg^{-1} \cdot K^{-1}$	850
18. Specific heat capacity of the steel sheets of the pit lid	c_{Fe}	$J \cdot kg^{-1} \cdot K^{-1}$	444
19. Thermal conductivity of the concrete (average value)	λ_c	$W \cdot m^{-1} \cdot K^{-1}$	1.28
20. Thermal conductivity of the log's insulating layers	λ_i	$W \cdot m^{-1} \cdot K^{-1}$	0.042
21. Thermal conductivity coefficient of the sandy-clay soil	λ_s	$W \cdot m^{-1} \cdot K^{-1}$	1.4
22. Specific mass of the heating elements of the radiator on 1 m^2 of the area of at the bottom of the pit	m_{he}	$kg \cdot m^{-2}$	100
23. Temperature of the heat carrier in the radiator of the pit	t_{hc}	ºC	130
24. Temperature of the surrounding air of the pit	t_{air}	ºC	10
25. Loading level of the pit, i.e. the degree of filling in with logs	f	%	45, 60,75

During the steaming or boiling process of wood materials, the pit is closed with a removable, well-insulated metal lid to protect workers from falling into the working area of the pit and to minimize heat losses into the surrounding air. The walls of the pit construction are finished with a groove filled with water, into which the protruding edge of the lid is immersed when the pit is closed, creating a perfect water seal.

The required operating temperature in the pit during log steaming is provided by direct saturated water steam, which is introduced into the pit through the heating elements of a tubular radiator. The radiator is located in the lower part of the pit and is supplied with water steam from a steam generator of appropriate performance. The tubular elements of the radiator are perforated on their underside, allowing steam to pass through a layer of condensed water as it heats the pit and the logs within. After steaming is completed, the pit is drained, and the condensed water is removed from it.

The heating of the water in the pit to the required operating temperature during log boiling is carried out indirectly using heating elements in the radiator, which is located at the lower end of the pit. In this case, its tubular elements are not perforated. The radiator connected to the plant's heating system is powered by steam or hot water with pressure higher than atmospheric and with a temperature of 120–140 °C (Dzurenda and Deliiski, 2019).

Logs and modes parameters used in the computer simulations

This research was conducted over unfrozen beech (*Fagus sylvatica* L.) logs, which are commonly used in veneer and plywood production.

Fig. 2 illustrates the variation in processing medium temperature (tm) in commonly applied modes for heating wood materials with hot water or saturated steam to plasticize them in equipment operating at atmospheric pressure (Shubin, 1990; Pervan, 2009). These modes consist of two stages, during which tm changes as follows:

- during the first stage, in the course of time 0 – τ1, an increase in tm from tm0 to tm1 takes place by fully or partially opening the valve to introduce a heat carrier to the pit;
- during the second stage of the modes, in the course of time τ1 – τ2, the dosed introduction of the heat carrier into the pit radiator is carried out to maintain a constant technologically permissible value of tm, equal to the maximum mode's value tm1.

When the time τ2 is reached, the logs subjected to steaming or boiling reach the optimal temperature required for their subsequent mechanical processing in the veneer production.

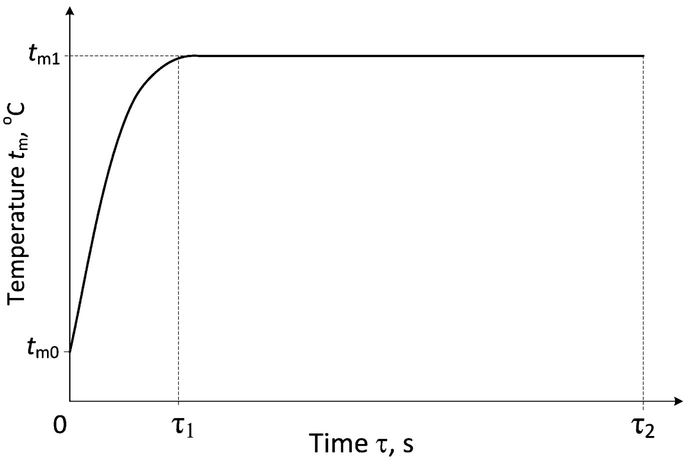


Fig. 2 Change of the processing medium temperature t_m in modes for steaming or boiling of wood materials in pits.

The symbols, units, and values of the logs' and also of the steaming and boiling modes' parameters involved in the equations of the models given below, which were used in the numerical calculations of the pit heat balances, are presented in Table 2.

Modelling the 1D temperature distribution in logs subjected to steaming or boiling

To calculate the heat balance of the pits for cases of heating unfrozen logs, it is necessary to know the duration of their steaming and boiling, τ2 (Fig. 2), which depends on the influencing factors.

Tab. 2 Main set parameters of the logs and their steaming and boiling modes used to solve models.

Parameter	Symbol	Unit	Value
1. Diameter of the logs subjected to steaming or boiling	D	m	0.4
2. Length of the logs	L	m	2.0
3. Volume of the logs loaded in the pit for steaming or boiling, which is equal to $f \cdot V_{pit}$: (a – at f = 75%; b – at f = 60%; c – at f = 45%)	V_w	m^3	15*a* 12*b* 9*c*
4. Moisture content of the logs	u	$kg \cdot kg^{-1}$	0.6
5. Fiber saturation point of beech wood at 293.15 K (20 ºC)	$u_{fsp(293.15K)}$	$kg \cdot kg^{-1}$	0.31
6. Basic density of the beech wood	ρ_b	$kg \cdot m^{-3}$	560
7. Density of the wood, equal to $\rho_b \cdot (1+u)$	ρ_w	$kg \cdot m^{-3}$	896
8. Specific heat capacity of the water in the pit	c_{H2O}	$J \cdot kg^{-1} \cdot K^{-1}$	4180
9. Initial average mass temperature of the logs	t_{wo}	ºC	0 10 20
10. Minimum temperature in the center of the logs at the end of their steaming or boiling (i.e. at $\tau = \tau_2$)	t_{wc-min}	ºC	62
11. Initial value of the operating temperature in the pit	t_{m0}, $t_{H2O-beg}$	ºC	10
12. Maximum value of the operating temperature in the pit	t_{m1}, t_{H2O}	ºC	80
13. Time constant of exponential increase of t_m from t_{m0} to t_{m1}	τ_e	s	3600
14. Duration of increase in t_m from t_{m0} to t_{m1}	τ_1	h	4.0
15. Entire duration of the steaming and boiling modes of the logs, depending on t_{w0} (d – at t_{wo} = 0 ºC; e – at t_{wo} = 10 ºC; g – at t_{wo} = 20 ºC)	τ_2	h	21.0*d* 20.0*e* 18.5*g*
16. Average temperature of all logs at the end (i.e. at $\tau = \tau_2$) of their steaming or boiling	$t_{avg-end}$	ºC	72.7
17. Specific heat capacity of the logs at the beginning of their steaming and boiling, depending on t_{w0}	c_{w0}	$J \cdot kg^{-1} \cdot K^{-1}$	2653*d* 2705*e* 2757*g*
18. Specific heat capacity of the logs at the end of their steaming or boiling (i.e. at $t_{avg-end}$ = 72.7 ºC)	$c_{w-avg-end}$	$J \cdot kg^{-1} \cdot K^{-1}$	3039
19. Thermal conductivity of the logs in the radial direction at the beginning of their steaming and boiling, depending on t_{w0}	λ_{w-r}	$W \cdot m^{-1} \cdot K^{-1}$	0.428*d* 0.442*e* 0.456*g*
20. Thermal conductivity of the logs at $t_w = t_{m1}$ = 80 ºC	$\lambda_{w-r(80\ C)}$	$W \cdot m^{-1} \cdot K^{-1}$	0.542
21. Condensation heat of steam in the pit at $\tau = \tau_2$ and 80 ºC	r_{steam}	$MJ \cdot kg^{-1}$	2308
22. Enthalpy of the condensation water in the pit at t_{m1}=80 ºC	h_{cw}	$MJ \cdot kg^{-1}$	335

Since the heating of the logs is a multifactorial process, the duration τ_2 is most suitable to be determined with the help of a non-stationary mathematical model adequate to the real process. When the length of the logs, L, is at least 4 times their diameter, D, their steaming and boiling duration can be determined using the following experimentally verified 1D model (Deliiski, 2011, 2013):

$$c_w(u,T)\cdot\rho_w(u,\rho_b)\cdot\frac{\partial T(r,\tau)}{\partial\tau}=\lambda_{w\text{-}r}\left(\frac{\partial^2 T(r,\tau)}{\partial r^2}+\frac{1}{r}\cdot\frac{\partial T(r,\tau)}{\partial r}\right)+\frac{\partial\lambda_{w\text{-}r}}{\partial T}\left(\frac{\partial T(r,\tau)}{\partial r}\right)^2 \quad (1)$$

at initial condition

$$T(r,0)=T_{w0} \quad (2)$$

and boundary condition, which is the same for steaming and boiling logs due to the very high heat transfer to the logs from the condensing water steam or hot water respectively:

$$T(0,\tau)=T_m(\tau) \quad (3)$$

Where: c_w is the specific heat capacities of the unfrozen wet wood, $J\cdot kg^{-1}\cdot K^{-1}$; $\lambda_{w\text{-}r}$– thermal conductivity coefficient in radial direction of the unfrozen wet wood, $W\cdot m^{-1}\cdot K^{-1}$; ρ_w – density of the wood, $kg\cdot m^{-3}$; ρ_b – basic density of the wood, equal to dry mass divided by green volume, $kg\cdot m^{-3}$; u – wood moisture content, $kg\cdot kg^{-1}$; r – coordinate along the log radius: $0 \le r \le R$, m; R – radius of the log, m; T – temperature, K; T_{w0} – initial average mass temperature of the log, K; T_m – operating temperature of the processing steaming or boiling medium in the pit, K; τ – time, s.

The specific heat capacity c_w, density ρ_w, and thermal conductivity $\lambda_{w\text{-}r}$ of the unfrozen wood above the hygroscopic range can be calculated according to the following equations (Deliiski, 2003, 2011, 2013; Deliiski and Dzurenda, 2010):

$$c_w=\frac{1}{1+u}(2862u+2.95T+5.49u\cdot T+0.0036T^2+555) \quad (4)$$

$$\rho_w=\rho_b\cdot(1+u) \quad (5)$$

$$\lambda_{w\text{-}r}=\lambda_{w0-r}\cdot\left\{1+\left[3.65\cdot\left(\frac{579}{\rho_b}-0.124\right)\cdot 10^{-3}\right]\cdot(T-273.15)\right\} \quad (6)$$

$$\lambda_{w0\text{-}r}=K_{ad\text{-}r}\cdot(0.1284-0.013u)\cdot\left[0.165+(1.39+3.8u)\cdot\left(3.3\cdot 10^{-7}\cdot\rho_b^2+1.015\cdot 10^{-3}\cdot\rho_b\right)\right] \quad (7)$$

Where: $\lambda_{w0\text{-}r}$ is the wood thermal conductivity at 273.15 K (i.e., at 0 °C), $W\cdot m^{-3}\cdot K^{-1}$; $K_{ad\text{-}r}$ – coefficient, which takes into account the influence on $\lambda_{w0\text{-}r}$ of the heat flux towards the radial anatomic direction of the wood. In Deliiski (2003, 2013), it was found that $K_{ad\text{-}r}$ = 1.35 for the beech wood.

During the solving of the model (1) – (3), the current average mass temperature of the log, T_{avg}^n, can be calculated according to the following equation (Deliiski, 2011):

$$T_{avg}^n=\frac{1}{R}\int_R T(r,n\cdot\Delta\tau)\mathrm{d}R \quad (8)$$

Where: R is the radius of the log, m; $\Delta\tau$ – step along the time coordinate, s; n – time level during the model solving: n = 0, 1, 2, 3, …, $\frac{\tau_2}{\Delta\tau}$.

The values of T_{avg} at the moment when the slowest changing temperature in the central point of the logs reaches the minimum temperature $T_{wc\text{-}min}$, required for optimal plasticization of the logs, i.e. value $T_{avg\text{-}end}$, nd this is an indicator of the completion of the log steaming or boiling modes at $\tau = \tau_2$ (Fig. 2), are needed below to calculate the energy consumed by the logs up to that moment.

Mathematical models of the heat balances of pits during the steaming or boiling of logs

The heat balances of the pit during the steaming or boiling of logs in it can be mathematically presented by the following models:

• during the steaming of logs:

$$Q_{\text{Pit-steaming}} = Q_{\text{Wood}} + Q_{\text{Constr.}} + Q_{\text{Cond. water}} + Q_{\text{Radiator}} + Q_{\text{Heat losses}} \quad (9)$$

• during the boiling of logs:

$$Q_{\text{Pit-boiling}} = Q_{\text{Wood}} + Q_{\text{Constr.}} + Q_{\text{Hot water}} + Q_{\text{Radiator}} + Q_{\text{Heat losses}} \quad (10)$$

Where: $Q_{\text{Pit-steaming}}$ and $Q_{\text{Pit-boiling}}$ are the total specific (relating to 1 m^3 wood) heat energies required for the implementation of the entire processes of plasticizing the logs subjected respectively to steaming or boiling in the pit; Q_{Wood} – the energy required for warming up of the logs themselves subjected to heating; $Q_{\text{Constr.}}$ – the energy required for heating the pit construction materials; $Q_{\text{Cond. water}}$ – energy in the condensed water that accumulates at the bottom of the pit during the steaming of the logs and is removed from the pit at the end of the steaming modes; $Q_{\text{Hot water}}$ – energy required to heat the water in the pit to the set maximum temperature t_{m1} of the boiling regime (Fig. 2); Q_{Radiator} – the energy required to heat the metal radiator of the pit, with the help of which saturated water vapor is introduced when steaming logs or the water in the pit is heated when boiling logs; $Q_{\text{Heat losses}}$ – the energy required to cover heat losses of the pit during the logs' steaming or boiling processes. The unit of all specific energies Q in equations (9) and (10), and also everywhere below, is $kWh{\cdot}m^{-3}$.

The mathematical model (10) differs from the analogous model proposed by Dzurenda and Deliiski (2011, 2019) in that it lacks the component that accounts for the energy required to heat the moist air in the space between the boiling water and the pit lid. According to the cited sources, this component has a negligibly small value, accounting for only 0.03% of the heat balance of the boiling pit.

Mathematical model of Q_{wood}

The specific energy required for heating the unfrozen logs subjected to steaming or boiling in the pit, Q_{wood}, can be calculated using the following equation (Deliiski, 2013; Deliiski *at al.*, 2023):

$$Q_{\text{Wood}} = \frac{\rho_{\text{w}}}{3.6.10^6} \cdot \frac{c_{\text{w}} \text{ at } T = T_{\text{w0}} + c_{\text{w}} \text{ at } T = T_{\text{avg-end}}}{2} \cdot \left(T_{\text{avg-end}} - T_{\text{w0}}\right) \quad (11)$$

Where: the specific heat capacity c_{w}, density ρ_{w} , and average mass temperature $T_{\text{avg-end}}$ (at $\tau = \tau_2$ according to Fig. 2) are calculated using equations (4), (5), and (8), respectively.

Mathematical model of $Q_{\text{Constr.}}$

The specific heat energy required for warming up the construction materials of the pit, $Q_{\text{Constr.}}$, can be expressed by the following model:

$$Q_{\text{Constr.}} = Q_{\text{Constr.1}} + Q_{\text{Constr.2}} + Q_{\text{Constr.3}} + Q_{\text{Constr.4}} \quad (12)$$

Where: $Q_{\text{Constr.1}}$ and $Q_{\text{Constr.2}}$ are the energies required for heating of the walls of the above-ground part and those located in the ground part, respectively, of the pit construction; $Q_{\text{Constr.3}}$ and $Q_{\text{Constr.4}}$ – the energies required for heating of the pit bottom and pit lid, respectively.

In (Dzurenda and Deliiski, 2010, 2011, 2019; Deliiski *et al.*, 2023) equations are given for the calculation of each of the four components of $Q_{\text{Constr.}}$ depending on the set of constructive and thermophysical factors influencing them, which are given in Table 1.

Mathematical model of $Q_{\text{Cond.water}}$

The specific heat energy accumulated in the condensed water, which during steaming is collected at the lower end of the pit and is removed from it at the end of the steaming regimes, $Q_{\text{Cond.water}}$, can be calculated by the following model:

$$Q_{\text{Cond.water}} = m_{\text{cw}} \cdot \frac{h_{\text{cw}}^{\tau_2}}{3.6 \cdot 10^6 \cdot V_{\text{w}}} \tag{13}$$

Where:

$$m_{\text{cw}} = 3.6 \cdot 10^6 \cdot V_{\text{w}} \cdot \frac{Q_{\text{Wood}} + Q_{\text{Constr.}} + Q_{\text{Heat losses}}}{r_{\text{steam}}^{\tau_2}} \tag{14}$$

The volume of the wood materials subjected to steaming or boiling in the pit, V_{w}, which participates in equations (13) and (14), is equal to

$$V_{\text{w}} = f \cdot V_{\text{pit}} \tag{15}$$

where f is the loading level of the pit with wood materials subjected to steaming, $\text{m}^3 \cdot \text{m}^{-3}$; V_{pit} – working space of the pit equal to (Fig. 1)

$$V_{\text{pit}} = l \cdot b \cdot h_{\text{w}} \tag{16}$$

The values of the mass of condensed water in the pit, m_{cw}, and the energy dependent on it, $Q_{\text{Cond.water}}$, are calculated with equation (14) for the conditions of the end of the second stage of the steaming regimes (Fig. 2), i.e., at $t_{\text{m}} = t_{\text{m1}}$ and $\tau = \tau_2$, when the valve for draining the condensed water from the pit is fully opened. The mass m_{cw} is formed by the amount represented in $\text{J} \cdot \text{m}^{-3}$ of the sum of the energies Q_{Wood}, Q_{Constr}, and $Q_{\text{Heat losses}}$ after dividing it by condensation heat of steam in the pit, r_{steam}, at the moment $\tau = \tau_2$. The values of enthalpy of the condensation water, h_{cw}, and of r_{steam}, are given in Table 2. They are taken from reference books on the thermodynamic parameters of water and saturated steam at $t_{\text{m1}} = 80$ °C (Dzurenda and Deliiski, 2019).

Mathematical model of $Q_{\text{Hot water}}$

The specific thermal energy required to heat the boiling water in the pit, $Q_{\text{Hot water}}$, can be expressed by the following model:

$$Q_{\text{Hot water}} = \frac{1}{3.6 \cdot 10^6 \cdot V_{\text{w}}} \left[\left(l \cdot b \cdot \left(h_{\text{w}} - h_{\text{d}} \right) - V_{\text{w}} \right) \right] \cdot \rho_{\text{H2O}} \cdot c_{\text{H}_2\text{O}} \cdot \left(t_{\text{H}_2\text{O}} - t_{\text{H}_2\text{O-beg}} \right) \tag{17}$$

The meaning and values of all variables in equation (17) are given in Table 1 and Table 2. Equation (17) applies to cases where the water in the pit at the beginning of the logs' boiling process is not contaminated with diluted organic acids and other water-leachable substances from the previous wood thermal treatment process.

Mathematical model of Q_{Radiator}

The specific heat energy required for warming up the metal radiator of the pit itself at the beginning of the wood steaming or boiling process, Q_{Radiator}, can be expressed by the following model:

$$Q_{\text{Radiator}} = \frac{1}{3.6 \cdot 10^6 \cdot V_{\text{w}}} \left[l \cdot b \cdot m_{\text{he}} \cdot c_{\text{Fe}} \cdot \left(t_{\text{hc}} - t_{\text{H2O-beg}} \right) \right], \tag{18}$$

The meaning and values of all variables in equation (18) are given in Table 1 and Table 2.

Mathematical model of $Q_{\text{Heat losses}}$

The specific heat energy required to cover the heat losses of the pit during the steaming or boiling processes, $Q_{\text{Heat losses}}$, can be expressed by the following model:

$$Q_{\text{Heat losses}} = Q_{\text{Heat losses1}} + Q_{\text{Heat losses2}} + Q_{\text{Heat losses3}} + Q_{\text{Heat losses4}} \tag{19}$$

where $Q_{\text{Heat losses1}}$, and $Q_{\text{Heat losses2}}$, are the energies required to cover the heat losses caused by the heat emission through the walls of the above-ground part and those located in the ground part of the pit construction, respectively; $Q_{\text{Heat losses3}}$, and $Q_{\text{Heat losses4}}$, − energies required to cover the heat losses caused by the heat emission through the pit bottom and pit lid, respectively.

In (Dzurenda and Deliiski 2011, 2019; Deliiski *et al*., 2023) equations are given for the calculation of each of the four components of $Q_{\text{Heat losses}}$, depending on the influencing structural, thermophysical and time factors, some of which are given in Tables 1 and 2.

Solving the models (1) – (3) and (4) − (19)

The mathematical descriptions of the thermo-physical characteristics of wood, as indicated in the Materials and Methods section, were entered into models (1)– (3), which were solved using the finite difference method with the aid of a custom software program in the Visual FORTRAN Professional computing environment. From the obtained change of the temperature along the radius of the logs, and in particular from that of the temperature in their center and of the average mass temperature t_{avg}, the duration of the steaming and boiling modes of the logs, τ_2, indicated in Table 2, was determined for the three investigated values of the initial average mass temperature of the logs, namely t_{w0} = 0, 10, and 20 °C.

An Excel program was prepared for joint solving of the equations involved in the models (4), (5), and (9) – (19) (http://www.gcflearnfree.org/excel2010). Using this program, the heat balances of the pit shown in Fig. 1 were investigated separately for the cases of steaming and boiling in it of the studied unfrozen beech logs at a degree of filling of the pit with logs, f, equal to 45%, 60%, and 75%. As input data relating to the design parameters of the studied pit (Fig. 1), as well as to the characteristics of the logs subjected to steaming or boiling and to the operating temperature in the pit (Fig. 2), those specified above in Table 1 and Table 2 were used.

RESULTS AND DISCUSSION

Fig. 3 shows the change in the slowest increasing temperature in the center of the studied logs, t_{wc}, and also the average mass temperature of the logs, t_{avg}, calculated with the model (1) − (3) and equation (8) during logs' steaming or boiling at the operating temperature t_m in the pit. The temperature t_m changes from the initial value t_{m0} = 10 °C to its maximum values t_{m1} = 80 °C.

The time constants in the equation for the exponential increase in t_m from t_{m0} = 10 °C to t_{m1} were so chosen during the simulations that the duration of this increase τ_1 (Fig. 2) was equal to 4 h (i.e., 14,400 s) for all three investigated values of t_{w0}, equal to 0, 10, and 20 °C.

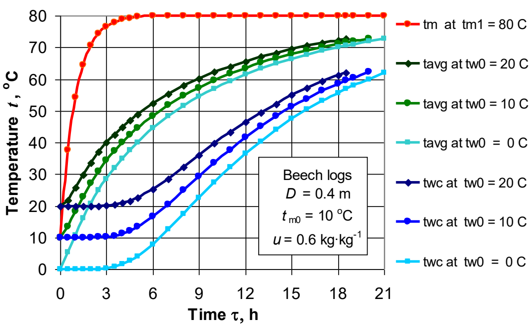


Fig. 3 Change in t_m, t_{wc}, and t_{avg} of the studied logs during their boiling, depending on t_{w0}.

In Fig. 3 it can be seen that both the steaming and the boiling at t_{m1} = 80 °C of the studied logs having a diameter of D = 0.4 m and a moisture content u = 0.6 kg·kg^{-1} ends as follows: after τ_2 = 21.0 h at t_{w0} = 0 °C, after τ_2 = 20.0 h at t_{w0} = 10 °C, and after τ_2 = 18.5 h at t_{w0} = 20 °C.

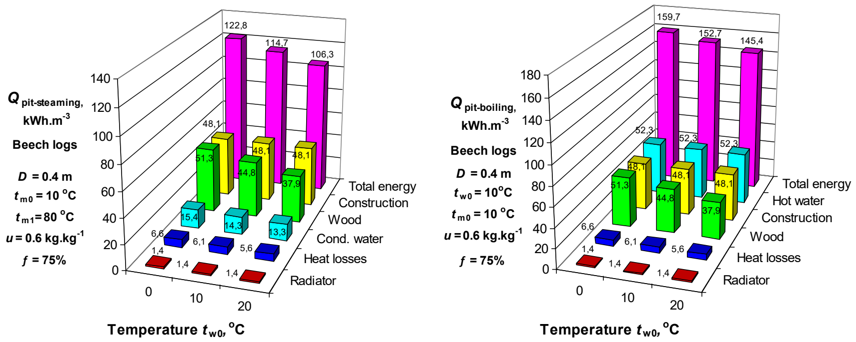
At these values of τ_2, the temperature of the slowest-heating central point of the logs reaches 62°C, which corresponds to the minimum required temperature necessary to obtain a quality veneer from the heated and plasticized beech logs (Mörath, 1949; Deliiski and Dzurenda, 2010). It is also seen that during both the steaming and the boiling processes, the average mass temperature of the logs rises from its initial values of t_{w0} = 0 °C, t_{w0} = 10 °C, and t_{w0} = 20 °C to the same final average mass temperature, equal to $t_{avg\text{-}end}$ = 72.7 °C.

Fig. 4 presents the change in all components of the heat balances of the tested pit at its loading level f = 75%, as well as the total energy consumption (in kWh·m^{-3}) of the pit required to carry out the entire steaming or boiling processes, depending on t_{w0}.

Fig. 5 shows the change of the individual components of the heat balances of the pit Q_i at f = 75% in % to the total energy consumption, $Q_{steam\text{-}total}$ and $Q_{boil\text{-}total}$ respectively, depending on the studied values of t_{w0}.

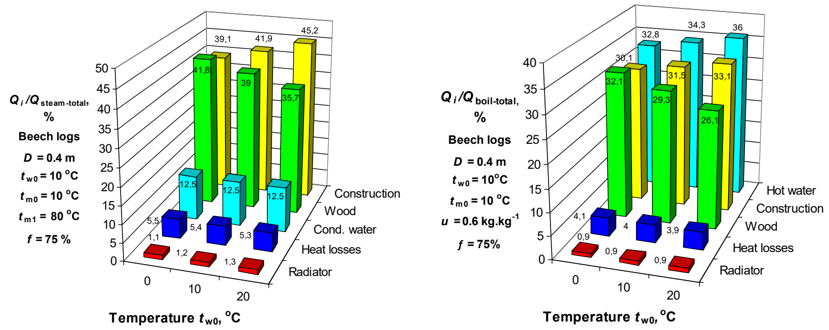
Fig. 6 presents the change in all components of the heat balances of the pit at t_{w0} = 10 °C, as well as the total energy consumption of the pit required to realize the entire steaming and boiling processes, depending on the studied values of the degree of filling of the pit with logs f = 45, 60 and 75%.

Fig. 7 shows the change of the individual components of the heat balances Q_i at t_{w0} = 10 °C in % to the total energy consumption, $Q_{steam\text{-}total}$ and $Q_{boil\text{-}total}$ respectively, depending on the loading level of the pit f.



a b

Fig. 4 Change in the components of the heat balances and the total energy (in kWh·m^{-3}) of the pit required for steaming (a) or boiling (b) the studied logs, depending on t_{w0}.



a b

Fig. 5 Change in the components of the pit heat balances in % to the total energy when steaming (a) or boiling (b) logs, depending on t_{w0}.

When expressing the heat balances of the pit in kWh·m^{-3}, an increase in t_{w0} from 0 °C to 20 °C caused a decrease in the total energy consumption of the pit from 122.8 to 106.3 kWh·m^{-3} for the steaming process and from 159.7 to 145.4 kWh·m^{-3} for the boiling process. In this case, the individual components of the heat balances of the pit changed as follows:

▪ *when steaming the logs:* Q_{Wood}, $Q_{\text{Cond.water}}$, and $Q_{\text{Heat losses}}$ decreased from 51.3 to 37.9 kWh.m^{-3}, from 15.4 to 13.3 kWh·m^{-3}, and from 6.6 to 5.6 kWh·m^{-3}, respectively; $Q_{\text{constr.}}$ and Q_{Radiator} remained unchanged with values of 48.1 kWh·m^{-3} and 1.4 kWh·m^{-3}, respectively.

▪ *when boiling the logs:* Q_{Wood} and $Q_{\text{Heat losses}}$ decreased in the same way as during the steaming – from 51.3 to 37.9 kWh·m^{-3} and from 6.6 to 5.6 kWh·m^{-3}, respectively; $Q_{\text{constr.}}$ and Q_{Radiator} remained unchanged as well as during the steaming – with values of 48.1 kWh·m^{-3} and 1.4 kWh·m^{-3}, respectively; $Q_{\text{Hot water}}$ remained unchanged with a value of 52.3 kWh·m^{-3}.

When expressing the individual components of the pit heat balances Q_i as a % of the total energies $Q_{\text{steam-total}}$ and $Q_{\text{boil-total}}$, an increase in t_{wo} from 0 °C to 20 °C caused the following change in the fraction of each component of these balances (Fig. 5):

▪ *when steaming the logs:* $Q_{\text{constr.}}$ and Q_{Radiator} increased from 39.1% to 45.2% and from 1.1% to 1.3%, respectively; Q_{Wood} and $Q_{\text{Heat losses}}$ decreased from 41.8% to 35.7% and from 5.5% to 5.3%; $Q_{\text{Cond.water}}$ remained unchanged with a value of 12.5%.

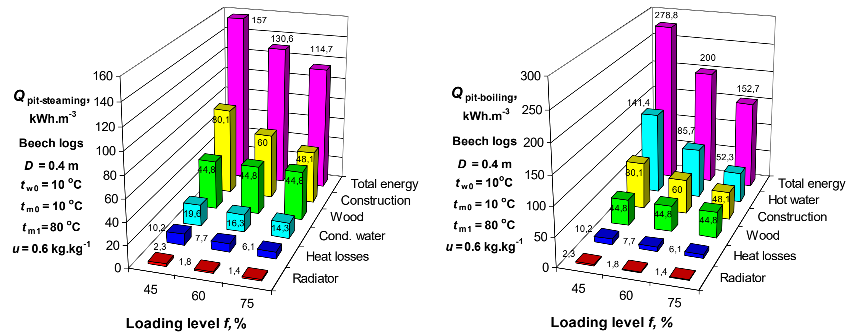


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Fig. 6 Change in the components of the pit heat balances in % to the total energy when steaming (a) or boiling (b) logs, depending on *f*.

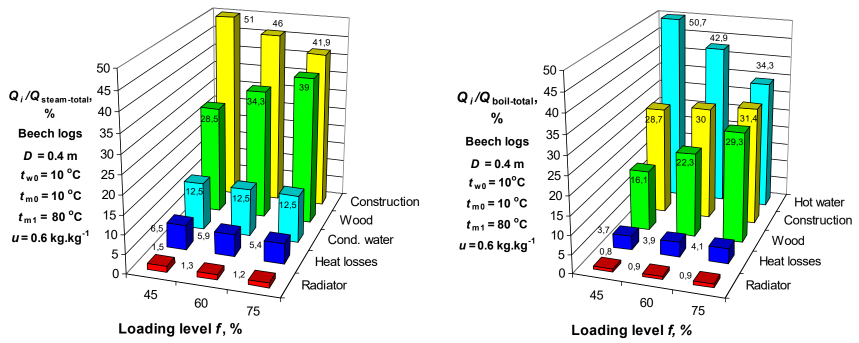

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Fig. 7 Change in the components of the pit heat balances in % to the total energy when steaming (a) or boiling (b) logs, depending on *f*.

▪ *when boiling the logs:* $Q_{\text{Hot water}}$ and $Q_{\text{constr.}}$ increased from 32.8% to 36.0% and from 30.1% to 33.1%, respectively; Q_{Wood} and $Q_{\text{Heat losses}}$ decreased from 32.1% to 26.1% and from 4.1% to 3.9%, respectively; Q_{Radiator} remained unchanged with a value of 0.9%.

When expressing the heat balances of the pit in kWh·m^{-3}, a decrease in the degree of filling of the pit with logs f from 75% to 45% caused at t_{w0} = 10 °C an increase in the total energy consumption of the pit from 114.7 kWh.m^{-3} to 157.0 kWh·m^{-3} for the steaming process and from 152.7 kWh.m^{-3} to 278.8 kWh·m^{-3} for the boiling process. In this case, the individual components of the heat balances of the pit changed as follows (Fig. 6):

▪ *when steaming the logs:* $Q_{constr.}$, $Q_{Cond.water}$, $Q_{Heat\ losses}$, and $Q_{Radiator}$ increased from 48.1 to 80.1 kWh·m^{-3}; from 14.3 to 19.6 kWh·m^{-3}, from 6.1 to 10.2 kWh·m^{-3}, and from 1.4 to 2.3 kWh·m^{-3}, respectively. The reason for the increase in the indicated components is the fact that their calculated total values for the entire pit were divided by a decreasing amount of log volume in the pit, namely: by 15 m^3 at f = 75%, by 12 m^3 at f = 60% and by 9 m^3 at f = 45%.

The specific energy for warming up the wood of the logs did not depend on f and it remained unchanged and equaled to Q_{Wood} = 44.8 kWh·m-3 when f decreased.

▪ *when boiling the logs:* $Q_{constr.}$, $Q_{Cond.water}$, $Q_{Heat\ losses}$, and $Q_{Radiator}$ increased in the same way as during the steaming, but $Q_{Hot\ water}$ increased much more than the increase in $Q_{Cond.water}$ – from 52.3 to 141.4 kWh·m^{-3} when f decreased. The energy Q_{Wood} remained unchanged and, as during the steaming of the logs, it was equal to 44.8 kWh·m^{-3}.

When expressing the components of the pit heat balances Q_i as a % of the total energies $Q_{steam\text{-}total}$ and $Q_{boil\text{-}total}$, a decrease in f from 75% to 45% caused the following change in the fraction of individual components of these balances (Fig. 7):

▪ *when steaming the logs:* $Q_{constr.}$, $Q_{Heat\ losses}$, and $Q_{Radiator}$ increased from 41.9% to 51.0%, from 5.4% to 6.5%, and from 1.2% to 1.5%, respectively; Q_{Wood} decreased from 39.0% to 28.5%, and $Q_{Cond.water}$ remained unchanged with a value of 12.5%.

▪ *when boiling the logs:* $Q_{Hot\ water}$ increased from 34.3% to 50.7%; $Q_{constr.}$, Q_{Wood}, $Q_{Heat\ losses}$, and $Q_{Radiator}$ decreased from 31.4% to 28.7%, from 29.3% to 16.1%, from 4.1% to 3.7%, and from 0.9% to 0.8%, respectively.

CONCLUSIONS

It was found that at the commonly used values of t_{w0} = 10 ºC, t_{m1} = 80 ºC and f = 75%, the total energy consumption of the pit is equal to 114.7 kWh·m^{-3} when steaming logs with u = 0.6 kg.kg^{-1} and to 152.7 kWh·m^{-3} when boiling the same logs in it.

The reason for the higher energy consumption during boiling of logs is the significant amount of energy required to heat the water in the pit, $Q_{Hot\ water}$, which is equal to 52.3 kWh·m^{-3} and constituting 34.3% of the total energy $Q_{boil\text{-}total}$. In the heat balance of the pit during steaming the logs, instead of energy $Q_{Hot\ water}$, energy $Q_{Cond.\ water}$ participates, which is contained in the condensed water removed from the pit at the end of the steaming modes. In the case under consideration, the energy $Q_{Cond.\ water}$ is equal to 14.3 kWh·m^{-3} and constitutes only 12.5% of the total energy $Q_{steam\text{-}total}$.

An increase in t_{w0} from 0 ºC to 20 ºC at f = 75% causes a decrease in the total energy $Q_{steam\text{-}total}$ from 122.8 kWh.m^{-3} to 106.3 kWh·m^{-3} (i.e., by 13.4%) and from 159.7 kWh·m^{-3} to 145.4 kWh·m^{-3} (i.e,. by 9.0%) of the energy $Q_{boil\text{-}total}$.

A decrease in f from 75% to 45% at t_{wo} = 10 ºC and t_{m1} = 80 ºC causes an increase in the energy $Q_{steam\text{-}total}$ from 114.7 kWh.m^{-3} to 157.0 kWh·m^{-3} (i.e., by 36.9%) and from 152.7 kWh.m^{-3} to 278.8 kWh·m^{-3} (i.e., by 82.6%) of the energy $Q_{boil\text{-}total}$.

The ratio of the calculated values of Q_{Wood} to those of the total energies $Q_{steam\text{-}total}$ and $Q_{boil\text{-}total}$ shows that when the initial temperature of the logs increases from 0 ºC to 10 ºC, the heat efficiency of the well-insulated concrete pit during steaming and boiling processes decreases from 41.8% to 35.7% and from 32.1% to 26.1%, respectively. The obtained results show that when the loading level of the pit decreases from 75% to 45%, the heat efficiency of the pit during steaming and boiling processes decreases from 39.0% to 28.5% and from 29.3% to 16.1%, respectively.

The presented approach can be applied to compute heat balances and energy consumption of pits during the steaming or boiling of frozen and unfrozen logs from various wood species and with different characteristics to achieve any desired final average mass temperature required for the mechanical processing of the plasticized logs. It could be easily modified and used to calculate the heat balance of concrete pits of any design and construction parameters.

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