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Article

IMPACT OF OPERATING TEMPERATURE ON THE HEAT BALANCE AND EFFICIENCY OF PITS WHEN STEAMING UNFROZEN LOGS

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ABSTRACT

An approach for calculating the heat balance and thermal efficiency of concrete pits during the steaming of unfrozen logs intended for peeled veneer production is presented. Using our non-stationary model, the heating times of beech logs with a diameter of 0.4 m, an initial temperature of 10°C, and a moisture content of 0.6 kg·kg^{-1} were determined at steaming-medium operating temperatures of 70, 80, and 90°C. Using the calculated heating times and our stationary model of the heat balance of concrete pits during log steaming, the total energy required for the entire steaming process and for each heat-balance component was calculated. Computations were performed for a concrete pit with overall dimensions of 7.4 × 2.8 × 2.5 m, a working volume of 20 m^3, and filling degrees of 45%, 60%, and 75%. Increasing the operating temperature from 70 to 90°C at the maximum filling degree of 75% increased the pit energy consumption from 103.4 to 127.0 kWh·m^{-3} and slightly decreased its thermal efficiency from 39.1% to 38.9%.

Keywords: *logs; steaming; pits; operating temperature; heat balance; heat efficiency*

1 INTRODUCTION

It is well known that the steaming of logs in pits is mostly carried out to plasticize them, in order to reduce the cutting resistance during the formation of high-quality veneer [1−13]. Such steaming is characterized by high energy consumption and low heat efficiency.

References [14−16] note that the efficiency of the heat treatment of unfrozen logs with saturated water steam in pits in veneer production does not typically exceed 18%. Reference [17] states that the loading level of the pits, that is, the degree of filling with logs cannot exceed 75% of their working space.

Publications devoted to the energy required to steam or boil logs in pits are very scarce. A model of heat balance of concrete pits was proposed in the open-access publication [18] and used to calculate such a balance of the pit shown in Fig. 1 during the boiling of unfrozen beech logs in it.

The aim of the present work is to supplement the model given in [18] for the case of steaming logs in concrete pits and to use it to study the influence of the operating temperature

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on the heat balance and heat efficiency of the same pit during steaming of unfrozen veneer logs in it.

2 MATERIALS AND METHODS

This study was carried out on the heat balance and efficiency of the pit shown in Figure 1 having the following overall dimensions: length L_p = 7.4 m, width B_p = 2.8 m, and depth H_p = 2.5 m. Part of the pit is located above ground level, and the rest is below it.

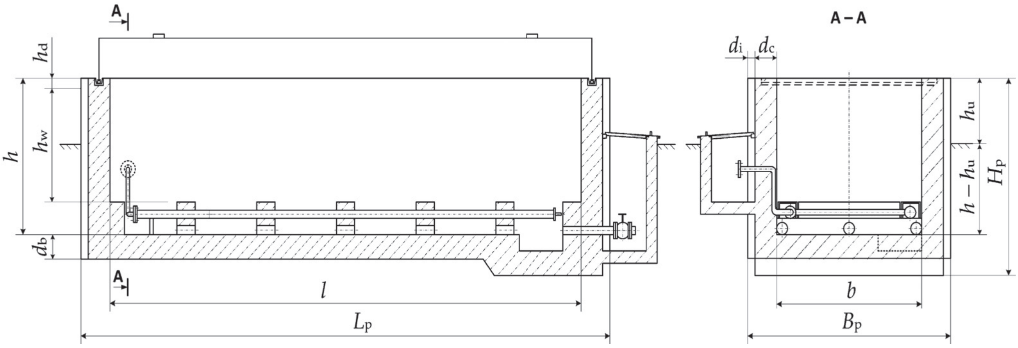

Figure 1. Longitudinal and transverse sections of the pit used for steaming wood materials in the heat-balance and efficiency calculations

A steaming pit of this design, proposed by the authors, is operated by Staroplaninski Buk in Glozhene, Lovech District, Bulgaria.

The symbols, units, and values of the pit parameters shown in Figure 1 are listed in the upper part of Table 1.

During the steaming of wood materials, the pit is closed with a removable well insulated metal lid in order to protect the service workers from falling into the working area of the pit, as well as to eliminate heat losses into the surrounding air.

The required operating temperature in the pit during steaming of logs in it is provided by direct steam, which is introduced into the pit using heating elements of a tubular radiator. The radiator is located in the lower part of the pit and is supplied with steam from a steam generator of suitable capacity.

The tubular elements of the radiator are perforated on their underside and the steam passes through a layer of condensed water when heating the pit and the logs in it. After the steaming is completed, the pit lid is removed, the plasticized logs are directed to the veneer machines, and the condensed water is drained from the pit.

Table 1. Basic set parameters used to solve the model of the pit's heat balance during steaming of logs

№	Parameter name	Symbol	Unit	Value
	Parameters of the steaming pit			
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.	Distance of the drainage channel from the upper edge of pit	h_d	m	0.13
4.	Depth of the working volume of the pit	h_w	m	1.52
5.	Depth of the upper (above-ground) part of the pit	h_u	m	0.8
6.	Thickness of the walls and bottom of the pit	d_c	m	0.3
7.	Thickness of the insulating layers of the walls and steel lid	d_i, $d_{i\text{-lid}}$	m	0.1
8.	Thickness of the steel sheets of the pit's lid	d_{Fe}	m	0.004
9.	Density of the concrete walls and bottom of the pit	ρ_c	$kg{\cdot}m^{-3}$	2300
10.	Density of the insulating layers of the pit's walls and steel lid	ρ_i, $\rho_{icov.}$	$kg{\cdot}m^{-3}$	350
11.	Density of the steel sheets of the lid	ρ_{Fe}	$kg{\cdot}m^{-3}$	7850
12.	Initial temperatures of the pit's concrete walls and bottom	t_{cu0}, t_{cg0}, t_{bg0}	°C	10
13.	Initial temperatures of the pit's insulation layers and soil	t_{iu0}, t_{ig0}, t_{s0}	°C	10
14.	Temperature of the heat carrier that feeds the pit's radiator	t_{hc}	°C	130
15.	Temperature of the ambient air, including above the pit's lid	t_{air}	°C	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 insul. layers of the walls and lid	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's 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 insulating layers	λ_i	$W{\cdot}m^{-1}{\cdot}K^{-1}$	0.042
21.	Thermal conductivity of the sandy-clay soil around the pit	λ_s	$W{\cdot}m^{-1}{\cdot}K^{-1}$	1.4
22.	Loading level of the pit, i.e. the degree of filling it with logs	f	%	45, 60, 75
	Technological parameters of the steaming modes of unfrozen beech logs in pit			
1.	Diameter of the logs	D	m	0.4
2.	Lengths of the logs	L	m	3.0
3.	Moisture content of the logs	u	$kg{\cdot}kg^{-1}$	0.6
4.	Fiber saturation point of the beech wood	u_{fsp}	$kg{\cdot}kg^{-1}$	0.31
5.	Basic density of the beech wood	ρ_b	$kg{\cdot}m^{-3}$	560
6.	Initial average mass temperature of the logs	t_{w0}	°C	10
7.	Initial value of the operating temperature in the pit	t_{m0}	°C	10
8.	Maximum operating temperature of the steaming modes	t_{m1}	°C	70, 80, 90
9.	Duration of the increase in t_m from t_{m0} to t_{m1}	τ_1	h	4.0
10.	Duration of the steaming modes of logs, depending on t_{m1}	τ_2	h	27,20, 16.5
11.	Minimum temperature in the center of the logs at $\tau = \tau_2$	$t_{wc\text{-}min}$	°C	62.0
12.	Average mass temperature of the logs at the end of their steaming modes	$t_{avg\text{-}end}$	°C	66.8 at 70o 72.7 at 80° 78.6 at 90°

The present study was carried out with unfrozen beech (*Fagus sylvatica* L.) logs, the steaming of which in a pit was simulated using modes commonly applied in practice. These steaming modes consist of two stages, during which the operating temperature t_m changes as follows (Figure 2):

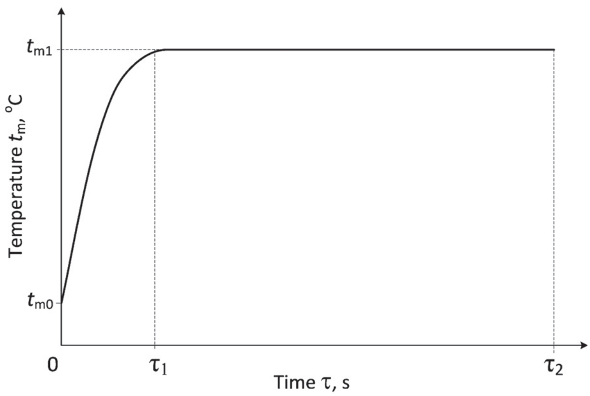

Figure 2. Change in the operating temperature t_m in modes for steaming of wood materials in pits

- During the first stage, during the interval 0 – τ_1, an increase in t_m from t_{m0} to t_{m1} occurs by fully or partially opening the valve to introduce saturated water steam to the pit;
- During the second stage, over the interval τ_1–τ_2, steam is metered into the pit radiator to maintain a constant operating temperature.

The symbols, units, and values of the logs' and also of the steaming modes' parameters, which were used in the numerical calculations of the pit's heat balance and efficiency, are presented in the lower half of Table 1.

MODEL OF THE PIT HEAT BALANCE DURING LOG STEAMING

The heat balance of the concrete pit during log steaming can be represented by the following mathematical model:

$$Q_{\text{Pit-steaming}} = Q_{\text{Wood}} + Q_{\text{Constr.}} + Q_{\text{Cond. water}} + Q_{\text{Radiator}} + Q_{\text{Heat losses}} \tag{1}$$

where $Q_{\text{Pit-steaming}}$ is the total specific (relating to 1 m^3 wood) heat energy, required for the carrying out of the entire process of plasticizing the logs subjected to steaming; Q_{Wood} – energy required for warming up of the unfrozen logs themselves; $Q_{\text{Constr.}}$ – energy required for heating of the pit's 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_{Radiator} – energy required to heat the metal radiator of the pit, with the help of which a steam is introduced when steaming logs; $Q_{\text{Heat losses}}$ – energy required to cover heat losses of the pit during the logs' steaming process. The unit of all specific energies Q in Eq. (1) and also everywhere below, is kWh·m^{-3}.

Mathematical descriptions of the individual components of $Q_{\text{Pit-steaming}}$, which participate in Eq. (1) are the same as those given in [18, 19].

The heat efficiency of the tested concrete pit when steaming logs with different wood moisture content *u* in it under conditions of different loading levels *f* of the pit with logs is calculated (in %) according to the following equation:

$$\eta_{\text{pit-steaming}} = 100\frac{Q_{\text{Wood}}}{Q_{\text{steam-total}}} \quad (2)$$

where $Q_{\text{steam-total}}$ and Q_{Wood} are the specific energies calculated using Eq. (1) and required to carry out the entire steaming process in the pit and to heat the unfrozen logs, respectively.

4 SOLVING THE MODEL OF PIT BALANCE

The mathematical descriptions of t_m and the thermo-physical characteristics of wood given in [20, 21] were entered into our 1D non-linear model of the temperature distribution along the radius of unfrozen logs during their steaming and it was solved with the help of the finite difference method using proprietary software written in Microsoft Visual FORTRAN.

From the calculated changes in the temperature field 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 process of the logs, τ_2, indicated in Table 1, was determined for the three investigated maximum values of the operating temperature in the pit, namely t_{m1} = 70, 80, and 90 ºC.

The value of t_{avg} (in K) at the end of the steaming regimes is needed to calculate the energy Q_{Wood} in Eq. (2).

An Excel program was prepared for simultaneous solution of the equations involved in the model (1). Using this program, the heat balance and heat efficiency of the pit shown in Figure 1 was investigated for the case of steaming unfrozen beech logs with an initial temperature t_{w0} = 10 ºC at a degree of filling of the pit with logs, *f*, equal to 45%, 60%, and 75%.

5 RESULTS AND DISCUSSION

5.1 Temperature change in logs during steaming

Figure 3 shows the change in the slowest-rising temperature in the center of the studied logs, twc, and also the average mass temperature of the logs, tavg, calculated with our 1D model during log steaming in the pit. The operating temperature tm changes from the initial value t_{m0} = 10ºC to its maximum values t_{m1} = 70, 80, and 90ºC within 4 hours.

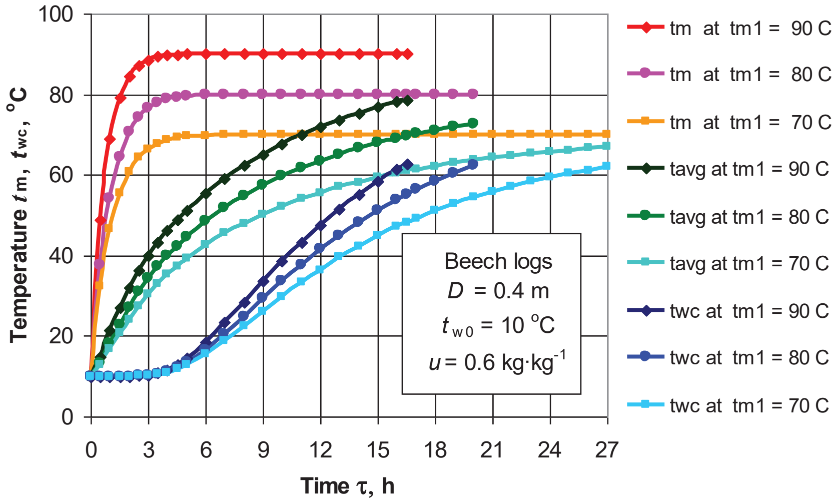

Figure 3. Change in t_m, t_{wc}, and t_{avg} of the studied logs during their steaming, as a function of t_{m1}

Figure 3 shows that the steaming process of the studied logs having initial temperature t_{w0} = 10 °C and moisture content u = 0.6 kg·kg^{-1} ends as follows: after τ_2 = 27.0 h at t_{m1} = 70°C; after τ_2 = 20.0 h at t_{m1} = 80°C and after τ_2 = 16.5 h at t_{m1} = 90°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 temperature required to obtain quality veneer from the heated and plasticized beech logs [11, 22]. At the same τ2 values, the average mass temperature of the logs rises from its initial value t_{w0} = 10 °C to final average mass temperature $t_{avg\text{-}end}$ = 66.8 °C at t_{m1} = 70 °C, $t_{avg\text{-}end}$ = 72.7 °C at t_{m1} = 80 °C, and $t_{avg\text{-}end}$ = 78.62 °C at t_{m1} = 90°C.

5.2 Change in the heat balance of the pit at the end of steaming

Figure 4 shows the change of all components of the heat balance of the tested pit at its maximum possible loading level f = 75%, as well as the total energy (in kWh·m^{-3}) of the pit required to carry out the entire steaming process, depending on the studied 3 values of tm_1.

Figure 5 presents the change of the individual components of the pit's heat balance Q_i at f = 75% as percentages of the total energy consumption, $Q_{steam\text{-}total}$, depending on t_{m1}.

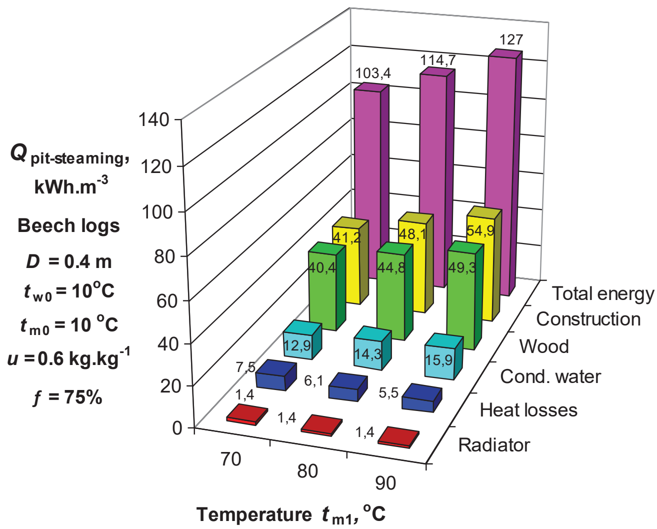

Figure 4. Change in the components of the heat balance and the total energy (in kWh·m^{-3}) of the pit required for steaming the studied logs, depending on t_{m1}

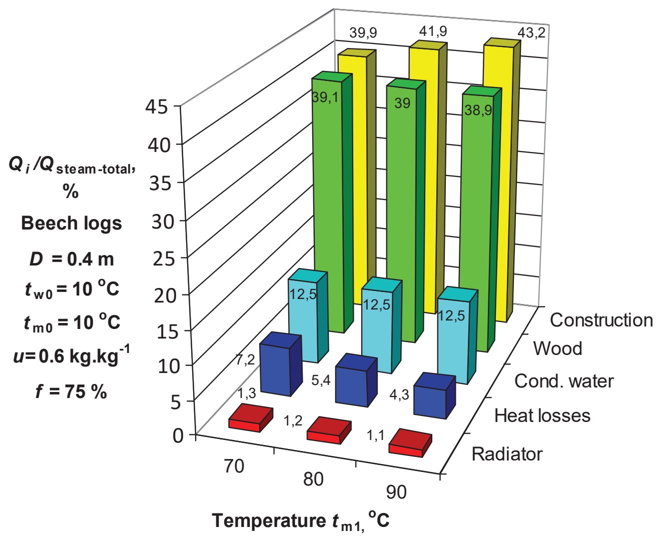

Figure 5. Change in the components of the pit's heat balance as percentages of $Q_{\text{steam-total}}$, depending on t_{m1}

When expressing the heat balance of the pit in kWh·m^{-3}, an increase in t_{m1} from 70 to 90°C causes an increase in the total energy consumption of the pit from 103.4 to 127.0 kWh·m^{-3}. In this case, the individual components of the heat balance of the pit change as follows (Fig. 4): the energies Q_{Wood}, $Q_{\text{constr.}}$, and $Q_{\text{Cond.water}}$ increase from 40.4 to 49.3 kWh.m^{-3}, from 41.2 to 54.9 kWh.m^{-3}, and from 12.9 to 15.9 kWh·m^{-3}, respectively; $Q_{\text{Heat losses}}$ decreases from 7.5 to 5.5 kWh·m^{-3}, and Q_{Radiator} remains unchanged with a value of 1.4 kWh·m^{-3}.

When expressing the individual components of the pit's heat balance Q_i as a % of the total energy $Q_{steam\text{-}total}$, the increase of t_{m1} from 70 to 90°C causes the following change in the fraction of each component of this balance (Fig. 5): Q_{Wood}, $Q_{Heat\ losses}$, and $Q_{Radiator}$ decrease from 39.1 to 38.9%, from 7.2 to 4.3%, and from 1.3 to 1.1% respectively; $Q_{Constr.}$ increases from 39.9 to 43.2%, and $Q_{Cond.water}$ remains unchanged with a value of 12.5%.

5.3 Change in the heat efficiency of the pit

Figure 6 presents the change in the thermal efficiency calculated using Eq. (2) heat efficiency of the pit when steaming the studied logs in it, depending on t_{m1} and f. It can be seen that increasing the operating temperature from 70 to 90°C causes the following slight decrease in the heat efficiency of the pit, $\eta_{pit\text{-}steaming}$, at a given value of the loading level.

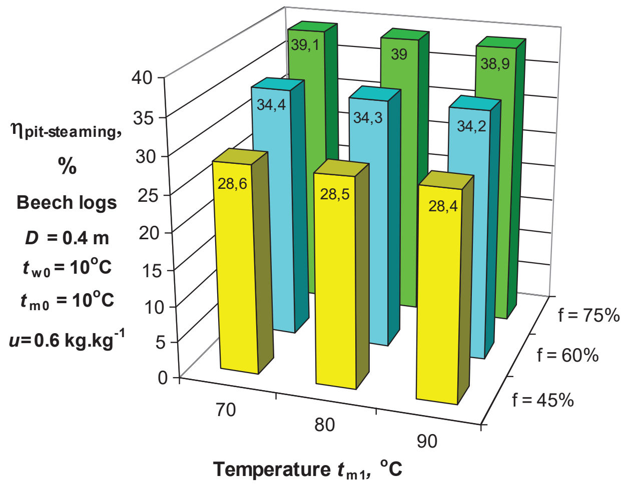

Figure 6. Change in the heat efficiency of the pit, depending on t_{m1} and f

- at f = 45%: from 28.6 to 28.4%;
- at f = 60%: from 34.4 to 34.2%;
- at f = 75%: from 39.1 to 38.9%.

Figure 6 also shows that reducing the pit's loading level from 75% to 45% causes a decrease in $\eta_{pit\text{-}steaming}$ at a given operating temperature, namely:

- at t_{m1} = 70°C: from 39.1 to 28.6%;
- at t_{m1} = 80°C: from 39.0 to 28.5%;
- at t_{m1} = 90°C: from 38.9 to 28.4%.

6 CONCLUSIONS

It was found that at the commonly used values of the operating temperature t_{m1} = 80°C, the total energy consumption, $Q_{steam\text{-}total}$, of the studied pit is equal to 114.7 kWh·m^{-3} when steaming beech logs with a diameter D = 0.4 m, initial temperature t_{w0} = 10°C, moisture content u = 0.6 kg.kg^{-1} at maximum possible loading level of the pit f = 75% aiming wood plasticizing for the production of peeled veneer.

The increase of t_{m1} from 70 to 90°C at f = 75% causes an increase in the energy $Q_{steam\text{-}total}$ from 103.4 to 127.0 kWh·m^{-3}, i.e. by 22.8%. The fractions of the individual heat-balance components of $Q_{steam\text{-}total}$ in this case changes as follows: Q_{Wood}, $Q_{Heat\ losses}$, and $Q_{Radiator}$ decrease from 39.1 to 38.9%, from 7.2 to 4.3%, and from 1.3 to 1.1% respectively; Q_{constr} increases from 39.9 to 43.2%, and $Q_{Cond.water}$ remains unchanged with a value of 12.5%.

The same increase of t_{m1} from 70 to 90°C at f = 75% causes a slight decrease in the heat efficiency of the pit, $\eta_{pit\text{-}steaming}$, from 39.1 to 38.9%. Reducing f from 75 to 45% at t_{m1} = 80°C causes a significantly greater decrease in $\eta_{pit\text{-}steaming}$ from 39.0 to 28.5%.

The presented approach can be applied to compute the heat balance and efficiency during the steaming of unfrozen logs from various wood species and with different dimensions and thermophysical characteristics. It could be easily modified and used to calculate the heat balance and efficiency of concrete pits of a wide range of design and construction parameters.

AUTHOR CONTRIBUTIONS

Conceptualization, N.D. and D.A.; methodology, N.D.; software, N.D.; validation, P.V. and K.A.; formal analysis, K.A.; investigation, D.A.; resources, N.D.; data curation, P.V.; writing – original draft preparation, N.D.; writing—review and editing, K.A.; visualization, D.A.; supervision, N.D.; project administration, K.A.; funding acquisition, P.V. All authors have read and agreed to the published version of the manuscript.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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