Bulletin of the *Transilvania* University of Brasov
Series II: Forestry • Wood Industry • Agricultural Food Engineering • Vol. 16(65) Special Issue 2023
https://doi.org/10.31926/but.fwiafe.2023.16.65.3.5

A SIMULATION STUDY OF THE HEAT BALANCE OF CONCRETE PITS DURING BOILING OF NON-FROZEN LOGS

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Abstract: *This paper presents an approach for computing the heat balance of boiling pits during plasticising of non-frozen logs intended for the production of peeled veneer. With the help of our own 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 water temperatures in the pit equal to 70, 80, and 90°C. Using the determined logs' boiling durations and the mentioned approach, the change in the total energy required to carry out the entire boiling process and that required for each of the individual components of the heat balance was calculated. Computer simulations were conducted for a concrete pit with overall dimensions of 8.0 × 2.6 x 2.5 m, working volume of 20 m^3, and a degree of filling with logs equal to 45, 60, and 75%. It was found that the increase in the water temperature from 70 to 90°C causes an increase in the total specific energy, as well as in the energy for the heating of the logs themselves, the construction and the water of the pit. At the same time, the energy required to cover the heat losses of the pit decreases and the energy for heating the metal heater/radiator itself does not change. A decrease in the degree of filling of the pit with logs from 75 to 45% causes an increase in both the total energy and all its components except the energy for heating the logs, which remains unchanged.*

Key words: *boiling pits, heat balance, simulation study, beech logs, plasticising, veneer production.*

1. Introduction

It is well-known that boiling wood is a technological process in which wet wood materials are heated in hot water and their physical, mechanical and partly chemical properties change [1, 12-17]. The thermal treatment of logs in boiling or

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steaming pits is carried out for the purpose of plasticising the wood, in order to reduce cutting resistance during the formation of quality veneer [2, 6, 18-26].

The boiling and steaming processes of wood materials in pits are characterised by high energy consumption and low energy efficiency. Lawniczak [14] and Sohor and Kadlec [20] note that the efficiency of the heat treatment of wood materials with water saturated steam in pits in veneer production does not typically exceed 18%.

The correct and effective control of the boiling and steaming processes is possible only when their physics and the weight of the influence of several dozen factors for the specific wood materials and equipment are well understood. Estimating the total impact of so many factors on the temperature distribution in the heated materials and on the energy consumption and efficiency of the equipment is a difficult task and its solution is possible only with the help of adequate mathematical models.

It can be noted that in the available literature, only Dzurenda and Deliiski [8, 9] propose a multifactorial mathematical model of the heat balance of a concrete pit shown below for the case of boiling in it non-frozen prismatic wood materials intended for veneer production. When using this model to study the balance of the pit for the case of boiling in it beech prisms with dimensions of 0.4 × 0.4 x 1.2 m, moisture content of 0.8 $kg{\cdot}kg^{-1}$, and 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 following results were obtained for the individual components in this balance when the filling of the pit's working volume with prisms was equal to 60%: 29.1% for warming up of the prisms themselves, 30.0% for heating of the pit's construction, 35.2% for heating up of the boiling water, 4.7% for covering the heat losses from the pit, 1.0% for heating of the metal heater/radiator itself, and 0.03% for heating the moist air in the space between the boiling water and the pit's lid. Using this model from Dzurenda and Deliiski [10], the components of the energy required to heat the individual four parts of the pit construction were calculated.

Of significant theoretical and practical interest is the study of the heat balance of the boiling pits for the case of heating in them logs intended for the production of veneer. Therefore, the aim of the present work is to update, that is to further develop and refine the model given in [8, 9] and conduct with it a thorough study of the heat balance of the same concrete pit, for the case of boiling non-frozen beech logs with industrial parameters.

2. Materials and Methods

2.1. Log Parameters Used in the Computer Simulations

The study was carried out with non-frozen beech (*Fagus sylvatica* L.) logs, which are commonly used in veneer production. During the numerical simulations with the mathematical models presented below, the following parameters of the logs, which influence the heat balance of the boiling pit, were set: diameter D = 0.4 m, length L = 2.0 m, initial temperature t_{w0} = 10°C, basic density of the wood equal to its mass in an absolutely dry state, divided by its green volume, ρ_b = 560 $kg{\cdot}m^{-3}$, moisture content u = 0.6 $kg{\cdot}kg^{-1}$, and fibre saturation point at T = 293.15 K (i.e. at t = 20°C) $u_{fsp}^{293.15} =$ 0.31 $kg{\cdot}kg^{-1}$ [2, 6, 26].

Beech logs of such dimensions and with such a moisture content above the hygroscopic range are relatively often subjected to boiling for veneer production in practice.

2.2. Design Features of the Boiling Pit, in Which the Logs are Subjected to Boiling

The computer simulations were carried out on the heat balance 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. The values of all the other pit parameters marked in Figure 1 are given in Table 1 below, at the end of this section.

The pit is a concrete tank with steel reinforced concrete walls and bottom. The body of the tank is waterproof, both against the escape of hot technological water from the pit, as well as against the penetration of ground water 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 hot water to the atmospheric air in the above-ground part of the pit's walls and the heat flow to the soil in the part of the pit located in the ground. The walls and the bottom are also well insulated hydrophobically using a foam-glass material.

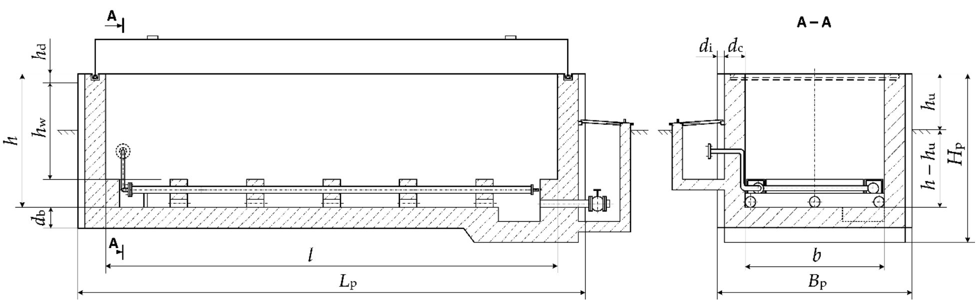

Fig. 1. *Longitudinal and traverse sections of the pit for boiling wood materials used during the computer simulations*

During the boiling process 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 in the form of intensive evaporation of hot technological water into the air and heat radiation losses.

The walls of the pit's 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 heating of the water in the pit to the required technological temperature is carried out indirectly by means of heating elements (heater/radiator) located at the lower end of the pit. The heaters/radiators connected to the plant's heating system are powered by steam or hot water with a temperature of 120-140°C.

2.3. Modelling of the 1D Unsteady Temperature Distribution in Non-Frozen Logs Subjected to Boiling

To calculate the heat balance of the boiling pits for the cases of heating logs in them, it is necessary to know the required duration of their heating (τ_2 – Figure 2), depending on the influencing factors. This duration is equal to the time from the start of the heating of the logs to the moment when their temperature field completely enters the optimal limits for the respective wood species [6], ensuring good plasticisation of the wood and obtaining quality veneer from it.

Since the heating of non-frozen 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 four times their diameter (D), their required heating duration can be determined using the following experimentally verified 1D model [3, 5]:

$$c_{w-nfr} \cdot \rho_w \cdot \frac{\delta T(r,\tau)}{\delta \tau} = \mathrm{div}\left(\lambda_{w-nfr} \mathrm{grad} T\right) \quad (1)$$

at

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

and boundary conditions for conductive heat transfer:

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

where:

$c_{w\text{-}nfr}$ is the specific heat capacity of the non-frozen wood [J·kg^{-1}·K^{-1}];

$\lambda_{w\text{-}nfr}$ – the thermal conductivity of the non-frozen wood [W·m^{-1}·K^{-1}];

ρ_w – the density of the wood [kg·m^{-3}];

r – the coordinate along the log's radius: $0 \le r \le D/2$ [m];

D – the diameter of the log [m];

T – the temperature [K];

T_{w0} – the initial temperature of the wood [K];

T_m – the operating medium temperature of the boiling water in the pit [K];

τ – the time [s].

Figure 2 shows the change of the water temperature t_m in the pit in the commonly applied regimes for boiling wood materials. These regimes consist of two stages, during which t_m changes as follows:

- During the first stage, in the course of time 0 – τ_1, an increase in t_m from its initial value t_{m0} to the set constant value of t_{m1} takes place by fully or partially opening the valve to introduce steam or hot water under pressure into the metal pipe heater/radiator located at the lower end of the pit, providing indirect heating of the water;
- During the second stage of the regimes, in the course of time τ_1 – τ_2, dosed introduction of the heating medium into the heater/radiator is carried out in order to maintain a constant technologically permissible value of t_m of the water, equal to the maximum regime value t_{m1}. When τ_2 is reached, the logs subjected to boiling reach the optimal temperature required for their subsequent mechanical processing in the veneer production.

Mathematical descriptions of all the thermo-physical characteristics of the non-frozen wood, which are involved in model (1) − (3), have been carried out and verified with foreign experimentally obtained dissertation data in Deliiski [2-5] and Deliiski et al. [7] as a function of the temperature and wood moisture content. The mathematical description of the operating medium temperature in the pit shown in Figure 1, t_m, is analogous to that proposed in Deliiski [2], and Deliiski and Dzurenda [6] for t_m in autoclaves for steaming wood materials.

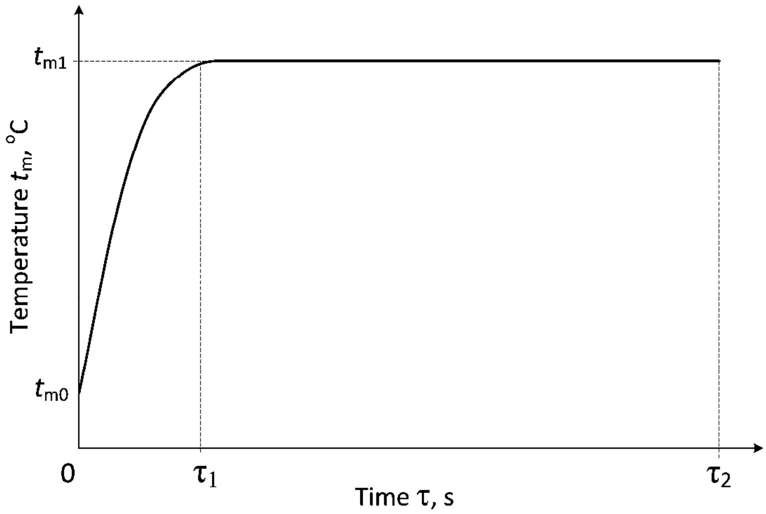

Fig. 2. *Typical change of water temperature t_m in regimes for boiling wood materials in pits*

When solving model (1) − (3), the non-stationary change in temperature along the radius of the log's central cross section is obtained, as well as the moment of reaching a temperature in the centre of the logs equal to t_{wc} = 62°C, which corresponds to the minimum required temperature necessary to obtain quality veneer from the plasticised beech logs [7, 19].

2.4. Mathematical Model of the Heat Balance of the Pits During Boiling of Logs

The heat balance of the pit during the boiling of logs can be mathematically presented by the following model:

$$Q_{Pit-boil} = Q_{Wood} + Q_{Constr.} + Q_{Water} + Q_{Radiator} + Q_{Losses} \quad (4)$$

where:

$Q_{Pit\text{-}boil}$ is the specific total heat energy (for 1 m^3 wood), required for the implementation of the entire process of plasticising the logs subjected to boiling in the pit;

Q_{Wood} – the energy required for warming up the logs subjected to boiling;

$Q_{Constr.}$ – the energy required for heating of the pit's construction materials;

Q_{Water} – the energy required to heat the water in the pit to the set temperature;

$Q_{Radiator}$ – the energy required to heat the metal pipe heater/radiator of the pit itself;

Q_{Losses} – the energy required to cover the heat losses of the pit during the log boiling process.

The dimension of all variables Q in equation (4), as well as everywhere below, is $kWh \cdot m^{-3}$.

Mathematical model (4) differs from the analogous model proposed in Dzurenda and Deliiski [8, 9] by the absence of the component that takes into account the energy required to heat the moist air in the space between the boiling water and the pit's lid. As stated above in the introduction, it was found in Dzurenda and Deliiski [8, 9] that such a component has a negligibly small value, equal to 0.03% of the heat balance of the boiling pit. In addition, with model (4) the specific energy $Q_{Pit\text{-}boil}$ and its components are calculated in $kWh \cdot m^{-3}$, while in the two cited literary sources they are calculated in $kJ \cdot m^{-3}$.

2.5. Mathematical Model of Q_{Wood}

When calculating the energy Q_{Wood}, it is appropriate to apply the well-known statement from thermodynamics that the specific energy required for the heating of 1 m^3 of a given solid body with an initial temperature T_0 to a temperature T_1 is determined using Equations (1), (6), (9) and (10):

$$Q = \frac{\rho \cdot c \cdot \left(T_1 - T_0\right)}{3.6 \cdot 10^6} \qquad (5)$$

where:

Q is the specific heat energy [$kWh \cdot m^{-3}$];

ρ – the density of the material of the body [$kg \cdot m^{-3}$];

c – the specific heat capacity of the material of the body [$J \cdot kg^{-1} \cdot K^{-1}$];

T_0 and T_1 – the temperatures of the body at the beginning and the end of the heating, respectively [K].

The multiplier $3.6 \cdot 10^6$ in the denominator of Equation (5) ensures that the values of Q are obtained in $kWh \cdot m^{-3}$, instead of $J \cdot m^{-3}$.

Based on equation (5), the specific heat energy required for heating the logs themselves subjected to boiling in the pit, Q_{Wood}, can be calculated using the following equation:

$$Q_{w\text{-}nfr} = \frac{\rho_w}{3.6 \cdot 10^6} \cdot \frac{c_{w-nfr} at T = T_{w0} + c_{w-nfr} at T = T_{avg-end}}{2} \cdot \left(T_{avg-end} - 272.15\right) \qquad (6)$$

where [2–7]:

$$\rho_w = \rho_b \cdot \left(1 + u\right) \qquad (7)$$

$$c_{w\text{-}nfr} = \frac{1}{1+u} \cdot \left(2862 \cdot u + 2.95 \cdot T + 5.49 \cdot u \cdot T + 0.0036 \cdot T^2 + 555\right) \qquad (8)$$

$$T_{avg}^{n} = \frac{1}{\frac{D}{2}} \int_{\frac{D}{2}} T(r, n \cdot \Delta\tau) dD \qquad (9)$$

In equations (6) – (9):

ρ_w denotes the density of the wet wood [kg·m^{-3}];

ρ_b – the basic density of the wood, equal to dry mass divided by green volume [kg·m^{-3}];

u – the wood moisture content [kg·kg^{-1}];

$c_{w\text{-}nfr}$ – the specific heat capacity of the non-frozen wood above the hygroscopic range [J·kg^{-1}·K^{-1}];

T – the temperature [K];

T_{avg} – the average mass temperature of the log [K];

$T_{avg\text{-}end}$ – the average mass temperature of the log at the end of its heating (i.e. at $\tau = \tau_2$ according to Figure 2) when the desired degree of plasticisation of the log is reached [K];

r – the coordinate along the log's radius during the solving of model (1) – (3): $0 \le r \le D/2$ [m];

D – the diameter of the log [m];

$\Delta\tau$ – the step along the time coordinate [s];

n – the time level during the model solving: $n = 0, 1, 2, 3, \ldots, \frac{\tau_2}{\Delta\tau}$; τ_2 - duration of the boiling regime [s].

2.6. Mathematical Model of $Q_{Constr.}$

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

$$Q_{Constr.} = Q_{Constr.1} + Q_{Constr.2} + Q_{Constr.3} + Q_{Constr.4} \qquad (10)$$

where:

$Q_{Constr.1}$ and $Q_{Constr.2}$ are the energies, required for heating the walls of the above-ground part and those located in the ground part, respectively, of the pit's construction;

$Q_{Constr.3}$ and $Q_{Constr.4}$ – the energies required for heating the pit's bottom and lid, respectively.

In (8) − (10) equations are given for the calculation of $Q_{Constr.1}$, $Q_{Constr.2}$, $Q_{Constr.3}$, and $Q_{Constr.4}$ depending on the influencing constructive and thermo-physical factors specified there, namely: $Q_{Constr.1}$ as a function of 16 factors, $Q_{Constr.2}$ – of 17 factors, $Q_{Constr.3}$ – of 10 factors, and $Q_{Constr.4}$ – of 12 factors. The top half of Table 1 below lists a total of 19 of the influencing factors considered.

2.7. Mathematical Model of Q_{Water}

The specific energy required for heating the technological water in the pit (Q_{Water}) can be calculated with the help of the model given in Dzurenda and Deliiski [8, 9], depending on a total of nine factors specified there. The bottom half of Table 1 lists four of these factors.

2.8. Mathematical Model of $Q_{Radiator}$

The specific thermal energy required for warming up the metal pipe heater/radiator of the pit itself at the beginning of the log boiling process

($Q_{Radiator}$) can be calculated with the help of the model given in Dzurenda and Deliiski [8, 9], depending on a total of seven factors specified there. Table 1 lists two of these factors.

2.9. Mathematical model of Q_{Losses}

The specific heat energy required to cover the heat losses of the pit (Q_{Losses}) can be expressed by the following model [8, 9]:

$$Q_{Losses.} = Q_{Losses1} + Q_{Losses2} + Q_{Losses3} + Q_{Losses4} \quad (11)$$

where:

$Q_{Losses1}$ and $Q_{Losses2}$ 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, respectively, of the pit's construction;

$Q_{Losses3}$ and $Q_{Losses4}$ – the energies required to cover the heat losses caused by the heat emission through the pit's bottom and lid, respectively.

In Dzurenda and Deliiski [8, 9], equations are given for the calculation of $Q_{Losses1}$, $Q_{Losses2}$, $Q_{Losses3}$, and $Q_{Losses4}$ depending on the influencing constructive and thermos-physical factors specified there, namely: $Q_{Losses1}$ as a function of 14 factors, $Q_{Losses2}$ – of 15 factors, $Q_{Losses3}$ – of 11 factors, and $Q_{Losses4}$ – of eight factors. Table 1 lists some of these factors.

2.10. Solving Models (1) – (3) and (4) – (11)

The mathematical descriptions of t_m and the thermo-physical characteristics of the wood indicated in the second subsection of Materials and methods were entered into model (1) – (3), which was solved with the help of the finite difference method using our own software program in the Visual FORTRAN computing environment. From the obtained change of 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 boiling process of the logs, τ_2, indicated in Table 1, was determined for the three investigated maximum values of the water temperature in the pit, namely t_{m1} = 70, 80, and 90°C.

An Excel program was prepared for joint solving of the equations involved in models (4) – (11) [11]. Using this program, the heat balance of the pit shown in Figure 1 was investigated for the case of boiling in it non-frozen beech logs with an initial temperature of t_{w0} = 10°C at a degree of filling of the pit with logs (*f*) equal to 45, 60, and 75%.

As input data relating to part of the design parameters of the studied pit (refer to Figure 1), as well as to the characteristics of the beech logs subjected to boiling and to the operating temperature of the water in the pit (Figure 2), those specified above in the Materials and methods section were used. The values of the basic remaining parameters involved in the equations of the models of the individual components of the pit's heat balance, which were used in the computer simulations, are given in Table 1.

Table 1

Basic set parameters used to solve the mathematical model of the pit's heat balance

No.	Parameter name	Symbol	Unit	Value
	Parameters of the boiling 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.	Depth of the working volume of the pit	h_w	m	1.52
4.	Depth of the upper (above ground) part of the pit	h_u	m	0.8
5.	Thickness of the walls and bottom of the pit	d_c, d_b	m	0.3
6.	Thickness of the insulating layers of the walls and steel lid	d_i, $d_{i\text{-lid}}$	m	0.1
7.	Thickness of the steel sheets of the pit's lid	d_{Fe}	m	0.004
8.	Density of the concrete walls and bottom of the pit	ρ_c	$kg{\cdot}m^{-3}$	2300
9.	Density of the insulating layers of the pit's walls and steel lid	ρ_i, $\rho_{icov.}$	$kg{\cdot}m^{-3}$	350
10.	Density of the steel sheets of the lid	ρ_{Fe}	$kg{\cdot}m^{-3}$	7850
11.	Initial temperatures of the pit's concrete walls and bottom	t_{cu0}, $t_{cg0,}$ t_{bg0}	°C	10
12.	Initial temperatures of the insulation layers and soil	t_{iu0}, t_{ig0}, t_{s0}	°C	10
13.	Specific heat capacity of the concrete (average value)	c_c	$J{\cdot}kg^{-1}{\cdot}K$	1134
14.	Specific heat capacity of the insul. layers of the walls and lid	c_i, $c_{i\text{-lid}}$	$J{\cdot}kg^{-1}{\cdot}K$	850
15.	Specific heat capacity of the steel sheets of the lid	c_{Fe}	$J{\cdot}kg^{-1}{\cdot}K$	444
16.	Thermal conductivity coefficient of the concrete	λ_c	$W{\cdot}m^{-1}{\cdot}K^{-1}$	1.28
17.	Thermal conductivity coefficient of the insulating layers	λ_i	$W{\cdot}m^{-1}{\cdot}K^{-1}$	0.042
18.	Specific mass of the heating elements of the heater/radiator on 1 m^2 of the area at the bottom of the pit	m_{he}	$kg{\cdot}m^{-2}$	100
19.	Distance of the drainage channel from the upper edge of pit	h_d	m	0.13
	Technological parameters of the boiling process of beech logs with a diameter of 0.4 m			
1.	Loading level of the pit, i.e. the degree of filling it with logs	f	%	45,60,75
2.	Moisture content of the logs	u	$kg{\cdot}kg^{-1}$	0.6
3.	Fibre saturation point of the beech wood	u_{fsp}	$kg{\cdot}kg^{-1}$	0.31
4.	Basic density of the beech wood	ρ_b	$kg{\cdot}m^{-3}$	560
5.	Density of the water in the pit	ρ_{H2O}	$kg{\cdot}m^{-3}$	998
6.	Initial average mass temperature of the logs	t_{w0}	°C	10
7.	Average temperature of the logs at the end of their boiling (*a* – at t_{m1} = 70°C; *b* – at t_{m1} = 80°C, and *c* – at t_{m1} = 90°C)	$t_{avg\text{-}end}$	°C	66.8*a*, 72.7*b* 78.6*c*
8.	Initial temperature of the boiling water in the pit	t_{m0}	°C	10
9.	Maximum temperature of the boiling water	t_{m1}	°C	70*a*,80*b*, 90*c*
10.	Average specific heat capacity of the boiling water	c_{H2O}	$J{\cdot}kg^{-1}{\cdot}K$	4180
11.	Temperature of the water steam that feeds the pit calorifer	t_{steam}	°C	130
12.	Temperature of the surrounding air near the pit	t_{air}	°C	10
13.	Duration of increase in water temperature t_m from t_{m0} to t_{m1}	τ_1	h	4.0
14.	Duration of the boiling process of logs, depending on wood moisture content u and t_{m1}	$\tau_2 = \tau_{boil}$	h	27.0*a*, 20.0*b* 16.5*c*

3. Results

Figure 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 using model (1) – (3) and Equation (9) during the logs' boiling at the temperature t_m of the water in the pit. The temperature t_m changes from the initial value t_{m0} = 10°C to its maximum values t_{m1} = 70, 80, and 90°C.

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

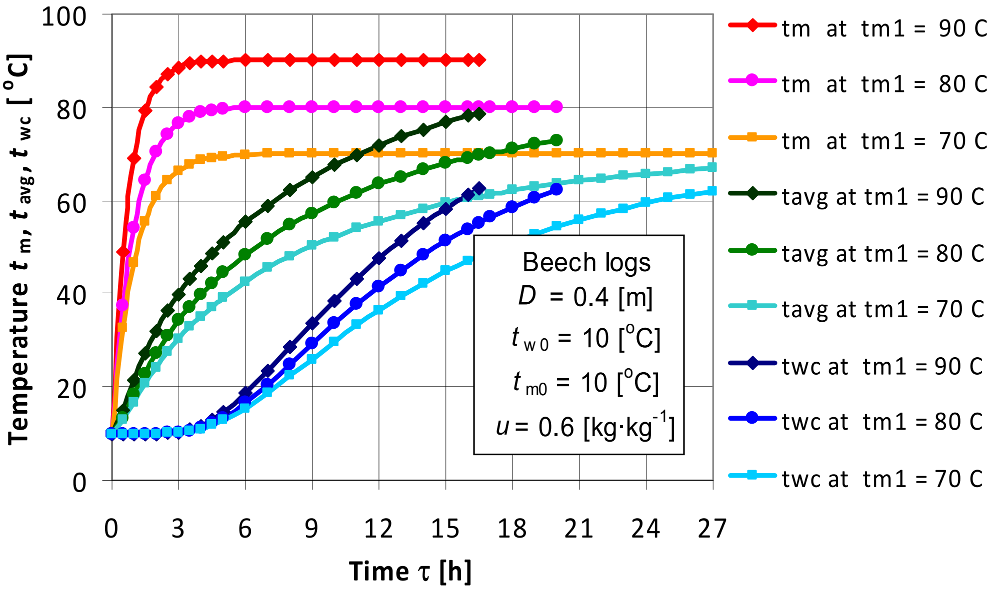

Fig. 3. *Change in t_m, t_{wc}, and t_{avg} of the studied logs during their boiling, depending on t_{m1}*

Figure 4 presents the change of all the components of the heat balance of the pit, as well as the total energy $Q_{pit\text{-}total}$ (in kWh·m^{-3}) required to carry out the entire boiling process, during which the average mass temperature of the logs rises from its initial value t_{w0} = 10°C to the 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. At these values of $t_{avg\text{-}end}$ the temperature in the centre of the logs becomes equal to t_{wc} = 62°C, which corresponds to the minimum required temperature necessary to obtain quality veneer from plasticised beech logs [2, 7, 19].

Figure 5 shows the change of the individual components of the heat balance of the pit Q_i in % to the total energy consumption ($Q_{pit\text{-}total}$) depending on the studied values of t_{m1}.

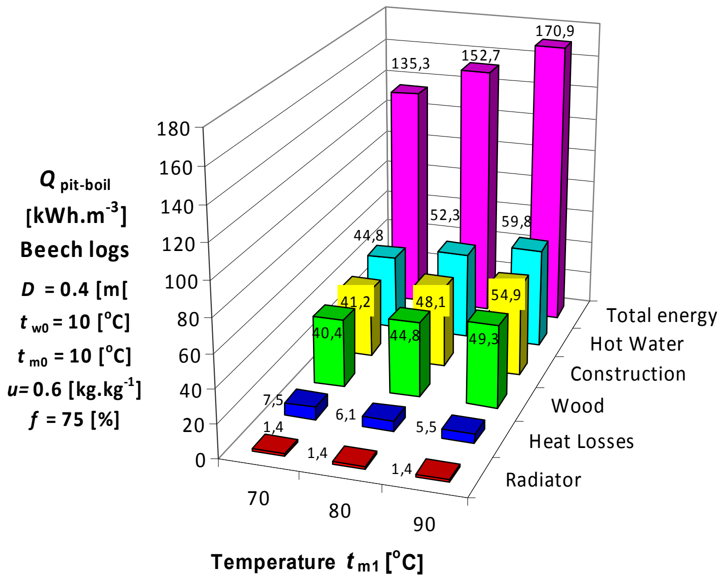

Fig. 4. *Change in the components of the heat balance and the total energy [kWh·m^{-3}] of the pit required for boiling the studied logs, depending on* t_{m1}

Figure 6 presents the change of all the components of the heat balance of the pit, as well as the total energy $Q_{\text{pit-total}}$ (in kWh·m^{-3}) required to realise the entire boiling process, during which the temperature of the logs increases from t_{w0} = 10°C to the specified value of $t_{\text{avg-end}}$ at t_{m1} = 80°C, depending on the studied values of the degree of filling of the pit with logs f = 45, 60, and 75%.

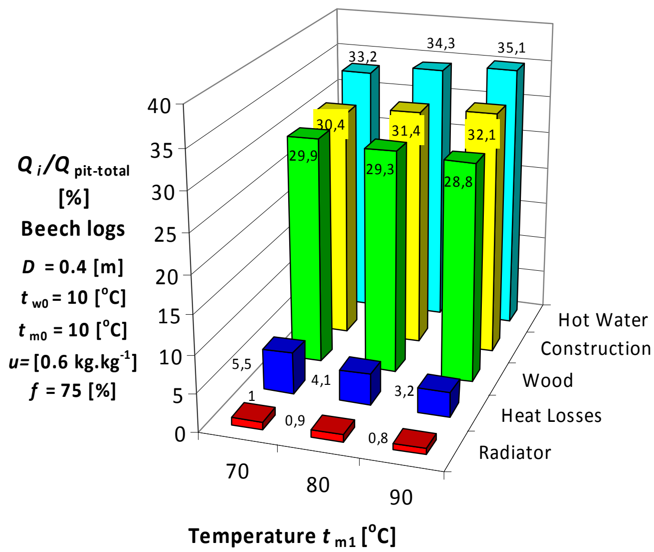

Fig. 5. *Change in the components of the pit's heat balance [%] to the total energy, depending on* t_{m1}

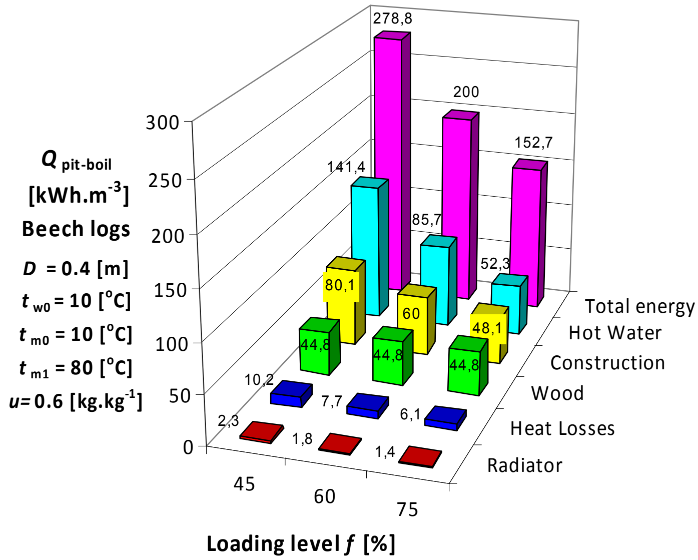

Fig. 6. *Change in the components of the heat balance and the total energy [kWh·m⁻³] of the pit, depending on f*

Figure 7 shows the change of the individual components of the heat balance Q_i in % to the total energy consumption, $Q_{pit\text{-}total}$, when t_{m1} = 80°C and u = 0.6 kg·kg^{-1}, depending on the loading level of the pit f.

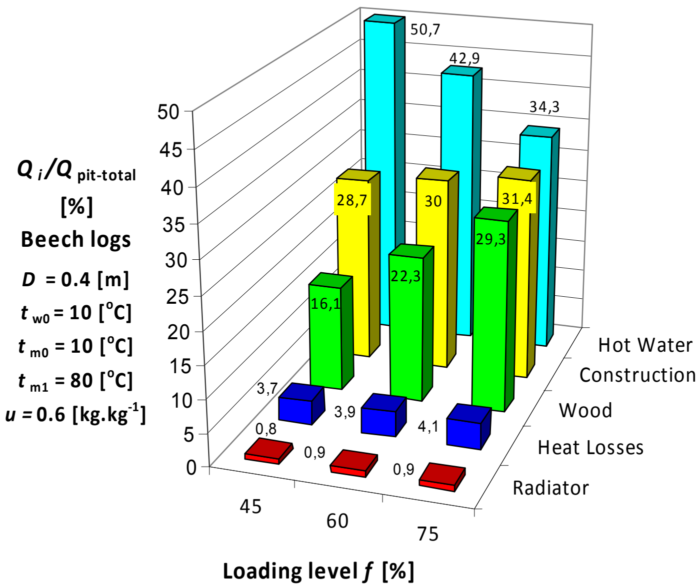

Fig. 7. *Change in the components of the pit's heat balance [%] to the total energy, depending on f*

4. Discussion

Figure 3 shows that the boiling process of the studied logs having the initial temperature t_{w0} = 10°C and the 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 required temperature necessary to obtain quality veneer from heated and plasticised beech logs [2, 7, 19, 25].

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 $Q_{Pit-total}$ and its components Q_{Water}, $Q_{Constr.}$, and Q_{Wood}, but at the same time Q_{Losses} decreases and $Q_{Radiator}$ does not change.

At 75% filling of the working volume of the pit with beech logs having the diameter D = 0.4 m, the moisture content u = 0.6 kg·kg^{-1}, and the initial temperature t_{w0} = 10°C, the increase of the water temperature t_{m1} from 70 to 90°C causes the following change in the components of the pit's heat balance (Figure 4):

- Q_{Water} increases from 44.8 to 59.8 kWh·m^{-3};
- $Q_{Constr.}$ increases from 41.2 to 54.9 kWh·m^{-3};
- Q_{Wood} increases from 40.4 to 49.3 kWh·m^{-3};
- Q_{Losses} decreases from 7.5 to 5.5 kWh·m^{-3};
- $Q_{Radiator}$ remains unchanged with a value of 1.4 kWh·m^{-3}.

In this case the total specific energy consumption of the pit, $Q_{Pit-total}$, increases from 135.3 to 170.9 kWh·m^{-3}.

When expressing the individual components of the pit's heat balance Q_i as a % of the total energy $Q_{Pit-total}$, an increase in t_{m1} from 70 to 90°C causes the following change in the fraction of each component of this balance (Figure 5):

- Q_{Water} increases from 33.2 to 35.1%;
- $Q_{Constr.}$ increases from 30.4 to 32.1%;
- Q_{Wood} decreases from 29.9 to 28.8%;
- Q_{Losses} decreases from 5.5 to 3.2%;
- $Q_{Radiator}$ decreases from 1.0 to 0.8%.

When expressing the components of the heat balance of the pit in kWh·m^{-3}, a decrease in the degree of filling of the pit with logs f from 75 to 45% causes an increase in both the total energy $Q_{Pit-total}$ and all its components except Q_{Wood}, which remains unchanged.

At D = 0.4 m, t_{w0} = 10°C, u = 0.6 kg·kg^{-1}, and t_{m1} = 80°C, the decrease of the loading level f from 75 to 45% causes the following change in the components of the pit's heat balance (Figure 6):

- Q_{Water} increases from 52.3 to 141.4 kWh·m^{-3};
- $Q_{Constr.}$ increases from 48.1 to 80.1 kWh·m^{-3};
- Q_{Losses} increases from 6.1 to 10.2 kWh·m^{-3};
- $Q_{Radiator}$ increases from 1.4 to 2.3 kWh·m^{-3};
- Q_{Wood} remains unchanged with a value of 44.8 kWh·m^{-3}.

In this case, the total energy consumption of the entire pit ($Q_{Pit-total}$) increases from 152.7 to 278.8 kWh·m^{-3}.

When expressing the components of the pit's heat balance Q_i as a % of the total energy $Q_{Pit-total}$, a decrease of f from 75 to

45% causes the following change in the fraction of the individual components of this balance (Figure 7):

- Q_{Water} increases from 34.3 to 50.7%;
- $Q_{Constr.}$ decreases from 31.4 to 28.7%;
- Q_{Wood} decreases from 29.3 to 16.1%;
- Q_{Losses} decreases from 4.1 to 3.7%;
- $Q_{Radiator}$ decreases from 0.9 to 0.8%.

5. Conclusions

This paper considers an approach for computing the heat balance of concrete boiling pits during heating in them for the purpose of plasticising logs intended for the production of peeled veneer.

With the help of our own non-stationary model, the boiling times of non-frozen 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 a water temperature in the pit, t_{m1}, equal to 70, 80, and 90°C and at a degree of filling of the pit with logs, f, equal to 45, 60, and 75%. Using the determined logs' boiling durations and the mentioned approach, the total specific energy required to carry out the entire boiling process in the pit, $Q_{pit\text{-}boil}$, and that required for each of the individual components of the heat balance were calculated.

It was found that at the commonly used values of t_{m1} = 80°C and f = 75%, the total energy consumption of the pit is equal to 152.7 kWh.m^{-3}. The fraction of the individual components of the thermal balance is as follows: 34.3% for heating the boiling water, 31.4% for heating the construction of the pit, 29.3% for heating the logs themselves, 4.1% for covering the heat losses of the pit in the surrounding space, and 0.9% for heating the metal heater/radiator of the pit itself.

The increase of t_{m1} from 70 to 90°C at f = 75% causes an increase of the energy consumption of the entire pit $Q_{Pit\text{-}total}$ from 135.3 to 170.9 kWh·m^{-3}, i.e. by 26.3%, which is equivalent to an increase of 1.32% for each degree increase in t_{m1}. The fraction of the individual balance components in this case change as follows: Q_{Water} and $Q_{Constr.}$ increase by 1.9 and 1.7%, respectively, but Q_{Wood}, Q_{Losses}, and $Q_{Radiator}$ decrease by 1.1, 2.3, and 0.2%, respectively.

The decrease of f from 75 to 45% at t_{m1} = 80°C causes an increase of the energy consumption of the pit $Q_{Pit\text{-}total}$ from 152.7 to 278.8 kWh·m^{-3}, i.e. by 82.6%, which is equivalent to an increase of 2.75% for each percent decrease in f.

The fraction of the individual balance components in this case changes as follows: Q_{Water} increases by 16.4%, but Q_{Wood}, $Q_{Constr.}$, Q_{Losses} and $Q_{Radiator}$ decrease by 13.2, 2.7, 0.4, and 0.1%, respectively.

The ratio of the calculated values of Q_{Wood} to those of $Q_{Pit\text{-}total}$ shows that when the loading level of the pit, f, decreases from 75 to 45%, the heat efficiency of the pit decreases from 29.3 to 16.1%. The reason for this is the very large increase in the specific energy required for heating the water in the pit, referring to 1 m^3 of wood, when f decreases. This shows how important it is for good heat efficiency of the pit to be densely filled with logs.

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