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INFLUENCE OF WOOD MOISTURE CONTENT ON THE HEAT BALANCES AND EFFICIENCIES OF CONCRETE PITS DURING STEAMING OR BOILING UNFROZEN VENEER LOGS

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Abstract: *A model-based approach for determining the heat balances and efficiencies of concrete pits during steaming or boiling of unfrozen veneer logs presented. With the help of a personal 1D model, the heating durations of beech logs with a diameter of 0.4 m, initial temperature of 10°C, and moisture content of 0.4, 0.6, and 0.8 kg·kg*$^{-1}$ *were calculated at operating temperature of 80°C in the pit. Using the determined logs' heating times and our own stationary model of the heat balances of concrete pits during steaming or boiling logs, the change in the heat balances and efficiencies of a pit with working volume of 20 m*^{3} *and loading level of 45, 60, and 75%, depending on the logs' moisture content was calculated. It was found that the change of the logs' moisture content from 0.4 to 0.8 kg·kg*$^{-1}$ *at maximum possible loading level of 75% leads to a rise in the energy consumptions and heat efficiencies of the pit from 104.3 to 125.2 kWh·m*$^{-3}$ *and from 34.3 to 42.9%, respectively, during the steaming process, and also from 143.5 to 161.8 kWh·m*$^{-3}$ *and 24.9 to 33.2%, respectively, during the boiling process. Reducing the pit load level from 75 to 45% at 0.6 kg·kg*$^{-1}$ *causes a decrease in the pit efficiencies from 39.0 to 28.5% during the log steaming process and from 29.3 to 16.1% during the log boiling process.*

Key words: *concrete pits, heat balance, heat efficiency, beech logs, steaming, boiling.*

1. Introduction

It is well known that the thermal treatment of logs in steaming or boiling pits is mostly carried out for the purpose of plasticizing the wood in order to reduce the

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cutting resistance during the formation of quality peeled veneer [1-3, 6, 8, 10, 13-17, 19-30]. The steaming and boiling processes of wood in pits require significant energy costs and show quite poor heat efficiencies [16, 22]. In Hnêtkovský [11] it is stated that filling the pits with logs cannot exceed 75% of their working space.

Very few publications have investigated the energy consumption necessary for steaming or boiling wood in pits. In Dzurenda and Deliiski [9, 10], the heat balance of the pit presented in Figure 1 during the boiling of unfrozen veneer prisms was studied using a model proposed by the authors.

Using in Deliiski et al. [7] an updated version of the model given in Dzurenda and Deliiski [9, 10], the heat balance and its components of the pit shown in Figure 1 were calculated for the case of boiling at water temperatures of 70, 80, and 90°C of beech logs with a diameter of 0.4 m, temperature of 10°C, and wood moisture of 0.6 $kg \cdot kg^{-1}$. It was found that at loading level of 75%, with an increase in the water temperature within these limits, the energy consumption of the pit changed from 135.3 to 170.9 $kWh \cdot m^{-3}$.

In this case, the following changes in the fraction of each component of the pit's balance were calculated: the energies required to heat the pit structure and the water in it increased from 30.4 to 32.1% and from 33.2 to 35.1%, respectively; the energies for warming up the logs, to cover the losses of the pit, and to heat the radiator in it decreased from 29.9 to 28.8%, from 5.5 to 3.2%, and from 1.0 to 0.8%, respectively.

The objective of this work is to supplement the updated and refined version of the model in Deliiski et al. [7] with a fragment for steaming logs in pits and to use it to study the impact of the moisture content of unfrozen logs on the heat balance and heat efficiency of the same pit during separate steaming or boiling.

2. Materials and Methods

2.1. Design Features of the Pits

This study was conducted on the pit presented in Figure 1, having a working volume calculated with Equation (1):

$$V_{pit} = l \cdot b \cdot h_w = 20\ m^3 \qquad (1)$$

where:

V_{pit} is the volume of the pits [m^3];
l – the length of the pits [m];
b – the width of the pits [m];
h_w – the thickness of the pits [m].

The meaning of the symbols, their units and the values of the parameters marked in Figure 1, as well as a total of 19 set parameters of the pit used to solve the mathematical models of the pit's heat balance and efficiencies are given in the first half of Table 1 of our open access publication [7].

2.2 Logs and Modes Parameters

This study was conducted on unfrozen beech (*Fagus sylvatica* L.) logs with a diameter of 0.4 m and moisture contents above the hygroscopic range equal to 0.4, 0.6, and 0.8 $kg \cdot kg^{-1}$.

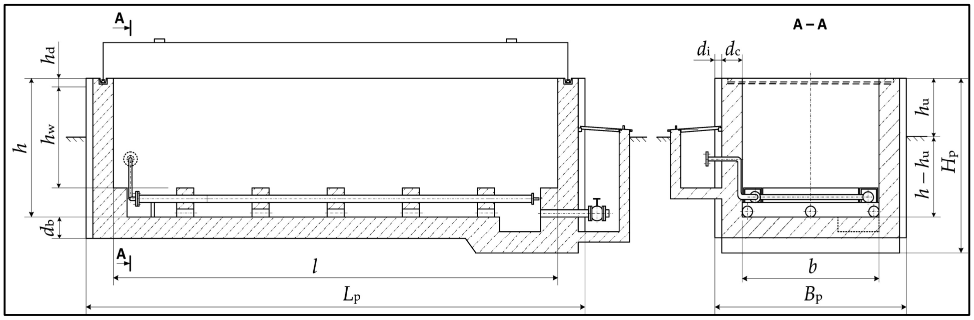

Fig. 1. *Longitudinal and transverse sections of the concrete pit used in the study*

Figure 2 shows the change of the temperature of the processing medium in the pit used in the study, t_m, from t_{m0} = 10°C to t_{m1} = 80°C = const in the modes for steaming or boiling of the logs [21, 23, 30].

The required operating temperature in the pit during log steaming is provided by direct saturated water steam, which is introduced into the pit using 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 and the steam passes through a layer of condensed water when heating the pit and the logs in it. After steaming is completed, the pit's lid is moved, the plasticized logs are directed to the veneer machines, and the condensed water is drained from the pit.

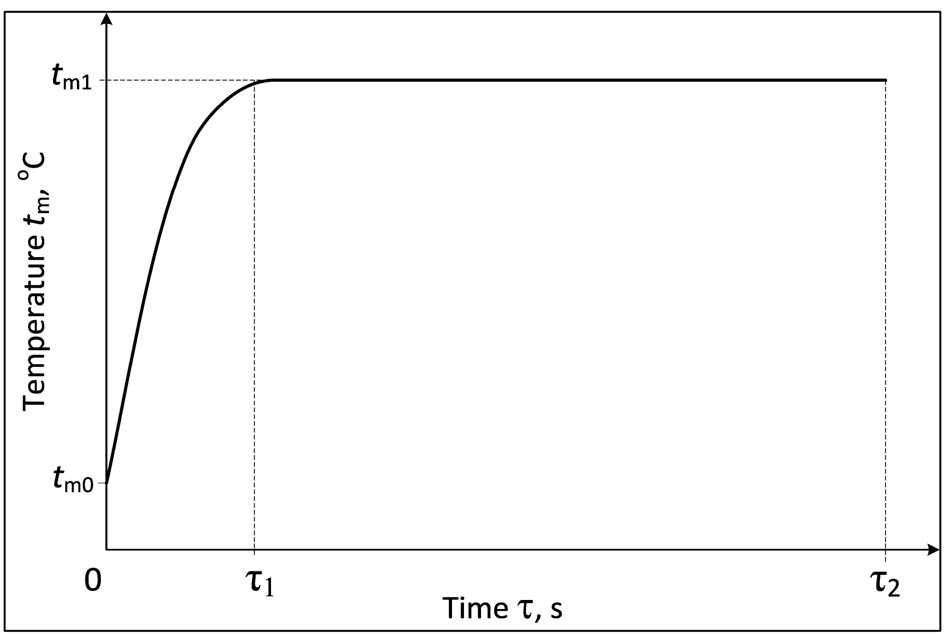

Fig. 2. *Change of t_m in modes for steaming or boiling of logs in pits*

The heating of the water in the pit during log boiling is carried out indirectly by means of steam or hot water under pressure in the heating elements of the radiator, and in this case its tubular elements are not perforated.

The symbols, units, and values of all the logs' thermo-physical characteristics, as well as total of 14 parameters of the steaming and boiling modes used in the computer simulations, are given in the second half of Table 1 of our open access article [7].

2.3. 1D Model of the Temperature Distribution in Unfrozen Logs During Steaming or Boiling

During the study, the following 1D model verified in Deliiski [4, 5] and Deliiski and Dzurenda [6]of the non-stationary heating of logs with moisture content above the hygroscopic range during their steaming or boiling was used Equations (2) to (4):

$$c_{w-nfr} \cdot \rho_w \cdot \frac{\partial T(r,T)}{\partial \tau} = div\left(\lambda_{wr-nf}\ gradT\right) \qquad (2)$$

at

$$T(r,0) = T_{w0} \qquad (3)$$

and

$$T(0,\tau) = T_m(\tau) \qquad (4)$$

where:

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

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

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

r – the coordinate along the log 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 temperature of the processing steaming or boiling medium in the pit [K];

τ – the time [s].

Mathematical descriptions of all the thermo-physical characteristics of the non-frozed wood, which are involved in models (1) to (3), have been made in Deliiski [3-5] and Deliiski and Dzurenda [6] and verified with experimentally obtained foreign dissertation data as a function of the temperature and wood moisture content.

2.4. Models of the Heat Balances of Pits During Steaming or Boiling

The following stationary models represent the indicated heat balances:

• during the steaming of logs – Eq. (5):

$$Q_{pit-steamin} = Q_{wood} + Q_{constr.} + Q_{cond.water} + Q_{radiator} + Q_{heat\ losses} \qquad (5)$$

• during the boiling of logs – Eq. (6):

$$Q_{pit-boiling} = Q_{wood} + Q_{constr.} + Q_{hot\ water} + Q_{radiator} + Q_{heat\ losses} \qquad (6)$$

where:

$Q_{pit\text{-}steaming}$ and $Q_{pit\text{-}boiling}$ are the total specific (relating to 1 m^3 wood) heat energy consumptions of the pit [$kWh \cdot m^{-3}$];

Q_{wood} – the energy for heating the logs themselves [$kWh \cdot m^{-3}$];

$Q_{constr.}$ – the energy for heating the pit's construction components [$kWh \cdot m^{-3}$];

$Q_{cond.\ water}$ – the energy contained in the condensed water in the pit [$kWh \cdot m^{-3}$];

$Q_{hot\ water}$ – the energy for heating to the set temperature t_{m1} of the boiling regime (refer to Figure 2) [$kWh \cdot m^{-3}$];

$Q_{radiator}$ – the energy required to heat the 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 [$kWh \cdot m^{-3}$];

$Q_{heat\ losses}$ – the energy to cover the heat losses of the pit [$kWh \cdot m^{-3}$].

Mathematical descriptions of each of the individual components of the heat balances, which participate in the right-hand sides of Equations (5) and (6), are given in Deliiski et al. [7, 8]. In these literature sources, only a mathematical description of the component $Q_{cond.\ water}$ in Equation (5) is missing.

Since in Equations (5) and (6) the first, second, fourth and fifth terms of their right-hand sides are the same, the mathematical description of only their fourth terms, namely $Q_{cond.\ water}$ and $Q_{hot\ water}$, is presented below.

2.5. Mathematical Description of $Q_{cond.\ water}$

The main part of the thermal energy that is spent on the production of steam, which is introduced into the pit ($Q_{\text{pit-steaming}}$), and condensing, with the released heat, provides the heating of the wood (Q_{wood}), the construction of the pit ($Q_{\text{constr.}}$), and covers its heat losses ($Q_{\text{heat losses}}$). When this steam is condensed, part of the energy spent on its production "remains" in the condensed water, which accumulates at the bottom of the pit until the end of steaming. This part of the energy in the condensed water is represented in Equation (5) as $Q_{\text{cond. water}}$ and, referred to 1 m^3 of wood subjected to steaming, it is equal to the following (Eq. (7) and (8)):

$$Q_{cond.\ water} = m_{cw} \cdot \frac{h_{cw}\ at\ t=t_{ml}\ \&\ \tau=\tau_2}{3.6 \cdot 10^6 \cdot V_w} \tag{7}$$

at

$$m_{cw} = 3.6 \cdot 10^6 \cdot V_w \cdot \frac{Q_{wood}+Q_{constr.}+Q_{heat\ losses}}{r_{steam}\ at\ t=t_{ml}\ \&\ \tau=\tau_2} \tag{8}$$

where:

m_{cw} is the mass of condensed water in the pit at the end τ_2 of the steaming process [kg];

h_{cw} – the enthalpy of the condensation water in the pit at $t = t_{m1}$ and $\tau = \tau_2$ (see Figure 2) [$J \cdot kg^{-1}$]; in this study h_{cw} = $2{,}308 \cdot 10^6$ $J \cdot kg^{-1}$ at t_{m1}= 80°C [6, 10];

r_{steam} – the condensation heat of steam in the pit at $t = t_{m1}$ and $\tau = \tau_2$ [$J \cdot kg^{-1}$]; in the case under consideration r_{steam} = $3{,}35 \cdot 10^5$ $J \cdot kg^{-1}$ at t_{m1}= 80°C [6, 10].

The values of m_{cw}, and the energy dependent on it, $Q_{\text{cond. water}}$, are calculated for the conditions at the end of the second stage of the steaming mode, 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 $J \cdot m^{-3}$ of the sum of the energies Q_{wood}, Q_{constr}, and $Q_{heat\ losses}$ after dividing it by condensation heat of steam in the pit, r_{steam}, at the moment $\tau = \tau_2$.

The volume of all logs in the pit, V_w, which participates in Equations (7) and (8), was calculated with Equation (9):

$$V_w = f \cdot V_{pit} \tag{9}$$

where:

f is the loading level of the pit with wood materials subjected to steaming or boiling [$m^3 \cdot m^{-3}$];

V_{pit} – the working space of the pit [m^3].

It was calculated with Equation (10):

$$V_{pit} = l \cdot b \cdot h_w \tag{10}$$

2.6. Mathematical Description of $Q_{hot\ water}$

This component of $Q_{pit\text{-}boiling}$ was calculated with Equation (11) – [8]:

$$Q_{hot\ water} = \frac{1}{3.6 \cdot 10^6 \cdot V_w} \cdot \left(V_{pit} - V_w\right) \cdot \rho_{H_2O} \cdot c_{H_2O} \cdot \left(t_{H_2O} - t_{H_2O-be}\ \right) \tag{11}$$

where:

ρ_{H_2O} is the density of the boiling water in the pit, equal to 998 $kg \cdot m^{-3}$;

c_{H_2O} – the average value of the specific heat capacity of boiling water, equal to 4180 $J \cdot kg^{-1} \cdot K$;

t_{H_2O} – the maximum temperature of the boiling water, equal to t_{m1} = 80°C;

$t_{H_2O\text{-}beg}$ – the initial temperature of the boiling water, equal to t_{m0} = 10°C.

Equation (11) applies to cases where the water in the pit at the beginning of the log boiling process is not contaminated with diluted organic acids and other water-leachable substances from the previous wood thermal treatment process.

2.7. Determination of the Heat Efficiencies of Pits

The heat efficiencies of the tested concrete pit when steaming or boiling beech logs with different wood moisture u in it under conditions of different filling levels f of the pit with logs are calculated (in %) according to the following equations:

- during steaming of logs – Eq. (12):

$$\eta_{pit-steaming} = \frac{Q_{wood}}{Q_{steam-total}} \cdot 100 \tag{12}$$

- during boiling of logs – Eq. (13):

$$\eta_{pit-boiling} = \frac{Q_{wood}}{Q_{boil-total}} \cdot 100 \tag{13}$$

where:

$\eta_{pit\text{-}steaming}$ is the heat efficiencies of the tested concrete pit when steaming [%];

$\eta_{pit\text{-}boiling}$ – the heat efficiencies of the tested concrete pit when boiling [%];

Q_{wood} – the energy needed for heating only the logs subjected to steaming or boiling [$kWh \cdot m^{-3}$];

$Q_{steam\text{-}total}$ and $Q_{boil\text{-}total}$ – the total pit's energy consumptions calculated by Equations (5) and (6), which are necessary for carrying out the entire processes of steaming or boiling the logs, respectively [$kWh \cdot m^{-3}$].

2.8. Solving Models (2) – (4) and (5) – (13)

The solution of models (2) – (4) was done with our software program in the Visual FORTRAN platform. Using it, the temperature changes in unfrozen logs with moisture u = 0.4, 0.6 and 0.8 kg·kg^{-1} were studied until such a duration τ_2 of the modes was reached that ensured optimal wood plasticization for obtaining quality veneer [3, 6, 18]. The solution of models (5) – (13) was conducted with our personal Excel program [12] at a degree of filling of the pit with logs, f, equal to 45, 60, and 75%.

3. Results

Figure 3 presents the changes in the temperature of the central point of the logs (t_{wc}), and also the average temperature of the logs (t_{avg}), calculated with model (2) – (4) during log steaming or boiling at the operating temperature (t_m). The values of t_{avg} (in K) at the end of the modes is needed to calculate the energy Q_{wood} in Equations (5), (6), and (8). The temperature t_m increases from t_{m0} = 10°C to t_{m1} = 80°C within τ_1 = 4 h (Figure 2) for all three investigated values of u, equal to 0.4, 0.6, and 0.8 kg·kg^{-1}.

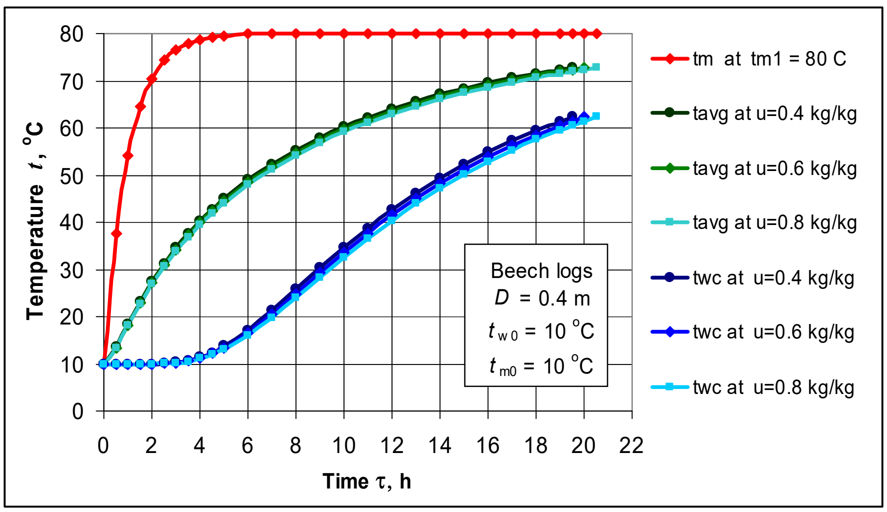

Fig. 3. *Change in t_m, t_{wc}, and t_{avg} of the logs during their steaming or boiling, depending on u*

Figure 4 shows the change of all components of the heat balances of the tested pit at its maximum possible loading level f = 75%, as well as the total energy consumption of the pit (in kWh·m^{-3}) when steaming or boiling logs, $Q_{steam\text{-}total}$ and $Q_{boil\text{-}total}$ respectively, depending on the studied values of u.

Figure 5 presents the change of each of the five components of the pit's heat balances Q_i at f = 75% to $Q_{steam\text{-}total}$ and $Q_{boil\text{-}total}$, depending on u.

Figure 6 shows the change in the heat efficiencies of the pit calculated with Equations (12) and (13), when steaming or boiling the studied logs in it, depending on u and f.

The legends of the Figures 4 to 6 give values for parameters of the logs and the modes for their steaming or boiling.

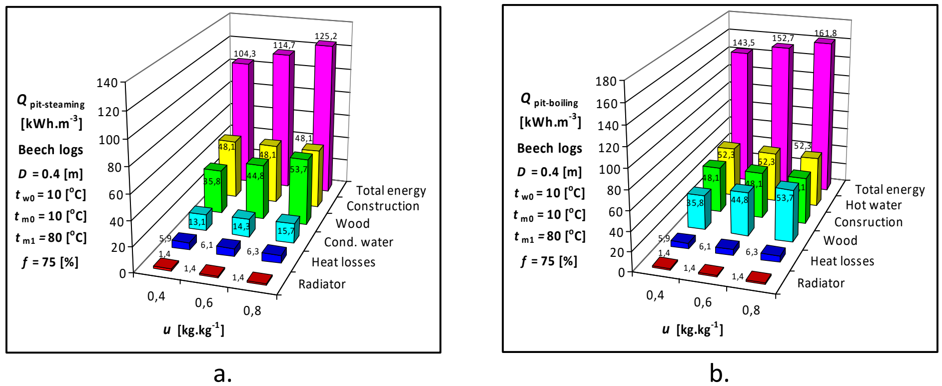

Fig. 4. *Change in the components of the heat balances and total energies (in kWh·m*$^{-3}$*) of the pit required for steaming (a.) or boiling (b.) of the logs, depending on u*

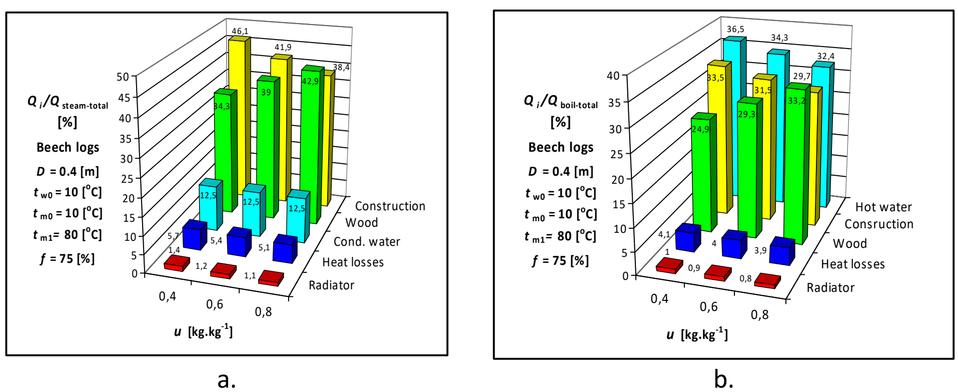

Fig. 5. *Change in the components of the pit's heat balances in % to the total energies when steaming (a.) or boiling (b.) logs, depending on u*

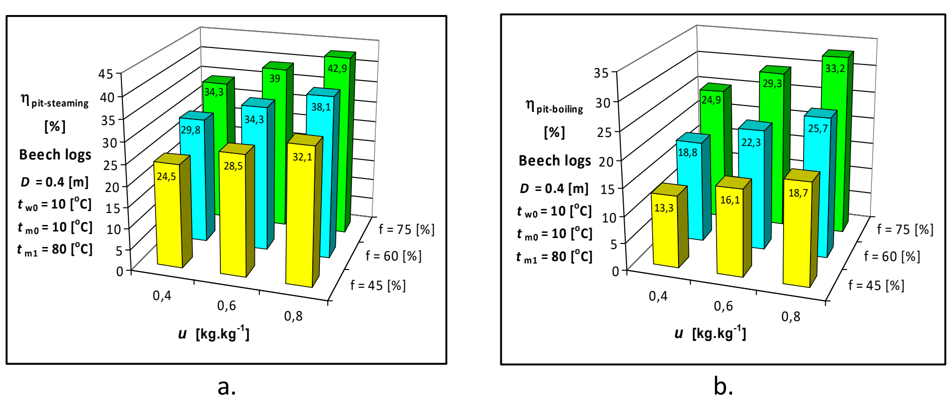

Fig. 6. *Change in the heat efficiencies of the pit when steaming (a.) or boiling (b.) logs, depending on u and f*

4. Discussion

In Figure 3 it can be seen that the duration of both the steaming and boiling modes of the logs is as follows: τ_2 = 19.5 h at u = 0.4 kg·kg^{-1}, τ_2 = 20.0 h at u = 0.6 kg·kg^{-1}, and τ_2 = 20.5 h at u = 0.8 kg·kg^{-1}. At these values of τ_2, the temperature t_{wc} reaches 62°C, which is the minimum temperature required for good plasticization of veneer beech logs [3, 6, 10, 18]. It is also seen that during both the steaming and the boiling processes, the temperature t_{avg} increases from t_{w0} = 10°C to $t_{avg\text{-}end}$ = 72.7°C in all modes.

Figure 4 shows that the change in u from 0.4 to 0.8 kg·kg^{-1} leads to an increase in the energy consumption of the pit, as follows: from 104.3 to 125.2 kWh·m^{-3} for $Q_{steam\text{-}total}$ and from 143.5 to 161.8 kWh·m^{-3} for $Q_{boil\text{-}total}$. In these cases, the components of the heat balances of the pit change in the following way (Figure 4):

- *when steaming the logs:* Q_{wood}, $Q_{cond.water}$, and $Q_{heat\ losses}$ increase from 35.8 to 53.7 kWh.m^{-3}, from 13.1 to 13.3 kWh·m^{-3}, and from 5.9 to 6.3 kWh·m^{-3} respectively; $Q_{constr.}$ and $Q_{radiator}$ remain unchanged with values of 48.1 and 1.4 kWh·m^{-3} respectively;
- *when boiling the logs:* Q_{wood} and $Q_{heat\ losses}$ increase in the same way as during the steaming − from 35.8 to 53.7 kWh·m^{-3} and from 5.9 to 6.3 kWh·m^{-3} respectively; $Q_{constr.}$ and $Q_{radiator}$ remain unchanged as well as during the steaming − with values of 48.1 and 1.4 kWh·m^{-3} respectively; $Q_{hot\ water}$ remains unchanged with a value of 52.3 kWh·m^{-3}.

As the wood moisture u increases within the specified limits, the percentage contribution of each component in the heat balances $Q_{steam\text{-}total}$ and $Q_{boil\text{-}total}$ changes as follows (Figure 5):

- *when steaming the logs:* $Q_{constr.}$, $Q_{heat\ losses}$, and $Q_{radiator}$ decrease from 46.1 to 38.4%, from 5.7 to 5.1%, and from 1.4 to 1.1% respectively; Q_{wood} increases from 34.3 to 42.9%; $Q_{cond.water}$ remains unchanged with a value of 12.5%;
- *when boiling the logs:* $Q_{hot\ water}$, Q_{constr}, $Q_{heat\ losses}$, and $Q_{radiator}$ decrease from 36.5 to 32.4%, from 33.5 to 29.7%, from 4.1 to 3.9%, and from 1.0 to 0.8%, respectively; Q_{wood} increases from 24.9 to 33.2%.

Figure 6 shows that increasing u within the specified limits leads to the following rise in the heat efficiencies of the pit at a given loading level f:

- from 24.5 to 32.1% and from 13.3 to 18.7% for $\eta_{pit\text{-}steaming}$ and $\eta_{pit\text{-}boiling}$ respectively at f = 45%;
- from 29.8 to 38.1% and from 18.8 to 25.7% for $\eta_{pit\text{-}steaming}$ and $\eta_{pit\text{-}boiling}$ respectively at f = 60%;
- from 34.3 to 42.9% and from 24.9 to 33.2% for $\eta_{pit\text{-}steaming}$ and $\eta_{pit\text{-}boiling}$ respectively at f = 75%.

Figure 6 also shows that reducing f from 75 to 45% leads to lowering the heat efficiencies of the pit at a given u, namely:

- from 34.3 to 24.5% and from 24.9 to 13.3% for $\eta_{pit\text{-}steaming}$ and $\eta_{pit\text{-}boiling}$ respectively at u = 0.4 kg·kg^{-1};
- from 39.0 to 28.5% and from 29.3 to 16.1% for $\eta_{pit\text{-}steaming}$ and $\eta_{pit\text{-}boiling}$ respectively at u = 0.6 kg·kg^{-1};
- from 42.9 to 32.1% and from 33.2 to 18.7% for $\eta_{pit\text{-}steaming}$ and $\eta_{pit\text{-}boiling}$ respectively at u = 0.8 kg·kg^{-1}.

5. Conclusions

It was found that at t_{w0} = 10°C, t_{m1} = 80°C and f = 75%, the total energy consumption of the studied concrete pit with working volume V_{pit} = 20 m^3 is 114.7 kWh·m^{-3} when steaming veneer beech logs with u = 0.6 kg.kg^{-1} and 152.7 kWh·m^{-3} when boiling the same logs.

The reason for the higher energy consumption during log boiling is the significant amount of energy required for heating 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 ($Q_{boil\text{-}total}$). During log steaming, instead of energy $Q_{hot\ water}$, the energy $Q_{cond.\ water}$ participates in the pit's heat balance. In the case under consideration, the energy $Q_{cond.\ water}$ is 14.3 kWh·m^{-3} and constitutes only 12.5% of the total energy ($Q_{steam\text{-}total}$).

The change of u from 0.4 to 0.8 kg.kg^{-1} at f = 75% leads to an increase of the energy $Q_{steam\text{-}total}$ from 104.3 to 125.2 kWh·m^{-3} (i.e. by 20.0%) and from 143.5 to 161.8 kWh·m^{-3} (i.e. by 12.8%) of the energy $Q_{boil\text{-}total}$.

When steaming the logs, the percentage of each component of $Q_{steam\text{-}total}$ in the case under consideration changes as follows: $Q_{constr.}$, $Q_{heat\ losses}$, and $Q_{radiator}$ decrease from 46.1 to 38.4%, from 5.7 to 5.1% and from 1.4 to 1.1% respectively; Q_{wood} increases from 34.3 to 42.9% and $Q_{cond.water}$ remains constant at 12.5%.

When boiling the same logs, the percentage of each component of $Q_{boil\text{-}total}$ changes as follows: $Q_{hot\ water}$, Q_{constr}, $Q_{heat\ losses}$, and $Q_{radiator}$ decrease from 36.5 to 32.4%, from 33.5 to 29.7%, from 4.1 to 3.9%, and from 1.0 to 0.8%, respectively; Q_{wood} increases from 24.9 to 33.2%.

The same rise of u from 0.4 to 0.8 kg.kg^{-1} at f = 75% leads to an increase in the pit's heat efficiencies $\eta_{pit\text{-}steaming}$ and $\eta_{pit\text{-}boiling}$ from 34.3 to 42.9% and from 24.9 to 33.2%, respectively.

The reducing of f from 75 to 45% at u = 0.6 kg.kg^{-1} leads to reduction of $\eta_{pit\text{-}steaming}$ and $\eta_{pit\text{-}boiling}$ from 39.0 to 28.5% and from 29.3 to 16.1%, respectively.

The results of the study show that at the same values of t_{m1}, u, and f, the heat efficiency $\eta_{pit\text{-}steaming}$ is about 10% greater than $\eta_{pit\text{-}boiling}$.

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