

INFLUENCE OF THE MOISTURE CONTENT OF FROZEN LOGS ON ENERGY REQUIRED FOR THEIR DEFROSTING IN BOILING PITS

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ABSTRACT

With the help of our own non-stationary model, the temperature field and defrosting durations of frozen beech logs with a diameter of 0.4 m, initial temperature of $-10\text{ }^{\circ}\text{C}$, and moisture content of $0.4\text{ kg}\cdot\text{kg}^{-1}$, $0.6\text{ kg}\cdot\text{kg}^{-1}$, and $0.8\text{ kg}\cdot\text{kg}^{-1}$ were determined at water temperatures in the boiling pit equal to $80\text{ }^{\circ}\text{C}$. Using the determined durations, the change in energy required for carrying out of the entire defrosting process and that for each of the 5 components of the pit's thermal balance was calculated. Computer simulations were performed for a well-insulated concrete pit with working volume of 20 m^3 and degree of filling with logs f equal to 25%, 50%, and 75%. It was found that at maximum possible value $f = 75\%$ the total energy consumption of the pit increases from $145.1\text{ kWh}\cdot\text{m}^{-3}$ to $180.2\text{ kWh}\cdot\text{m}^{-3}$, i.e. by 24.2% when the moisture content of the frozen logs increases from $0.4\text{ kg}\cdot\text{kg}^{-1}$ to $0.8\text{ kg}\cdot\text{kg}^{-1}$. With a decrease in f , the thermal efficiency of the pit decreases almost proportional to f , mainly due to the increase in the specific energy required to heat the water in the pit.

Key words: concrete boiling pits, heat balance, defrosting of logs, wood moisture content, energy consumption.

INTRODUCTION

It is well known that the thermal treatment of logs in boiling or steaming pits is carried out for the purpose of plasticizing the wood, in order to reduce the cutting resistance during the formation of quality veneer (Chudinov 1968, Kollmann and Côté 1984, Shubin 1990, Trebula and Klement 2002, Videlov 2003, Câmpean, 2005, Deliiski and Dzurenda 2010, Hadjiski et al. 2021, Niemz et al. 2023).

The boiling and steaming processes of wood materials in pits are characterized by high energy consumption and low energy efficiency (Sohor and Kadlec 1990, Lawniczak 1995). The correct and effective control of considered processes is possible only when their physics and the weight of the influence of too much 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 required energy consumption is a difficult task and its solution is possible only with the help of adequate mathematical models.

In (Dzurenda and Deliiski 2011, 2019), a mathematical model of the heat balance of the shown below in Fig.1 pit is proposed only when boiling in it non-frozen prismatic wood materials. In (Deliiski et al. 2023a, 2023b), this model has been updated and supplemented with equations allowing to investigate the heat balance of concrete pits during defrosting and subsequent heating of frozen logs. In (Deliiski et al. 2023a), the influence of the initial temperature of frozen beech logs with a diameter of 0.4 m on the energy expenditure required for their defrosting at a water

temperature in the pit of 80°C was investigated. It was found that the decrease of the initial temperature from -10 °C to -30°C at maximum possible degree of filling of the concrete pit shown in Fig. 1 with logs of 75%, causes an increase of the energy consumption of the entire pit from 163.6 kWh·m⁻³ to 177.6 kWh·m⁻³, i.e. by 8.6%.

The aim of the present work is to conduct with the updated model given in (Deliiski et al. 2023a, 2023b) a study of the heat balance of the same concrete pit for the case of complete defrosting in it of frozen logs with different moisture content.

MATERIALS AND METHODS

The computer simulations in this study were carried out with frozen beech (*Fagus sylvatica* L.) logs subjected to defrosting in boiling pit shown in Fig. 1. The influence of moisture content above the hygroscopic range on the heat balance of the pit was investigated.

The main set parameters of the pit and studied logs used to solve the mathematical model of the pit’s heat balance during defrosting of logs are given in Table 1. Logs with such parameters and especially with moisture content of 0.4, 0.6, and 0.8 kg·kg⁻¹ contain significant amounts of frozen both free and bound water, the melting of which will favor the increase of the differences between the corresponding energy consumptions of the pit.

The walls of the pit’s construction are well insulated and 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. During the heating of the logs, the pit is closed with a removable well insulated metal lid. The heating of the water in the pit to the required operating temperature is carried out indirectly by means of metal radiator located at the lower end of the pit. The radiator connected to the plant’s heating system is heated by steam or hot water under pressure with a temperature of 120–140°C.

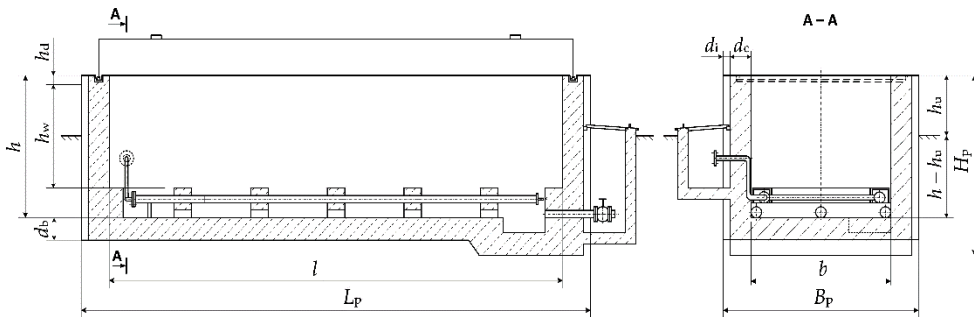


Figure 1: A longitudinal and transverse section of pit for boiling wood materials used during the computer simulations on complete defrosting of frozen beech logs.

During the simulations, commonly applied regimes for boiling frozen wood materials were used (Deliiski et al. 2023a, 2023b). In these regimes, the temperature of the water in the pit rises exponentially over the course of 4 hours from an initial value of 10°C to reaching and maintaining a maximum constant value of 80°C (refer to Table 1).

MODEL OF HEAT BALANCE OF BOILING PIT DURING LOGS DEFROSTING

The heat balance of the concrete pit during defrosting of logs can be represented by the following mathematical model in a general form:

$$Q_{\text{Pit-total}} = Q_{\text{Wood}} + Q_{\text{Constr.}} + Q_{\text{Water}} + Q_{\text{Radiator}} + Q_{\text{Losses}}. \quad (1)$$

where $Q_{\text{Pit-total}}$ is the total specific (for 1 m³ wood) heat energy, required for complete defrosting of the logs; Q_{Wood} – energy required for warming up of the logs themselves subjected to defrosting; $Q_{\text{Constr.}}$ – energy required for heating of the pit's construction materials; Q_{Water} – energy required to heat the water in the pit to the set operating temperature; Q_{Radiator} – energy required to heat the metal radiator of the pit itself; Q_{Losses} – energy required to cover heat losses of the pit during the logs' defrosting process. The dimension of all variables Q in equation (1), and also everywhere below, is kWh·m⁻³.

The energy required for defrosting of the logs themselves, Q_{Wood} , can be expressed by the following model:

$$Q_{\text{Wood}} = Q_{\text{w-fr}} + Q_{\text{ice-bw}} + Q_{\text{ice-fw}} + Q_{\text{w-nfr}} \quad (2)$$

where $Q_{\text{w-fr}}$ is the energy required for the heating of the frozed wood to a condition necessary to melt the frozen bound water in it; $Q_{\text{ice-bw}}$ – energy required to melt the temperature dependent amount of frozen bound water in the wood; $Q_{\text{ice-fw}}$ – energy required to melt the entire amount of frozen free water in the wood; $Q_{\text{w-nfr}}$ – energy required to heat the already.

Defrosted (non-frozen) layers of the wood until reaching 0°C in the central point of the logs subjected to defrosting. Mathematical descriptions of each of the 4 members of the right-hand side of (2) depending on the set of influencing factors are made in (Deliiski et al. 2023b).

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

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

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's construction; $Q_{\text{Constr.3}}$ and $Q_{\text{Constr.4}}$ – energies required for heating of the pit's bottom and pit's lid, respectively. In (Dzurenda and Deliiski 2010, 2011, 2019) are given equations for calculation of each of the components $Q_{\text{Constr.1}}$, $Q_{\text{Constr.2}}$, $Q_{\text{Constr.3}}$, and $Q_{\text{Constr.4}}$ depending on specified there influencing constructive and thermo-physical factors.

The specific heat energies required for heating of the technological water in the pit, Q_{Water} , and for warming up of the metal radiator of the pit itself at the beginning of the logs' defrosting, Q_{Radiator} , can be calculated with the help of the models given in (Dzurenda and Deliiski 2011, 2019).

The specific heat energy required to cover the losses of the pit, Q_{Losses} , can be expressed by the following model:

$$Q_{\text{Losses}} = Q_{\text{Losses1}} + Q_{\text{Losses2}} + Q_{\text{Losses3}} + Q_{\text{Losses4}} \quad (4)$$

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

Mathematical descriptions of each of the 4 members of the right-hand side of (4) depending on the set of influencing factors are made in (Dzurenda and Deliiski 2011, 2019).

Table 1: Basic set parameters used to solve the mathematical model of the pit's heat balance during defrosting of logs

№	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.	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-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·m ⁻³	2300
10.	Density of the insulating layers of the pit's walls and steel lid	$\rho_i, \rho_{icov.}$	kg·m ⁻³	350
11.	Density of the steel sheets of the lid	ρ_{Fe}	kg·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 insulation layers and soil	t_{iu0}, t_{ig0}, t_{s0}	°C	10
14.	Loading level of the pit, i.e. the degree of filling it with logs	f	%	25, 50, 75
15.	Specific mass of the heating elements of the radiator on 1m ² of the area at the bottom of the pit	m	kg·m ⁻²	100
Technological parameters of the defrosting process of frozed beech logs				
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·kg ⁻¹	0.4, 0.6, 0.8
4.	Fiber saturation point of the beech wood	u_{fsp}	kg·kg ⁻¹	0.31
5.	Basic density of the beech wood	ρ_b	kg·m ⁻³	560
6.	Density of the ice in the wood	ρ_{ice}	kg·m ⁻³	917
7.	Density of the water in the pit	ρ_{H2O}	kg·m ⁻³	998
8.	Initial average mass temperature of the logs	t_{w0}	°C	-10
9.	Initial temperature of the process water in the pit	t_{m0}	°C	10
10.	Maximum operating temperature of the boiling water in the pit	t_{m1}	°C	80
11.	Specific heat capacity of the process water in the pit	c_{H2O}	J·kg ⁻¹ ·K	4180
12.	Temperature of the water steam that feeds the pit's radiator	t_{steam}	°C	130
13.	Temperature of the surrounding air near the pit	t_{air}	°C	10
14.	Duration of increase in water temperature t_m from t_{m0} to t_{m1}	τ_1	h	4.0
15.	Duration of the defrosting process of logs, depending on u	$\tau_2 = \tau_{defr}$	h	9.5, 12, 14

SOLVING THE MODEL (1) – (4)

The mathematical descriptions of t_m and the thermo-physical characteristics of wood given in (Deliiski 2003, 2011, Deliiski and Dzurenda 2010, Hadjiski et al. 2021) were entered into own 1D non-linear model of the temperature distribution along the radius of frozen logs during their defrosting and it was solved with the help of the finite difference method using own software program in Visual FORTRAN platform developed by Microsoft.

From the obtained change of the temperature field in the logs, and in particular from that of the temperature in their center, the duration of the defrosting process, τ_{defr} , at water temperature $t_{m1} = 80^\circ\text{C}$ was determined for logs with a diameter of 0.4 m, initial temperature of -10°C , and three values of moisture content of 0.4 kg·kg⁻¹, 0.6 kg·kg⁻¹, and 0.8 kg·kg⁻¹.

An Excel program has been prepared for joint solving of all equations involved in the model (1). Using this program, the heat balance of the pit shown in Fig. 1 was investigated for the case of defrosting in it of frozed beech logs at a degree of filling of the pit with logs equal to 25%, 50%, and 75%. The study was limited only to the moment of complete defrosting of the logs, in which the temperature in their central point becomes equal to 0°C.

The heat energy efficiency of the pit, $\eta_{\text{Pit-defr}}$, at the end of the logs' defrosting is equal to

$$\eta_{\text{Pit-defr}} = 100 \frac{Q_{\text{Wood}}}{Q_{\text{Pit-total}}} \tag{5}$$

where $Q_{\text{Pit-total}}$ and Q_{Wood} are the calculated by Eqs. (1) and (2) values of the specific energies required for for carrying out the entire defrosting process in the pit and for the heating of the logs themselves respectively, kWh·m⁻³.

RESULTS AND DISCUSSION

Figure 2 shows the calculated change of the temperature in the central point of the studied logs, t_{wc} , and also of the average mass temperature of the logs, t_{avg} , during their defrosting at temperature t_m of the hot water. The temperature t_m in the pit rises exponentially from its initial value $t_{m0} = 10^\circ\text{C}$ to $t_{m1} = 80^\circ\text{C} = \text{const}$ over the course of 4 hours.

In Fig. 2 it can be seen that complete defrosting of the investigated logs occurs as follows: after 9.5 h at $u = 0.4 \text{ kg}\cdot\text{kg}^{-1}$, after 12.0 h at $0.6 \text{ kg}\cdot\text{kg}^{-1}$, and after 14.0 h at $0.8 \text{ kg}\cdot\text{kg}^{-1}$. At these values of τ_{defr} , the temperature of the slowest heating central point of the logs reaches 0°C, at which the melting of the entire amount of frozen water in the wood ends.

Figure 3 presents the change of all individual components of the heat balance of the pit $Q_{\text{pit-defr}}$, as well as the total energy $Q_{\text{pit-total}}$ (in kWh·m⁻³) required for the complete defrosting of the studied beech logs from their initial temperature of -10°C to final temperature of 0°C in their center, depending on the moisture content of the logs u . Figure 4 shows the change of the individual components of the heat balance of the pit in % to the total energy consumption, $Q_{\text{pit-total}}$, depending on the studied values of u . Figure 5 presents the calculated by Equation (8) change of the heat efficiency of the pit $\eta_{\text{Pit-defr}}$, depending on the studied values of the wood moisture content u and the degree of filling of the pit with logs $f = 25, 50$ and 75% .

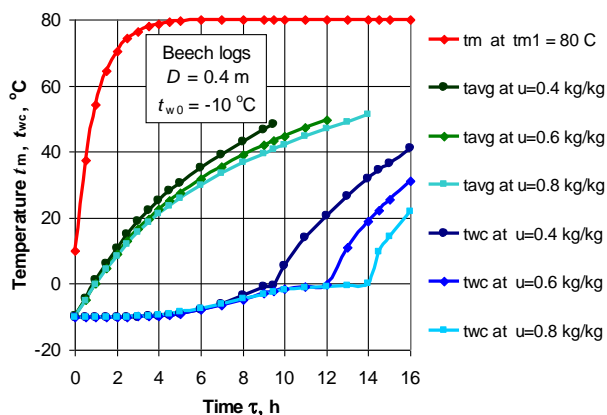


Figure 2: Change in t_m , t_{wc} , and t_{avg} of the studied logs during their defrosting, depending on u .

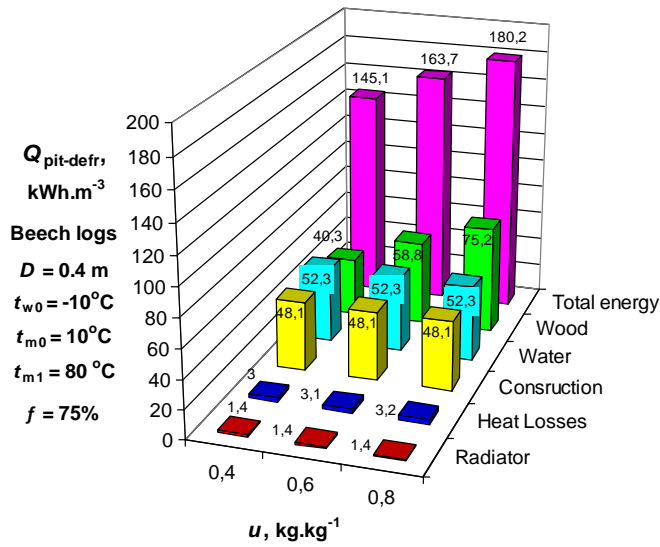


Figure 3: Change in the components of the heat balance (in kWh·m⁻³) of the pit at the end of defrosting of the studied logs in it, depending on u .

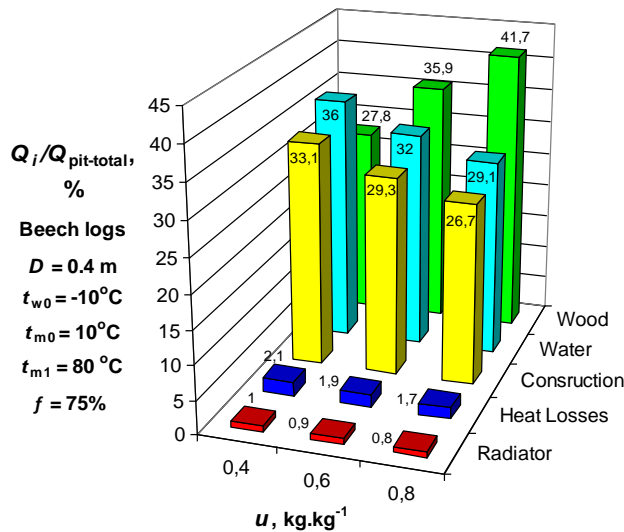


Figure 4: Change in the individual components of the pit's thermal balance in % to the total energy, depending on u .

When expressing the pit heat balance in kWh·m⁻³, an increase of u from 0.4 kg·kg⁻¹ to 0.8 kg·kg⁻¹ causes the following change in the components of the pit's heat balance at $t_{m1} = 80^\circ\text{C}$ and $f = 75\%$ (Fig. 3):

- Q_{Wood} increases from 40.3 kWh·m⁻³ to 75.2 kWh·m⁻³;
- Q_{Losses} increases from 3.0 kWh·m⁻³ to 3.2 kWh·m⁻³;

- Q_{Water} remains unchanged with a value of $52.3 \text{ kWh}\cdot\text{m}^{-3}$;
- $Q_{\text{Constr.}}$ remains unchanged with a value of $48.1 \text{ kWh}\cdot\text{m}^{-3}$;
- Q_{Radiator} remains unchanged with a value of $1.4 \text{ kWh}\cdot\text{m}^{-3}$.

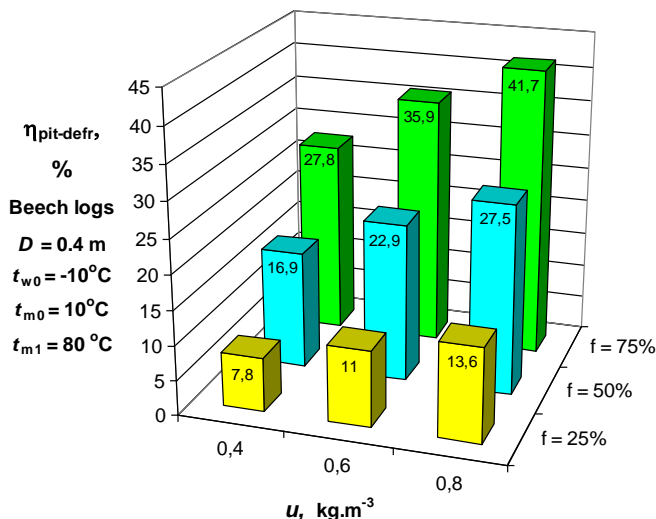


Figure 5: Change in the heat efficiency of the pit, depending on t_{w0} and f .

In this case the total specific energy consumption of the pit $Q_{\text{Pit-total}}$ increases from $145.1 \text{ kWh}\cdot\text{m}^{-3}$ to $180.2 \text{ kWh}\cdot\text{m}^{-3}$.

When expressing the individual components of the pit's heat balance Q_i as a % of the total energy $Q_{\text{Pit-total}}$, an increase of u from $0.4 \text{ kg}\cdot\text{kg}^{-1}$ to $0.8 \text{ kg}\cdot\text{kg}^{-1}$ causes the following change in the fraction of individual components of this balance (Fig. 4):

- Q_{Wood} increases from 27.8% to 41.7%;
- Q_{Water} decreases from 36.0% to 29.1%;
- $Q_{\text{Constr.}}$ decreases from 33.1% to 26.7%;
- Q_{Radiator} decreases from 1.0% to 0.8%;
- Q_{Losses} decreases from 2.1% to 1.7%.

If the degree of filling of the pit with logs decreases from its maximum possible value of 75% to 25%, the increase of u from $0.4 \text{ kg}\cdot\text{kg}^{-1}$ to $0.8 \text{ kg}\cdot\text{kg}^{-1}$ causes the following change in heat energy efficiency of the pit $\eta_{\text{Pit-defr}}$ (Fig. 5):

- $\eta_{\text{Pit-defr}}$ decreases from 27.8% to 7.8% at $u = 0.4 \text{ kg}\cdot\text{kg}^{-1}$;
- $\eta_{\text{Pit-defr}}$ decreases from 35.9% to 11.0% at $u = 0.6 \text{ kg}\cdot\text{kg}^{-1}$;
- $\eta_{\text{Pit-defr}}$ decreases from 41.7% to 13.8% at $u = 0.8 \text{ kg}\cdot\text{kg}^{-1}$.

CONCLUSIONS

With the help of our own non-stationary model, the defrosting times 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 $\text{kg}\cdot\text{kg}^{-1}$ were determined at a water temperature in the pit, t_{m1} , equal to 80°C . Using the determined logs' defrosting durations and the mentioned approach, the total energy required to completely defrost

the logs in the pit, $Q_{\text{pit-total}}$, and that required for each of 5 individual components of the heat balance were calculated.

It was found that the increase of u from $0.4 \text{ kg}\cdot\text{kg}^{-1}$ to $0.8 \text{ kg}\cdot\text{kg}^{-1}$ at maximum possible loading level of the pit with logs $f = 75\%$, causes an increase of the energy consumption of the entire pit $Q_{\text{pit-total}}$ from $145.1 \text{ kWh}\cdot\text{m}^{-3}$ to $180.2 \text{ kWh}\cdot\text{m}^{-3}$, i.e. by 24.2%, which is equivalent to an increase of 0.6% for each $0.01 \text{ kg}\cdot\text{kg}^{-1}$ increase of u .

At the commonly used values of $t_{\text{m1}} = 80^\circ\text{C}$ and $f = 75\%$, the heat energy efficiency of the pit $\eta_{\text{Pit-defr}}$ is equal to 27.8% at $u = 0.4 \text{ kg}\cdot\text{kg}^{-1}$, to 35.9% at $u = 0.6 \text{ kg}\cdot\text{kg}^{-1}$, and to 41.7% at $u = 0.8 \text{ kg}\cdot\text{kg}^{-1}$. With a decrease in f , this efficiency decreases almost proportional to f , mainly due to the increase in the specific energy required to heat the water in the pit.

The presented approach can be applied to compute heat balances of pits both during defrosting only and during complete boiling of frozen logs with different parameters to a desired final mass temperature required for the subsequent mechanical processing of the logs.

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INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

1/2024

INNO vol. XIII Sofia

ISSN 1314-6149
e-ISSN 2367-6663

Indexed with and included in CABI

INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

Science Journal

Vol. 13/ p. 1–126

Sofia 1/2024

ISSN 1314-6149

e-ISSN 2367-6663

Edition of

FACULTY OF FOREST INDUSTRY – UNIVERSITY OF FORESTRY – SOFIA

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Printed by: INTEL ENTRANCE

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