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MATHEMATICAL MODELLING OF WOODEN BIOMASS TORREFACTION

Torrefaction is used for initial biomass valorisation prior to energetic utilization. The produced biocarbon is characterized by high energy density, and high calorific value. Moreover, it contains less moisture, and has hydrophobic character. Due to that, this technology is being found perspective, but the relation between process parameters, and biomass, and biocarbon properties should be still optimized. The presented work shows the mathematical modelling of torrefaction of the wooden biomass particle. The dependence between technological parameters (process temperature, and retention time), and biomass properties (density, calorific value of the biomass), and calorific value of biocarbon has been examined. The parameters of IInd degree polynomial functions, allowing the estimation of the required retention time or required process temperature to achieve desired calorific value of biocarbon have been determined. The modelling showed, that the process temperature and retention time are the most significant factors influencing the torrefaction efficiency. Also, the calorific value of biocarbon may be an important parameter, but biomass properties are not significant, with recommendation to neglect the biomass density.

Keywords: torrefaction, biomass valorisation, mathematical modelling, technological parameters, biomass properties, biocarbon

Introduction

Torrefaction is the method of biomass valorization before further thermal processes, mostly co-incineration with coal, or gasification. In literature, the torrefaction process also goes by several names, such as roasting, slow and mild pyrolysis, wood-cooking and high-temperature drying. Torrefaction is a thermo-chemical treatment, in a narrow temperature range from 200°C to 300°C, where mostly hemicellulose components of biomass depolymerize [Dhungana 2011]. This treatment is carried out under atmospheric pressure conditions in a non-oxidizing environment at low heating rates (< 50°C/min) and for a relatively long reactor residence time (typically 1 hour) [Bergman et al. 2005]. During the

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process, the biomass partly decomposes, releasing various condensable and non-condensable gases. The final product is a carbon rich solid, which is referred to as torrefied biomass, biochar or biocarbon [Lehmann et al. 2011]. The principal characteristics of torrefied product – biocarbon are as follows: I) High Energy Density: Torrefied biomass contains 70-80% of the original weight while retaining 80-90% of the original energy of the biomass. In effect, there can be an increase of around 30% in its energy density [Bergman 2005]; II) Hydrophobicity: Torrefied biomass becomes hydrophobic, i.e., it does not absorb moisture or its equilibrium moisture percentage decreases significantly. The equilibrium moisture content of torrefied biomass is very low (from 1 to 3%) [Lipinsky et al. 2002]; III) Increased Fixed Carbon: The fixed carbon content of torrefied biomass is high. For example, depending on the treatment temperature and duration, it is between 25% and 40%, while the ash content is low. This property makes the torrefied material a very attractive reducing agent [Bergman 2005]; IV) Reduced Oxygen: Torrefaction reduces the O/C ratio through a reduction in oxygen. This makes a biomass better suited for gasification [Prins 2005]. In addition to its higher heating value, torrefied biomass also produces less smoke when it burns. This is because the smoke-causing volatiles are already driven off during the torrefaction process and the biomass is also dry; V) Improved Grindability: Torrefied biomass grindability is superior to that of raw biomass. The output of a pulverizing mill can increase by 3-10 times [Phanphanich and Mani 2011]; VI) Combustion Properties: Torrefied biomass takes less time for ignition due to less moisture and it burns longer due to a larger percentage of fixed carbon compared to raw biomass [Bridgeman et al. 2008].

The determination of proper technological parameters, such as the process temperature, and retention time, is a key factor affecting the economy of the biomass treatment. The torrefaction reactor heating to high ranges of temperature, and the prolongation of the biomass retention in the reactor increases the operational costs. Due to that, the dependence between technological parameters (process temperature, and retention time), and biomass properties (density, calorific value of the biomass), and the calorific value of biocarbon is theoretically, and experimentally researched.

In the practical experimental process, before the main laboratory work which aims to validate the hypotheses, on the basis of data obtained during previous experiments, or found in literature, the mathematical simulation of the phenomenon (process) may be executed. Such simulations are aimed at the forecasting of process kinetics, estimation of the values of key parameters, and initial determination of technological parameter ranges, when the highest process efficiency is expected. In literature several wooden biomass torrefaction models can be found [Felfli et al. 2005; Bergman et al. 2005; Carrasco et al. 2013; Patuzzi et al. 2014]. These models are based on the 1st-order kinetics of the

processes of water and volatile organic compounds evaporation, and organic matter degradation.

One of the significant technological parameters, affecting the torrefaction plant capacity, is the biomass retention time in the reactor. Usually, the treated biomass does not have uniform properties, such as: density, and higher heating value. On the other hand, the main task of the torrefaction plant operator, is to produce biocarbon with relatively constant properties. The technological parameters which can be modulated, are the process temperature and the retention time. Therefore, the question concerning the dependencies between biomass properties, torrefaction technological parameters and the final product properties, arises. In the presented work, the wooden biomass torrefaction mathematical modelling experiments aimed at the determination of equation parameters which allow the prediction of technological parameters, process temperature and retention time depending on the initial biomass, and biocarbon properties, has been shown.

Materials and methods

The structure of the wooden biomass torrefaction model

The proposed, and examined model covered:

- wooden particle analysis in a one-dimensional sphere,
- the synthesis of the process products,
- the temperature changes at the particle surface, and inside the particle as a function of time,
- high heating value changes of generated biocarbon as a function of time.

The process of the substrate analysis (wet biomass – A) has been divided by three parallel processes of the products generation: steam (B), torgas (C), biocarbon (D). These processes are based on Arrhenius kinetics (fig. 1) [van der Stelt 2010].

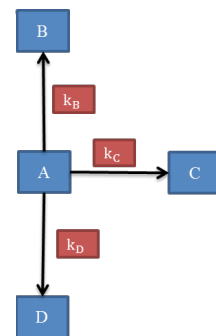


Fig. 1. The construction of the torrefaction model: A – wet biomass, B – steam, C – torgas, D – biocarbon, k_B – the kinetic rate constant of steam production, k_C – the kinetic rate constant of torgas production, k_D – the kinetic rate constant of biocarbon production

Arrhenius kinetic rate constant may be described (1), and is related to the temperature.

$$k_x = A_0 \cdot e^{\left(\frac{-E_0}{R \cdot f(T)}\right)} \quad (1)$$

where: k_x – the kinetic rate constant ($x = B, C, D$), s^{-1} ; A_0 – the pre-exponential factor, s^{-1} ; E_0 – the activation energy, $\text{kJ} \cdot \text{mol}^{-1}$; R – the universal gas constant, $\text{kJ} \cdot (\text{mol} \cdot \text{K})^{-1}$; $f(T)$ – the function of particle temperature changes in time, K.

The mass/density changes (2-5) of each torrefaction products (B, C, D) in time τ may be determined as a product of mass/density, and kinetic rate constant:

$$\frac{dA}{d\tau} = -(k_B + k_C + k_D) \cdot A \quad (2)$$

$$\frac{dB}{d\tau} = k_B \cdot A \quad (3)$$

$$\frac{dC}{d\tau} = k_C \cdot A \quad (4)$$

$$\frac{dD}{d\tau} = k_D \cdot A \quad (5)$$

where: $\frac{dA}{d\tau}$ – the substrate (A) mass/density changes in time, $\text{kg} \cdot \text{m}^{-3}/\text{kg}$;

$\frac{dB}{d\tau}$ – the steam (B) mass/density changes in time, $\text{kg} \cdot \text{m}^{-3}/\text{kg}$; $\frac{dC}{d\tau}$ – the

torgas (C) mass/density changes in time, $\text{kg} \cdot \text{m}^{-3}/\text{kg}$; $\frac{dD}{d\tau}$ – the biocarbon (D)

mass/density changes in time, $\text{kg} \cdot \text{m}^{-3}/\text{kg}$

For the modelling, the phenomena of unsteady heat conduction, what is understood as substrate heating, or cooling until the thermodynamic balance with the environment [Pudlik 2012; Wiśniewski and Wiśniewski 2000]. Below is the derivation of the equation on temperature changes in time. The temperature distribution, and heat stream changes may be described by Fourier's equation (6) [Pudlik 2012]:

$$\frac{dt}{d\tau} = \alpha \cdot \nabla^2 \cdot \tau = \alpha \cdot \left(\left(\frac{dt}{dx} \right)^2 + \left(\frac{dt}{dy} \right)^2 + \left(\frac{dt}{dz} \right)^2 \right) \quad (6)$$

where: $\frac{dT}{d\tau}$ – the particle temperature changes in time, K; α – the heat transfer coefficient (diffusivity), $\text{m}^2 \cdot \text{s}^{-1}$; ∇^2 – the temperature gradient defined in the

Cartesian coordinate system, as partial derivatives $\left(\frac{dt}{dx} \right)^2 + \left(\frac{dt}{dy} \right)^2 + \left(\frac{dt}{dz} \right)^2$, $\text{K} \cdot \text{m}^{-1}$.

In the proposed model, the finite difference method has been applied. This method is used for calculation of heat transformations in a one-dimensional sphere. It is based on substitution of the derivative equation by the equation based on the finite difference method (7) [Pudlik 2012]:

$$\frac{\Delta t}{\Delta \tau} = \alpha \cdot \left(\frac{\Delta^2 t}{\Delta x^2} \right) \quad (7)$$

where: $\frac{\Delta t}{\Delta \tau}$ – the particle temperature changes in time, K; α – the heat transfer coefficient (diffusivity), $\text{m}^2 \cdot \text{s}^{-1}$; $\left(\frac{\Delta^2 t}{\Delta x^2} \right)$ – the temperature gradient along the axis ox , $\text{K} \cdot \text{s}^{-1}$

This method assumes the dividing of the object on equal parts (the numerical elements $n - 1$, n , $n + 1$ are determined). For each of the elements a time compartment is assigned, analogically to: $k - 1$, k , $k + 1$. The temperature of the object n in time $\Delta \tau$ is $t_{n,k}$ the course of the temperature is a broken curve. Therefore, the temperature distribution in the object with the length n is characterized by two curves, which slope may be described according to equations 8 and 9 [Pudlik 2012]:

$$\left(\frac{\Delta t}{\Delta x} \right)_+ = \frac{t_{n+1,k} - t_{n,k}}{\Delta x} \quad (8)$$

$$\left(\frac{\Delta t}{\Delta x} \right)_- = \frac{t_{n,k} - t_{n-1,k}}{\Delta x} \quad (9)$$

where: $\left(\frac{\Delta t}{\Delta x} \right)_{+,-}$ – the value of differentia quotient forward, and back, $\text{K} \cdot \text{m}^{-1}$; $t_{n+1;n-1,k}$ – the object temperature at the length $n + 1; n - 1$ from the boundary conditions, in the time interval k , K; $t_{n,k}$ – the object temperature at the length n , in the time interval k , K; Δx – the distance, m

On that basis, the second derivative from equation (7) may be expressed as (10):

$$\left(\frac{\Delta^2 t}{\Delta x^2} \right) = \frac{1}{\Delta x} \cdot \left(\left(\frac{\Delta t}{\Delta x} \right)_+ - \left(\frac{\Delta t}{\Delta x} \right)_{+,-} \right) = \frac{1}{\Delta x^2} \cdot (t_{n+1,k} + t_{n-1,k} - 2 \cdot t_{n,k}) \quad (10)$$

The solution of derivative temperature in relations to time is given (11):

$$\frac{\Delta t}{\Delta \tau} = \frac{t_{n+1,k} - t_{n,k}}{\Delta \tau} \quad (11)$$

The higher heating value generated biocarbon has been simulated according to (12) [Soponpongipat et al. 2016]:

$$HHV_T = \frac{\frac{dA}{d\tau} \cdot HHV_r + \frac{dD}{d\tau} \cdot HHV_c}{\frac{dA}{d\tau} + \frac{dD}{d\tau}} \quad (12)$$

where: HHV_T – higher heating value changes in time, $\text{MJ}\cdot\text{kg}^{-1}$; $\frac{dA}{d\tau}$ – substrate (biomass) mass changes, kg ; $\frac{dD}{d\tau}$ – biocarbon mass changes, kg ; HHV_r – biomass higher heating value, $\text{MJ}\cdot\text{kg}^{-1}$, HHV_c – biocarbon higher heating value, $\text{MJ}\cdot\text{kg}^{-1}$.

Assumed initial, and boundary conditions of the model

Below are the initial, and boundary conditions, and the ranges of the independent variables of the model in time $\tau = 0$, have been given:

- $T = T_0$ – initial temperature (25°C),
- T_{stop} – torrefaction temperature: the range – 7 values, with incremental interval of 20°C ($200:20:320^\circ\text{C}$),
- τ_{max} – maximal time of torrefaction (10800 s),
- ρ_A – true density of wood, 4 values (600, 700, 800, 900 $\text{kg}\cdot\text{m}^{-3}$),
- $\rho_B = \rho_C = \rho_D$ – true density of steam, torgas, and biocarbon ($0 \text{ kg}\cdot\text{m}^{-3}$),
- M_A – weigh of wood particle (0.001 kg),
- $M_B = M_C = M_D$ – initial mass of steam, torgas, and biocarbon (0.000 kg),
- HHV_r – higher heating value of wood, 5 values: 15, 16, 17, 18, 19 $\text{MJ}\cdot\text{kg}^{-1}$,
- HHV_c – higher heating value of biocarbon, 8 values: 20, 21, 22, 23, 24, 25, 26, 27 $\text{kJ}\cdot\text{kg}^{-1}$.

The thermodynamic, and physical properties of the wood particle, have been shown in table 1.

Table 1. Thermodynamic and physical properties used to solve the torrefaction model

Parameter	Formula/value/source
True density of wood, $\text{kg}\cdot\text{m}^{-3}$	600, 700, 800, 900 ^a
Formula for the heat capacity of wood, $\text{J}\cdot(\text{kg}\cdot\text{K})^{-1}$	$cpw = (1112.3 + 4.85 \cdot T)^b$
The formula for the heat capacity of biocarbon $\text{J}\cdot(\text{kg}\cdot\text{K})^{-1}$	$cpc = (1003.2 + 2.09 \cdot T)^b$
Formula for the coefficient of thermal conductivity of wood, $\text{W}\cdot(\text{m}\cdot\text{K})^{-1}$	$kw = (0.13 + 0.0003 \cdot T)^b$
Formula for the coefficient of thermal conductivity of biocarbon, $\text{W}\cdot(\text{m}\cdot\text{K})^{-1}$	$kw = (0.08 - 0.0001 \cdot T)^b$
Heat transfer coefficient, $\text{W}\cdot(\text{m}^2\cdot\text{K})^{-1}$	$h = 40^a$
The pre-exponential factor, $1\cdot\text{s}^{-1}$	$A_B = 4.5^{a,c}$
	$A_C = 23460^{a,c}$
	$A_D = 0.135^{a,c}$
Activation energy, $\text{kJ}\cdot\text{mol}^{-1}$	$E_B = 58^{a,c}$
	$E_C = 77.636^{a,c}$
	$E_D = 22.777^{a,c}$

Source: ^aBates and Ghoniem [2014]; ^bGranados et al. [2016]; ^cSoponpongpipat et al. [2016].

Calculation script code

Below, the script calculation code for the torrefaction modelling has been show:

clc, clear all, close all;

```

rhow = 900;           % Biomass density, kg/m3
M=0.001;             % Biomass mass, kg
d = 0.02;            % Particle diameter, m
T0 = 25+273;         % Temperature start, K
Tstop = 200+273;    % Temperature stop, K
tmax = 10800;        % Time, s
h = 40;              % Heat transfer coefficient, W/m2*K
HHVr = 19;           % HHV Biomass, MJ/kg
HHVc1= 20; HHVc2= 21; HHVc3= 22; HHVc4= 23; HHVc5= 24; HHVc6= 25;
HHVc7= 26; HHVc8= 27; % HHV biocarbon, MJ/kg

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```

A1 = 4.5;           E1 = 57;           % Water vapor
A2 = 23460;         E2 = 77.636;         % Torgas
A3 = 0.135;         E3 = 22.777;         % Biocarbon
R = 0.008314;
b = 1;
r = d/2;

```

```

nt = 400;
dt = tmax/nt;
t = 0:dt:tmax;
m = 200;
krok = m-1;
dr = r/krok;

i = 1:m;
T(i,1) = T0;
TT(1,i) = T0;
pw(1,i) = rhow;
pg(1,i) = 0;
pt(1,i) = 0;
pc(1,i) = 0;

for i = 2:nt+1

[rww, rwg, rwt, rwc] = kinetic(A1,E1,A2,E2,A3,E3,R,T',pw(i-1,:));
pw(i,:) = pw(i-1,:) + rww.* dt;
pg(i,:) = pg(i-1,:) + rwg.* dt;
pt(i,:) = pt(i-1,:) + rwt.* dt;
pc(i,:) = pc(i-1,:) + rwc.* dt;
Yw = pw(i,:)/(pw(i,:) + pc(i,:));
Yc = pc(i,:)/(pw(i,:) + pc(i,:));
cpw = 1112.3 + 4.85.*(T')/1000;
kw = 0.13 + (3e-4).*(T')/1000;
cpc = 1003.2 + 2.09.*(T')/1000;
kc = 0.08 - (1e-4).*(T')/1000;
cpbar = Yw.*cpw + Yc.*cpc;
kbar = Yw.*kw + Yc.*kc;
pbar = pw(i,:) + pc(i,:);
Tn = temperature (pbar,cpbar,kbar,h,Tstop,b,m,dr,dt,T);
[rww, rwg, rwt, rwc] = k(A1,E1,A2,E2,A3,E3,R,Tn',pw(i,:));
pw(i,:) = pw(i-1,:) + rww.* dt;
pg(i,:) = pg(i-1,:) + rwg.* dt;
pt(i,:) = pt(i-1,:) + rwt.* dt;
pc(i,:) = pc(i-1,:) + rwc.* dt;
Yw = pw(i,:)/(pw(i,:) + pc(i,:));
Yc = pc(i,:)/(pw(i,:) + pc(i,:));
cpw = 1112.3 + 4.85.*(Tn')/1000;
kw = 0.13 + (3e-4).*(Tn')/1000;
cpc = 1003.2 + 2.09.*(Tn')/1000;
kc = 0.08 - (1e-4).*(Tn')/1000;

```



```

cpbar = Yw.*cpw + Yc.*cpc;
kbar = Yw.*kw + Yc.*kc;
pbar = pw(i,:) + pc(i,:);
Tn = temperature (pbar,cpbar,kbar,h,Tstop,b,m,dr,dt,T);
T = Tn;
TT(i,:) = T';
end

```

```

K1W = A1*exp(-E1./(R.*TT(:,m)));
K2W = A2*exp(-E2./(R.*TT(:,m)));
K3W = A3*exp(-E3./(R.*TT(:,m)));
K = K1W + K2W + K3W;

```

```

mww = M.*exp(-K'.*t);
mwg = ((K1W').*M./K').*(1-exp(-K'.*t));
mwt = ((K2W').*M./K').*(1-exp(-K'.*t));
mwc = ((K3W').*M./K').*(1-exp(-K'.*t));

```

```

deltaHHVc1=mwc(1,:).*HHVc1;
deltaHHVc2=mwc(1,:).*HHVc2;
deltaHHVc3=mwc(1,:).*HHVc3;
deltaHHVc4=mwc(1,:).*HHVc4;
deltaHHVc5=mwc(1,:).*HHVc5;
deltaHHVc6=mwc(1,:).*HHVc6;
deltaHHVc7=mwc(1,:).*HHVc7;
deltaHHVc8=mwc(1,:).*HHVc8;

```

```

deltaHHVr=mww(1,:).*HHVr;
HHVm1=(deltaHHVc1(1,:)+deltaHHVr(1,:))./(mwc(1,:)+mww(1,:));
HHVm2=(deltaHHVc2(1,:)+deltaHHVr(1,:))./(mwc(1,:)+mww(1,:));
HHVm3=(deltaHHVc3(1,:)+deltaHHVr(1,:))./(mwc(1,:)+mww(1,:));
HHVm4=(deltaHHVc4(1,:)+deltaHHVr(1,:))./(mwc(1,:)+mww(1,:));
HHVm5=(deltaHHVc5(1,:)+deltaHHVr(1,:))./(mwc(1,:)+mww(1,:));
HHVm6=(deltaHHVc6(1,:)+deltaHHVr(1,:))./(mwc(1,:)+mww(1,:));
HHVm7=(deltaHHVc7(1,:)+deltaHHVr(1,:))./(mwc(1,:)+mww(1,:));
HHVm8=(deltaHHVc8(1,:)+deltaHHVr(1,:))./(mwc(1,:)+mww(1,:));

```

figure(1)

```

plot(t./60,HHVm1,t./60,HHVm2,t./60,HHVm3,t./60,HHVm4,t./60,HHVm5,t./60,
,HHVm6,t./60,HHVm7,t./60,HHVm8);
xlabel('Time, min'); ylabel('HHV,MJ/kg');

```

```

figure(2)
plot(t./60,TT(:,1)-273,'b',t./60,TT(:,m)-273,'r')
hold on
plot([0 tmax./60],[Tstop-273 Tstop-273],':k')
hold off
xlabel('Time, min'); ylabel('Temperature, °C');
legend('Tinside','Toutside',[Tmax ',num2str(Tstop-273),'°C'],'location',
'southeast');

figure(3)
plot(t./60,pw(:,m),'-',':color',[0 0.7 0])
grid on
hold on
plot(t./60,pg(:,m),'b')
hold on
plot(t./60,pt(:,m),'k')
hold on
plot(t./60,pc(:,m),'r')
hold off
xlabel('Time, min'); ylabel('Density, kg/m^3');
legend('Biomass density','Water vapor density','Torgas density','Biocarbon
density');
set(gca,'FontSize',12)

figure(4)
plot(t./60,mww, t./60,mwg,'b', t./60,mwt,'k', t./60,mwc,'r')
grid on
xlabel('Time, min'); ylabel('Mass, kg');
legend('Biomass mass','Water vapor mass','Torgas mass','Biocarbon mass')
set(gca,'FontSize',12)

function [rww, rwg, rwt, rwc] = kinetic(A1,E1,A2,E2,A3,E3,R,T,pw);
K1 = A1.*exp(-E1./(R.*T));
K2 = A2.*exp(-E2./(R.*T));
K3 = A3.*exp(-E3./(R.*T));
K = K1 + K2 + K3;
rww = pw.*(-K);
rwg = (K1.*pw);
rwt = (K2.*pw);
rwc = (K3.*pw);
end

function = Temperature (pbar,cpbar,kbar,h,Tstop,b,m,dr,dt,T);

```

```

alpha = kbar./(pbar.*cpbar);
Fo = alpha.*dt./(dr^2);
Bi = h.*dr./kbar;

```

```

A(1,1) = 1 + 2*(1+b)*Fo(1);
A(1,2) = -2*(1+b)*Fo(2);
C(1,1) = T(1);
for k = 2:m-1
    A(k,k-1) = -Fo(k-1)*(1 - b/(2*(k-1)));
    A(k,k) = 1 + 2*Fo(k);
    A(k,k+1) = -Fo(k+1)*(1 + b/(2*(k-1)));
    C(k,1) = T(k);
end
A(m,m-1) = -2*Fo(m-1);
A(m,m) = 1 + 2*Fo(m)*(1 + Bi(m) + (b/(2*m))*Bi(m));
C(m,1) = T(m) + 2*Fo(m)*Bi(m)*(1 + b/(2*m))*Tstop;

T = A\C;
end

```

Modelling execution

Torrefaction modelling of wooden biomass has been done with the application of Octave – 4.0.3 software run on a Dell Precision T7910 work station. For the given initial and boundary conditions, the retention time T_{stab} , when the desired biocarbon HHV_c was achieved, had been determined.

Obtained data processing

Based on the obtained modelling results, the multiple regression analysis, (based on Π^{nd} degree polynomial) which, for the initial biomass conditions and desired HHV_c , allows the prediction of the required torrefaction technological parameters: temperature, and retention time of biomass in the reactor, has been done.

For the prediction of the retention time (T_{stab}) the following formula has been used (13), where (b_1 - b_9) are regression coefficients:

$$T_{stab} = b_1 \cdot \rho_A + b_2 \cdot \rho_A^2 + b_3 \cdot T_{stop} + b_4 \cdot T_{stop}^2 + b_5 \cdot HHV_r + b_6 \cdot HHV_r^2 + b_7 \cdot HHV_c + b_8 \cdot HHV_c^2 + b_9 \quad (13)$$

For the prediction of the torrefaction temperature (T_{stop}) the following formula has been used (13), where (b_1 - b_9) are regression coefficients:

$$T_{stop} = b_1 \cdot \rho_A + b_2 \cdot \rho_A^2 + b_3 \cdot T_{stab} + b_4 \cdot T_{stab}^2 + b_5 \cdot HHV_r + b_6 \cdot HHV_r^2 + b_7 \cdot HHV_c + b_8 \cdot HHV_c^2 + b_9 \quad (14)$$

The determined regression coefficients were statistically validated, on the significance level of $p < 0.05$. Multiple regression, and statistical validation of the regression coefficients were done with the use of the *Statistica 12.0* software.

Results and discussion

The executed modelling, and multiple regression analysis have shown, that biomass true density has no significant ($p < 0.05$) influence on both T_{stab} (table 2), and T_{stop} (table 3). It is confirmed by the values of statistical estimators F , and p of regression coefficients F i p (table 2 and 3). The high values of correlation, and determination coefficients, show a good fitting degree of determined, on the basis of both models (13, and 14) parameters, to data obtained during modelling with the application of equations 1-12 (table 4).

Table 2. Assessment of model parameters of impact of biomass and biocarbon properties, and torrefaction temperature on the required retention time

Regression coefficient by the equation (13)	Value of the regression coefficient	Standard error of regression coefficient	Value of the standardized regression coefficient	Value of the calculated probability for the regression coefficient	Boundary of the confidence interval for the regression coefficient -95.00%	Boundary of the confidence interval for the regression coefficient +95.00%
b_1	0.0005	0.02649	0.0012	0.986065	-0.0515	0.0524
b_2	0.0000	0.00002	0.0000	0.985459	0.0000	0.0000
b_3	-3.9373	0.06631	-3.5728	0.000000	-4.0674	-3.8071
b_4	0.0055	0.00013	0.0050	0.000000	0.0053	0.0058
b_5	8.9879	3.58475	0.2884	0.012308	1.9543	16.0216
b_6	-0.3516	0.10537	-0.0113	0.000877	-0.5583	-0.1448
b_7	19.2491	1.80999	1.0006	0.000000	15.6977	22.8005
b_8	-0.3528	0.03848	-0.0183	0.000000	-0.4283	-0.2773
b_9	414.9739	39.14779	-	0.000000	338.1619	491.7858

On the basis of the determined models parameters, the example of technological parameters prediction has been done. The following parameters describing the biomass, and biocarbon parameters have been assumed:

1. $\rho_A = 650 \text{ kg}\cdot\text{m}^{-3}$,
2. $HHV_r = 16.4 \text{ MJ}\cdot\text{kg}^{-1} \text{ d.m.}$,
3. $HHV_c = 21.5 \text{ MJ}\cdot\text{kg}^{-1} \text{ d.m.}$.

Firstly, for the $T_{stop} = 250^\circ\text{C}$, on the basis of regression coefficient values from table 2, the T_{stab} , when the HHV_c reaches $21.5 \text{ MJ}\cdot\text{kg}^{-1} \text{ d.m.}$ has been

estimated. The obtained result of T_{stab} was 80.5 minutes. This value was then used in model (14), and for the same initial biomass, and biocarbon parameters, with the use of regression coefficient values from table 3, the required torrefaction temperature was estimated. T_{stop} was 249.8°C.

Table 3. Assessment of model parameters of impact of biomass and biocarbon properties, and the retention time on the required process temperature

Regression coefficient by the equation (14)	Value of the regression coefficient	Standard error of regression coefficient	Value of the standardized regression coefficient	Value of the calculated probability for the regression coefficient	Boundary of the confidence interval for the regression coefficient -95.00%	Boundary of the confidence interval for the regression coefficient +95.00%
b_1	0.0005	0.02649	0.0018	0.986065	-0.0515	0.0524
b_2	0.0000	0.00002	0.0000	0.985459	0.0000	0.0000
b_3	-3.9373	0.06631	-1.5759	0.000000	-4.0674	-3.8071
b_4	0.0055	0.00013	0.0041	0.000000	0.0053	0.0058
b_5	8.9879	3.58475	0.3256	0.012308	1.9543	16.0216
b_6	-0.3516	0.10537	-0.0118	0.000877	-0.5583	-0.1448
b_7	19.2491	1.80999	0.9115	0.000000	15.6977	22.8005
b_8	-0.3528	0.03848	-0.0171	0.000000	-0.4283	-0.2773
b_9	414.9739	39.14779	–	0.000000	338.1619	491.7858

Table 4. Test SS for the full terms of SS model residuals for both models by equations 13 and 14

Variable	The correlation coefficient, R	Coefficient of determination, R^2	SS	df	MS	SS	df	MS	F	p
$T_{stabilization}$	0.9911	0.9822	2137561	8	267195.1	38683.3	1111	34.8	7673.9	0.00
T_{stop}	0.9999	0.9998	77487241	8	9685905	16759.2	1112	15.1	642673.7	0.00

During estimation of the influence of particular independent variables of a given parameter (dependent), due to that, independent variables often are described by different units, it is hard to assess the impact strength of individual variables. To solve this problem, the regression coefficient standardization was done, according to a general equation (15):

$$b^* = b \cdot \frac{S_{xi}}{S_y} \quad (15)$$

where: b^* – standardized regression coefficient; b – estimated regression coefficient; S_{xi} – standard deviation of independent variable i ; xi – values of

independent variables; S_y – standard deviation of dependent variable; y – values of dependent variables

The values of standardized regression coefficients were presented in table 2, and 3. Obtained according to formula 15, values are comparable between each other's. In this way, it has been shown, that the strongest influence on the T_{stab} was the HHV_c (table 2). The initial HHV_r influences to a lower degree, but the biomass true density may be neglected (table 2). Similarly, on the T_{stop} the strongest effect of HHV_c has been found. No significant effect of the biomass true density has been determined (table 3). The regression analysis showed a very strong negative relation between technological parameters: T_{stab} , and T_{stop} . It means that to obtain a biocarbon with the desired HHV_c value, the shortening of the retention time requires the increase in the torrefaction temperature, and the lowering of the torrefaction temperature requires an increase of retention time.

Conclusions

The given research, and obtained results have a model character and require experimental validation. However, they allow the initial determination of the influence of key factors on wooden biomass torrefaction, and the process efficiency. It has been determined, that the most important factor needed is a higher heating value of biocarbon. It has been also shown, that the initial higher heating value of biomass is less important, but, the biomass true density may be neglected. In practice, when the final biocarbon properties are required by industry, the initial biomass parameters are not factors with a high importance. The technological parameters of the process: temperature and retention time are much more important. The presented relations between torrefaction temperature, and retention time, may indicate the need for further optimization experiments. For the expected biocarbon higher heating value, with the given biomass parameters, the optimum configuration of torrefaction temperature, and retention time, will be researched, to use the least amount of energy per unit of produced biocarbon mass. Due to that, wooden biomass torrefaction technology is at the early stage of development, further research in this field is likely.

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