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Modeling of drying and pyrolysis in a gasifier during the startup phase

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Abstract

An appropriate arrangement of particular zones in the gasifier is of practical importance for the gasification process effectiveness. One of the parameters that affects the optimum reactor operation and has to be taken into account is the speed of bed movement. The transient one-dimensional model describing the heat and mass transfer in the upper section of the biomass fixed bed gasifier that covers the zones of evaporation and pyrolysis, was introduced. To study the effect of packed bed settling resulted from the wood particles' volume change due to their devolatilization, the simulations for various bed movement speeds were performed. The computation results indicated, as expected, on the different distribution of pyrolysis and drying zones, depending on the speed value. The clear tendency towards the reduction of pyrolysis zone, and on the other hand, towards the expansion of drying zone, with an increasing movement speed was observed.

Keywords: Moisture; Evaporation; Condensation; Pyrolysis

Nomenclature

a_I –   specific surface area

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$\dot{W}$	–	mass source term, kg/(m^{3}s)
c	–	specific heat, J/(kg K)
h	–	specific enthalpy, J/kg
j	–	mass flux of water/steam phase change
K	–	permeability, m^2
k	–	devolatilization rate, 1/s
L	–	bed height, m
p	–	pressure, Pa
T	–	temperature, K
t	–	time, s
v	–	velocity, m/s
x	–	space coordinate, m
Y	–	mass fraction, kg/kg
Z	–	mass loss, $m_s/m_{s,0}$, kg/kg

Greek symbols

λ	–	thermal conductivity, W/(m K)
μ	–	dynamic viscosity, kg/(m s)
ε	–	volume fraction, m^3/m^3
ϱ	–	density, kg/m^3

Subscripts and superscripts

0	–	initial
∞	–	limit value
c	–	combustion
g	–	gas
s	–	solid
sg	–	solid to gas
w	–	water
w, g	–	water vapor
wg	–	water to gas (vapor)
$cond$	–	conduction
rad	–	radiation
sat	–	saturation

1   Introduction

The thermochemical conversion processes of biomass has attracted many researchers worldwide due to the trends in developing the green technologies of energy production. One of these is the gasification technology that aims at generating producer gas that may further be used as a fuel to run the engines or turbines for the purpose of electricity production. The process consists of four stages which correspond with the characteristic zones in a reactor. These are the areas of: (i) drying where the moisture is released, (ii) pyrolysis in which the dry fuel decomposes and the gas is being evolved,

(iii) oxidation where the devolatilized fuel particles undergo combustion and finally, (iv) the reduction where the surface reactions between char (solid residue) and gas take place. The variety of physical and chemical phenomena occurring in the gasifier covers large number of problems, including heat transfer, gas flow, phase transitions regarding both, the moisture and tars, as well as the homo- and heterogeneous chemical reactions.

Many research have been conducted in order to analyze different aspects of biomass gasification process and to provide the data on the key parameters affecting its course and quality of syngas. The approaches to mathematical modeling of the process, focusing mainly on temperature change dynamics and gas composition, were presented for instance in [1–3]. Jayah *et al.* [4] studied experimentally and numerically the downdraft gasifier performance to determine the impact of operating parameters, fuel characteristics and design features on the conversion efficiency. Their experimental results of temperature distribution and producer gas composition were in satisfactory agreement with the model predictions obtained by Roy *et al.* [5]. One of the latest works devoted to gasification process is the one by Lamarche *et al.* [6], in which the authors report the experimental data and results of two-dimensional modeling of fixed bed pyrolysis reactor constituting the first stage of a continuous staged gasification.

Most of the models proposed in the literature are basically steady state and do not take into account the movement of a biomass bed that results from its settling due to volume change of devolatilizing particles. The problem of packed bed settling seems to be of practical importance in improving process effectiveness since it has an impact on the layout (height) of particular zones in the reactor, and thus on the yield and quality of produced gas. To analyze an influence of bed movement speed on the dynamics of the process the one-dimensional model of heat and mass transfer in biomass-based downdraft gasifier was proposed in the paper. At this stage of model development, the study is limited to the description of phenomena occurring in the upper reactor section (involving drying and pyrolysis zones), which is located right above the combustion zone.

2 Mathematical model

A schematic of a considered downdraft gasifier is presented in Fig. 1. The reactor part, which is the subject of the analysis carried out, is the part of the chamber extending upwards from the level located right above the

oxidation zone, $x = 0$, to the upper surface of a biomass bed, $x = L$. The mathematical model developed to describe the biomass feedstock de-
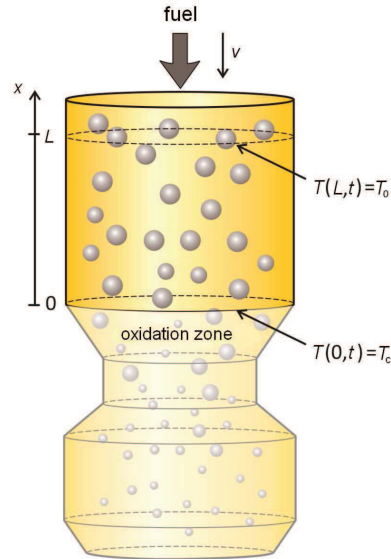

Figure 1: The schematic of analyzed gasifier.

hydratation and decomposition assumes the transport processes in both, solid and gaseous phases, to be one-dimensional and nonstationary. As experiments show, the speed of bed settling varies along the bed height [7]. In this study, to simplify the problem the speed of bed movement, v, is considered to be constant in time and along the bed height. Since the moisture is contained in the moving particles, the same value of velocity for moisture mass balance was assumed.

2.1   Modeling details

Taking into account the volume fractions of each phase – solid, pyrolysis gas and water (moisture) – which are determined by ε_s, ε_g and ε_w, respectively, the heat and mass exchange processes are governed by:

- **Mass balances for:**

biomass particles (solid phase)

$$\frac{\partial \left(\varepsilon_s \varrho_s\right)}{\partial t} + v \frac{\partial \left(\varepsilon_s \varrho_s\right)}{\partial x} = -\dot{W}_{sg}\,, \tag{1}$$

moisture

$$\frac{\partial \left(\varepsilon_w \varrho_w\right)}{\partial t} + v \frac{\partial \left(\varepsilon_w \varrho_w\right)}{\partial x} = -\dot{W}_{wg}\,, \tag{2}$$

water steam

$$\frac{\partial \left(\varepsilon_g Y_{w,g} \varrho_g\right)}{\partial t} + \frac{\partial \left(\varepsilon_g Y_{w,g} \varrho_g v_g\right)}{\partial x} = \dot{W}_{wg}\,, \tag{3}$$

gas phase

$$\frac{\partial \left(\varepsilon_g \varrho_g\right)}{\partial t} + \frac{\partial \left(\varepsilon_g \varrho_g v_g\right)}{\partial x} = \dot{W}_{sg} + \dot{W}_{wg}\,, \tag{4}$$

where ϱ [kg/m^3] denotes density, t [s] time, $\dot{W}_{sg}$ and $\dot{W}_{wg}$ [kg/(m^{3}s)] are the mass source terms for, pyrolysis gas generation and vapor, respectively, and v_g [m/s] is the velocity of released gas.

- **Momentum for gas phase**

$$\frac{\partial \left(\varepsilon_g \varrho_g v_g\right)}{\partial t} + \frac{\partial \left(\varepsilon_g \varrho_g v_g^2\right)}{\partial x} = -\frac{\partial \left(\varepsilon_g p_g\right)}{\partial x} - \frac{\mu \varepsilon_g v_g}{K} + \mu \varepsilon_g \frac{\partial^2 v_g}{\partial x^2}\,, \tag{5}$$

where K [m^2] denotes bed permeability and μ [kg/(m s)] gas dynamic viscosity.

- **Energy balance for wet biomass**

$$\frac{\partial \left(\varepsilon_s \varrho_s c_s T + \varepsilon_w \varrho_w c_w T\right)}{\partial t} + v \frac{\partial \left(\varepsilon_s \varrho_s c_s T + \varepsilon_w \varrho_w c_w T\right)}{\partial x} =$$
$$= \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) - \dot{W}_{sg} h_{sg} - \dot{W}_{wg} h_{wg}\,, \tag{6}$$

where T [K] denotes bed temperature, h_{sg} and h_{wg} [J/kg] are the enthalpies of pyrolysis and vaporization, respectively. λ [W/(m K)] is the effective thermal conductivity of wet biomass

$$\lambda = \lambda_{cond} + \lambda_{rad} = \varepsilon_s \lambda_s + \varepsilon_w \lambda_w + \lambda_{rad}$$

with the radiative conductivity between particles λ_{rad} estimated using Rosseland approximation [8].

Mass source term for gases is determined basing on the relationship

$$\dot{W}_{sg} = k\varepsilon_{s,0}\varrho_{s,0}\left(Z - Z_\infty\right),\tag{7}$$

where Z [kg/kg] is the pyrolysis progress being defined as the biomass mass loss, $Z = m_s/m_{s,0}$ and k [1/s] is the rate of devolatilization reported in [9]. Subscripts 0 refers to the initial value, whereas ∞ to the limit value obtained for very low heating rates, which is derived from thermogravimetry analysis [11].

Volumetric mass flux of vapor is a function of specific surface area a_I and the net mass flux of water/steam phase change j_{wg}, as written in form:

$$\dot{W}_{wg} = a_I \times j_{wg}\,,\tag{8}$$

where

$$j_{wg} = f\left(T, p_w^{sat}, p_{w,g}\right)\tag{9}$$

with $p_{w,g}$ denoting the water vapor pressure above the liquid surface and p_w^{sat} representing the water pressure at the fluid-particle interface. The details regarding the determination of the vapor mass flux defined by Eq. (9) can be found in [12].

The following conditions were assumed:

Initial:

$$T(x,0) = T_0\,,\tag{10}$$

$$p_g(x,0) = p_0\,,\tag{11}$$

$$v_g(x,0) = 0\,,\tag{12}$$

Boundary:

$$T(x = 0, t) = T_c\,,\tag{13}$$

$$T(x = L, t) = T_0\,,\tag{14}$$

$$p_g(x = 0, t) = p_0\,,\tag{15}$$

$$p_g(x = L, t) = p_g(L, t) + a\frac{p_g(L - \Delta x, t - \Delta t) - p_g(L, t - \Delta t)}{\Delta x/\Delta t}\,,\tag{16}$$

$$v_g(x = L, t) = 0\,.\tag{17}$$

Quantity a in Eq.(16) represents the propagation speed of sound, $a = (\partial p_g/\partial \varrho_g)$ [12].

3 Results and discussion

The set of governing equations was resolved using partly implicit numerical schemes. To analyze the impact of the bed settling on the process dynamics, the computations were performed for three different values of movement speed of the bed v, i.e., 1, 2 and 3 cm/h. The set value of the bed height corresponded to the real height of the drying/pyrolysis section in the reactor constructed at IMP PAN laboratory, which is approximately $L = 0.5$ m. The values of ambient temperature $T_0 = 300$ K and atmospheric pressure $p_0 = p_{atm} = 10^5$ Pa were adopted as initial values. The temperature at the interface between combustion and pyrolysis zones T_c, was assumed to be maintained at 1273 K. The physical properties for solid phase (pine chips) and water are summerized in Tab. 1.

Table 1: Assumed properties.

Property	Value		Ref.
ϵ_s, $-$	0.40		
ρ_s, kg/m^3	460.00		
λ_s, W/(m K)	0.35		[10]
c_s, J/(kg K)	$\begin{cases} 1500 + T & \text{for } T \leq 500 \text{ K,} \\ 420 + 2.09T + 6.85 \times 10^{-4}T^2 & \text{for } T > 500 \text{ K.} \end{cases}$		[10]
K, m^2	$10^{-10.5}$		
ρ_w, kg/m^3	1000.00		
λ_w, W/(m K)	0.60		
c_w, J/(kg K)	4200.00		

Figure 2 presents the model predictions regarding the temperature distribution along the biomass bed height for various movement speed values after 1.5 hour of the process duration. It is seen that depending on the speed of bed movement the different temperature distribution is being established. Consequently, the extent of the pyrolysis and drying zones changes. The faster the bed moves, the smaller is the high-temperature layer and hence the narrower is the pyrolysis zone (the most intensive stage of pine chips pyrolysis covers the temperature area between 553 and 653 K [11]). It is then shifted towards the combustion zone. This in turn leads to the extension of evaporation/condensation zone. As shown in Fig. 3, in which the evolution of gas release is plotted, in case of the speed movement of 1 cm/h, the up-

per boundary of the section where the pyrolysis takes place is situated at the height of approx. 0.18 m, whereas for the maximum speed considered, $v = 3$ cm/h, this boundary is displaced onto the lower level $x = 0.09$ m.
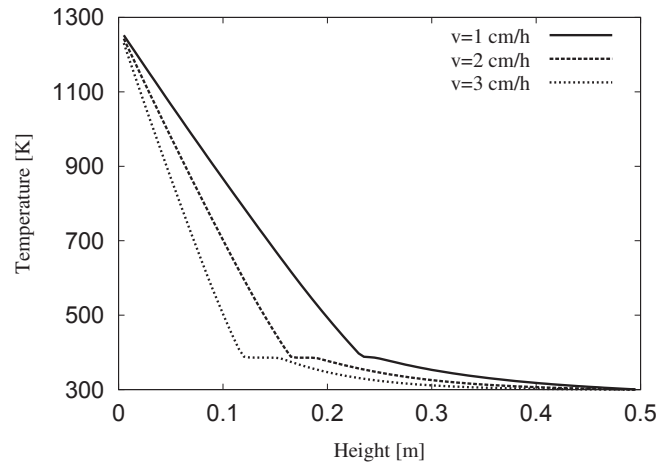

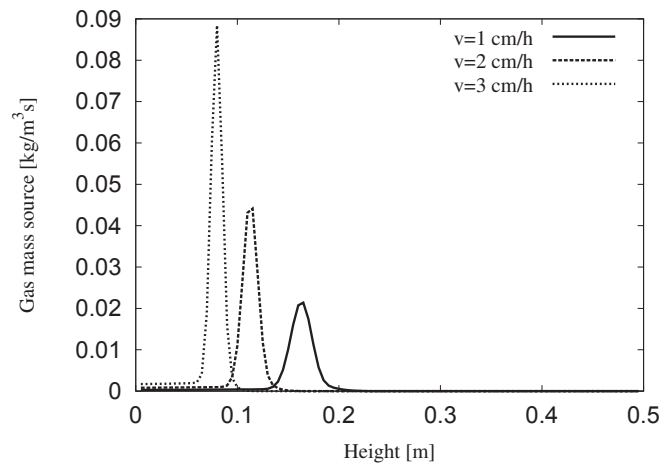Figure 2: Predicted temperature distribution within the biomass bed after 1.5 h of the process duration.

Figure 3: The results of simulation of pyrolysis gas release inside the biomass bed after 1.5 h of the process duration.

The comparison of vaporization and condensation fronts for various bed movement speeds is presented in Fig. 4. As observed, at a lower speed the moisture evaporation zone extends from ca. $x = 0.23$ m up to $x = 0.24$ m. Released water vapor re-condenses when entering cooler parts of the bed being at temperature below 373 K, which is reflected in the negative vapor mass source and in this case occurs between about $x = 0.24$ m and $x = 0.25$ m. In case of larger speed $v = 3$ cm/h the drying zone extends from the level of $x = 0.11$ m up to $x = 0.13$ m, whereas the condensation takes place in the area between $x = 0.14$ m and $x = 0.16$ m.
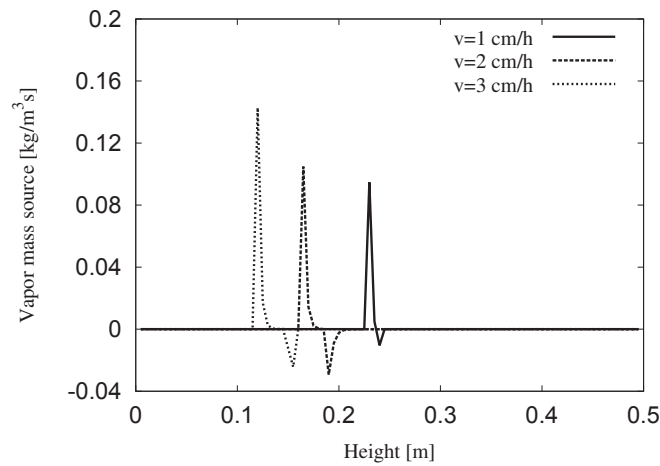

Figure 4: The calculation results of moisture release inside the biomass bed after 1.5 h of the process duration.

The devolatilization and evaporation processes have their impact on the gas pressure inside the reactor, which is depicted in Fig. 5. It clearly shows that the internal gas pressure increases in the area where the pyrolysis occurs. Also a small pressure increase may be observed at the horizontal cross-sections in which the evaporation front is located. Thus, at the set gas outlet, $x = 0$, the pressure maintains at the atmospheric level as assumed, whether it rises with increasing amount of evolved gases in the upper levels of the biomass bed and achieves constant overpressure in the upper section of the gasifier occupied by nonconverted supplied feedstock. For instance, in case of $v = 3$ cm/h, the pressure increases up to about 230 Pa at $x = 0.11$ m, then decreases slightly when passing the evaporation front (at $x = 0.13$ m) and eventually remains constant at ca. 225 Pa in the gasifier section above

$x = 0.15$ m. For the lowest speed considered a pressure increase in the area covering the drying process was not observed.
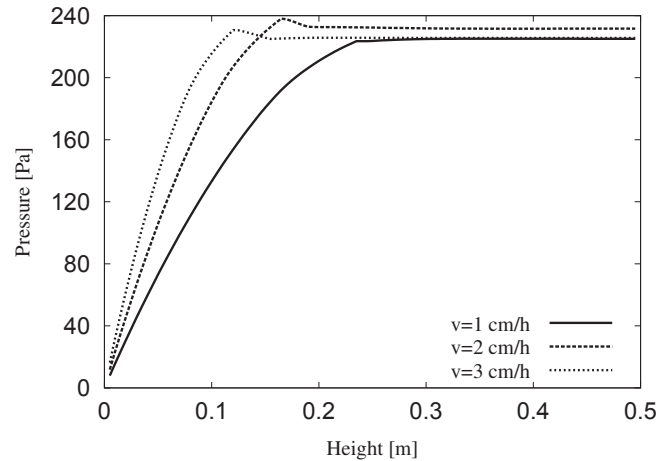

Figure 5: Predicted pressure distribution within the biomass bed after 1.5 h of the process duration.

4   Conclusions

The evaporation and pyrolysis processes of pine chips in a fixed bed were studied to analyze the performance of a gasifying reactor in its upper part where these phenomena take place. A transient one-dimensional model was proposed to predict the temperature, pressure, gas and moisture release distributions within the settling packed bed. The mathematical description comprises the problems of: heat transfer, including conduction and radiation mechanisms, moisture evaporation, solid particle devolatilization due to thermal decomposition and gas transport through the bed. The computation results obtained for various speeds of bed movement assumed were compared and discussed. They clearly showed that the area of high temperature reduces with an increasing movement speed which, in consequence, leads to the narrowing of the bed layer which undergo pyrolysis and to the extension of the drying zone.

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