

Modeling Moisture and Density Behaviors of Wood in Biomass Torrefaction Environments

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Abstract—Worldwide interests for the renewable energy are increasing due to environmental and climate changes from traditional petroleum related energy sources. To account for these social needs, ligneous biomass energy is considered as one of the environmentally friend energy solutions. The wood torrefaction process is a feasible method to improve the properties of the biomass fuel and makes the wood have low moisture, lower smoke emission and increased heating value. In this work, therefore, the moisture evaporation model which largely affects energy efficiency of ligneous biomass through moisture contents and heating value relative to its weight is studied with numerical modeling approach by analyzing the effects of torrefaction furnace temperature. The results show that the temperature and moisture fraction of wood decrease by increasing the furnace temperature. When the torrefaction temperature is lower than 423K, there were little changes of the moisture fraction in the wood. Also, it can be found that charcoal is produced more slowly when the torrefaction temperature is lower than 573K.

Keywords—Modeling, Torrefaction, Biomass, Moisture Fraction, Charcoal.

I. INTRODUCTION

IN recent years, worldwide concerns for environmental pollutants emission and green-house gases problems are increasing due to the use of fossil fuels such as oil, coal, and natural gases. One of the approaches to solve these pollutants and green-house gas emissions from fossil fuels has been focused on the renewable energy such as biomass fuels. The lignocellulosic biomass fuels, however, have low energy density, economic and storage problems due to absorbed moisture inside in it. The torrefaction technology, which is a thermal treatment process in the temperature range of 225–300 °C is widely used to produce biomass fuel with increased energy density by decomposing the reactive hemicellulose fraction [1]–[4]. The torrefied wood has found valuable applications such as barbecue and firelighter fuels as well as renewable fuels in future with increased energy density for gasification and co-combustion.

Blasi [1], [2] investigated both the solid and gas phases reaction mechanism for solid fuels with PMMA and summarized the modeling and simulation processes. Blasi [2] has also suggested heat, momentum and mass transfer through a shrinking biomass particle exposed to thermal radiative heat

transfer. Lee et al. [3] found that the large biomass particles have shown significant shrinkage in the charcoal layer as the pyrolysis front propagates through the solid through experiments. On the other hand, Morel et al. [4] investigated effect of particle size on charcoal gasification to find the disintegration of the solid structure at some critical conversion level. Chan et al. [5] presented the need for information both on charcoal deposition rates during carbonization of a range of fuel types and on charcoal thermal properties over a wide range of temperatures and porosities. Prins et al. [6] studied the weight loss kinetics for torrefaction of willow, a deciduous wood type with isothermal thermogravimetry and Turner et al. [7] analyzed chemical mechanism in temperature condition of 200–300 °C by examining the pyrolysis of hemicellulose, cellulose, and lignin.

In order to design a torrefaction furnace for wood, it is necessary to find thermal behavior of biomass such as temperature rise, weight loss through water vapor evaporation, and charcoal generation in torrefaction environments. In this work, therefore, effect of torrefaction furnace temperature on moisture fraction, wood and charcoal density is investigated with wide range of furnace temperature with time by using the one-dimensional modeling and numerical simulation. In the following, after introducing the mathematical formulations of the present numerical model with detailed kinetic parameters, some parametric studies to find thermal development of wood in torrefaction environments are conducted. Finally, some concluding remarks are presented.

II. MATHEMATICAL FORMULATION

A. Governing Equations

In this study, the balance equations for solid and gaseous species, moisture, water vapor, and energy are considered to model the moisture transfer and wood and charcoal density changes in torrefaction furnace. The torrefaction kinetics are based on three different reactions from biomass to gas (K_1), tar (K_2), and charcoal (K_3) [8]. The solid species conservation equations can be written as,

$$\frac{\partial \rho_w}{\partial t} = -(K_1 + K_2 + K_3) \rho_w \quad (1)$$

$$\frac{\partial \rho_c}{\partial t} = K_3 \rho_w \quad (2)$$

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where ρ_w and ρ_c are the apparent density of wood and charcoal in kg/m^3 , respectively. K_1 , K_2 , and K_3 are the species reaction rates for gas, tar, and charcoal, which are calculated following Arrhenius type equations,

$$K_i = A_i \exp\left(-\frac{E_i}{RT}\right) \quad 1 \leq i \leq 3 \quad (3)$$

where A_i , E_i , R , and T are pre-exponential factor in $1/\text{s}$, activation energy in kJ/mol , gas constant in kJ/molK , and temperature in K , respectively. The gaseous species balance equation becomes,

$$\frac{\partial}{\partial y}(\rho_g u) = (K_1 + K_2) \rho_w \quad (4)$$

where ρ_g and u are the volatile (i.e., gas and tar) mass concentration in kg/m^3 and volatile velocity in m/s , respectively. The moisture balance equation can be expressed as,

$$\frac{\partial(x\rho_w)}{\partial t} = -r_{ev} \quad (5)$$

where x and r_{ev} are the moisture fraction in the wood and moisture evaporation rate in $\text{kg/m}^3\text{s}$ given by

$$r_{ev} = x\rho_w A_0 \exp\left(-\frac{E_0}{RT}\right) \quad (6)$$

The final water vapor balance equation becomes

$$r_{ev} = x\rho_w A_0 \exp\left(-\frac{E_0}{RT}\right) \quad (7)$$

where ρ_v and u are the water vapor density in kg/m^3 and water vapor velocity in m/s , which is usually assumed equal to volatile velocity. The energy conservation equation is appeared as,

$$\begin{aligned} & \frac{\partial}{\partial t}[(\rho_w c_w + \rho_c c_c + x\rho_w c_M)T] \\ & = \frac{\partial}{\partial y}\left(k_{eff} \frac{\partial T}{\partial r}\right) - \frac{\partial}{\partial y}[(\rho_g u c_g + \rho_v u c_v)T] - \sum_{i=1}^3 \Delta h_i r_i - \Delta h_{ev} r_{ev} \end{aligned} \quad (8)$$

where c_w , c_c , and c_M are the specific heats (kJ/kgK) of the wood, char, and moisture, T and k_{eff} are the temperature (K) in the solid matrix and effective heat conductivity

(kJ/mK). While r_i is conversion rate of species, Δh_i and Δh_{ev} are the heat of chemical reaction and moisture evaporation (kJ/kg), respectively. This energy balance equation means the accumulation of the enthalpy of condensed phase and gas phase species is equal to summation of conductive and convective transports of heat, and heat release associated with chemical reaction and moisture evaporation. Here, the effective conductivity is calculated with interpolation between heat conductivities of the wood, k_w , and char, k_c , such that $k_{eff} = \Phi k_w + (1 - \Phi) k_c$, where $\Phi = \rho_w / \rho_c$. Meanwhile, conversion rate of species are estimated as $r_i = K_i \rho_w$.

To close the governing equations, initial and boundary conditions are needed. At $t = 0$, temperature of the biomass is set to room temperature (i.e., $T = T_0$), apparent density of wood is equal to initial density of the substrate (i.e., $\rho_w = \rho_0$), there is no charcoal (i.e., $\rho_c = 0$) and evaporation (i.e., $u = 0$). In the centerline of the substrate (i.e., at $y = 0$), no temperature gradient (i.e., $\partial T / \partial y = 0$) and no evaporation (i.e., $u = 0$) conditions are imposed, while the convective boundary condition is applied at the outer boundary (i.e., $-k_{eff} \partial T / \partial y = h(T - T_f)$ at $y = R$), where T_f and h are the torrefaction temperature and convective heat transfer coefficient, respectively.

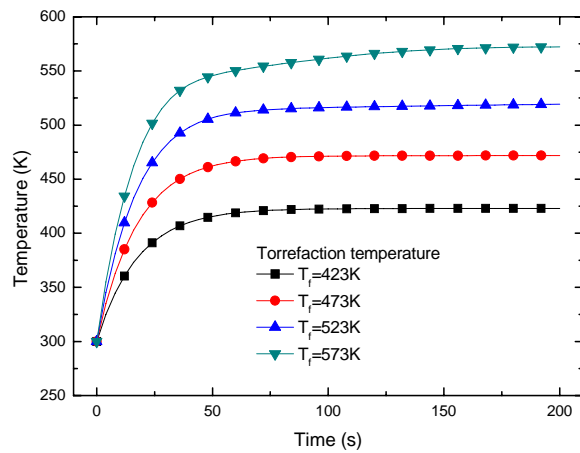


Fig. 1 The effect of torrefaction furnace temperature on wood temperature with time

III. RESULTS AND DISCUSSION

To find the thermal behavior of the wood in torrefaction environments, numerical simulations for water vapor evaporation and resulting changes in moisture fraction, wood and charcoal density are conducted with Pinuslab ($1\text{m} \times 1\text{m}$). The kinetic data used in this work are from Felfli et al. [8, 9], i.e., pre-exponential factors of $A_1 = 1.3 \times 10^8 \text{ 1/s}$,

$A_2 = 2 \times 10^8 \text{ 1/s}$, $A_3 = 1.08 \times 10^7 \text{ 1/s}$, activation energies of $E_1 = 140 \text{ kJ/mol}$, $E_2 = 133 \text{ kJ/mol}$, $E_3 = 121 \text{ kJ/mol}$, and heat of chemical reactions of $\Delta h_1 = \Delta h_2 = \Delta h_3 = 418 \text{ kJ/kg}$. The kinetic data for water vapor evaporation rate are $A_0 = 5.13 \times 10^6 \text{ 1/s}$ and $E_0 = 80 \text{ kJ/mol}$, while heat for moisture evaporation is $\Delta h_{ev} = 2,257 \text{ kJ/kg}$. The physical properties adopted for Pinus are as follows [8]: initial density of wood is $\rho_0 = 500 \text{ kg/m}^3$, specific heats for wood, gas, and charcoal are $c_w = 1.5 \text{ kJ/kgK}$ and $c_g = c_c = 1.5 \text{ kJ/kgK}$, and heat conductivities for wood and charcoal are $k_w = 0.16 \text{ W/mK}$ and $k_c = 0.071 \text{ W/mK}$, respectively. The assumed initial moisture in the furnace is 15% and the convective heat transfer coefficient is assumed as $h = 60 \text{ W/m}^2\text{K}$. The initial temperature of Pinus sample is set to 300 K.

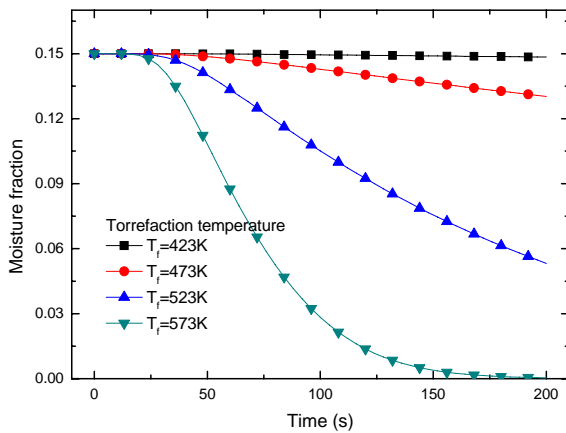


Fig. 2 The effect of torrefaction furnace temperature on moisture fraction in wood with time

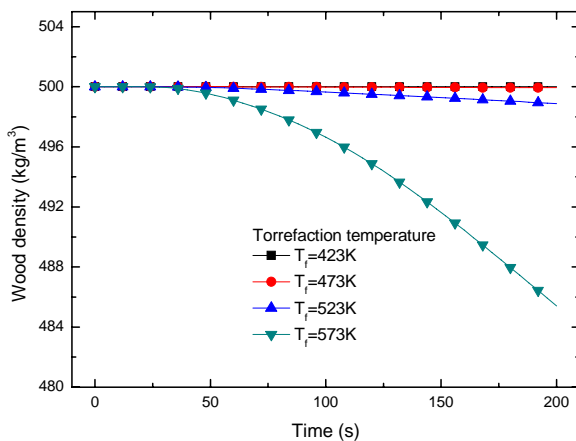


Fig. 3 The effect of torrefaction furnace temperature on wood density with time

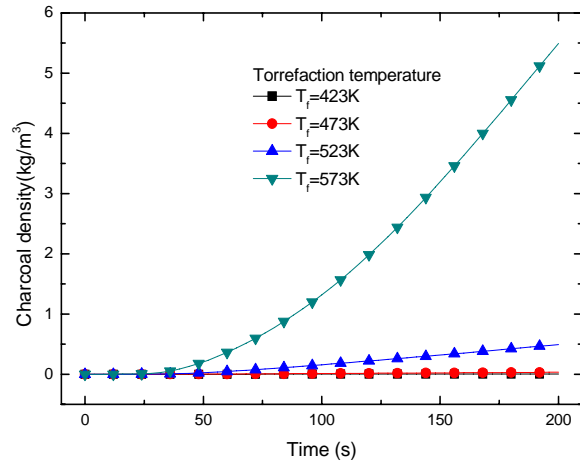


Fig. 4 The effect of torrefaction furnace temperature on charcoal density with time

Fig. 1 shows effect of torrefaction temperature on the wood temperature in the furnace with time. Here, the torrefaction temperatures are supposed to change from 423 to 573K. In an early stage of furnace process nearly until 50 seconds the temperature of the wood is increasing rapidly because the temperature difference between wood and furnace is very. After 50 seconds, however, the rate of temperature increase of the wood is observed to be flat because the temperature of the wood is high enough. It also can be found in the figure that the wood temperature is saturated as furnace temperature with time. The change of wood moisture fraction is illustrated in Fig. 2. Here, it can be observed that the moisture fraction in the wood only slightly decreases with time when the torrefaction temperature is 423K. As the furnace temperature increases, however, more water vapor is evaporated with time. At the highest torrefaction temperature of 573K, most of the moisture is evaporated in 200 seconds considered in this work because of high temperature environments.

Figs. 3 and 4 represent the wood and charcoal density profiles with time in the furnace, respectively. As the torrefaction temperature increases from 423K to 573K, lower wood density and higher charcoal density are estimated because moisture is evaporated and the charcoal is generated. When the furnace temperatures are 423 and 473, it can be observed that only very small changes in wood and charcoal densities occur because moisture fraction is slightly changed. As the furnace temperature increases to 523K, however, wood density is changed about 0.2% compared to initial density and charcoal density becomes 0.5 kg/m^3 , which is initially zero. When the furnace temperature increases to 573K, the wood density is decreased about 3% and charcoal density increases to about 5 kg/m^3 .

IV. CONCLUSION

In this work, numerical simulation of biomass torrefaction process has been conducted to evaluate the effect of

torrefaction temperature and initial moisture fraction. An one-stage multi-reaction model has been implemented into in-house code. The following conclusions can be drawn from this work:

- (1) The wood temperature increases as the torrefaction temperature increases, and saturates to its environmental furnace temperature.
- (2) The moisture fraction of wood decreases as the torrefaction temperature increases. However, when the furnace temperature is below 423K, no water vapor evaporates.
- (3) The wood and charcoal densities do not change when the torrefaction temperature is below 473K.

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