Influence of Product Yield, Density, Heating Conditions and Conversion on Pyrolysis of Biomass

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Abstract – Biomass is an attractive option as a fuel for power generation. The pyrolysis process consists of the thermal degradation of biomass feedstock in the absence of oxygen/air. In the present study, the simultaneous chemical kinetics and heat transfer model is used to predict the effects of heating conditions, density of biomass, product yields and conversion on pyrolysis of biomass fuels. Finite difference pure implicit scheme utilizing Tri-Diagonal Matrix Algorithm is employed for solving heat transfer model equation. Runge-Kutta 4th order method is used for solving chemical kinetics model equations. Simulations are carried out for different geometries (slab, cylinder and sphere) considering equivalent radius ranging from 0.0000125 m to 0.011 m, and temperature ranging from 303 K to 2100 K.

Key words: biomass, pyrolysis, modeling, kinetics, heat transfer

1. Introduction

There are many ways by which the energy, available in abundance around us, can be stored, converted and amplified for our use. Energy sources will play an important role in the world's future. The cost of producing energy from biomass fuels is less than that from fossil fuels. The term biomass is used to describe all the biologically produced matter. Biomass is the oldest form of energy used by human beings, mainly in the form of wood. It has either been burned directly in furnaces, or processed to increase its energy content (Haykiri-Açma, 2003). Biomass is useful to meet different kinds of energy needs, including fueling vehicles, providing process heat for industrial facilities, generating electricity and heating homes.

A promising route for processing biomass is pyrolytic conversion, which has been conducted under variety of experimental conditions (Demirbaş, 2002). Pyrolysis is basically the thermal degradation of biomass in the absence of air to produce liquid (bio-oil or bio-crude), charcoal and non-condensable gases.

2. Background

Many researchers have developed the models for pyrolysis of biomass (Bamford et al., 1946; Fan et al., 1977; Miyanami et al., 1977; Liliedahl and Sjöström, 1998; Jalan and Srivastava, 1999). Several of these models do not include; density as a function of time, secondary reactions, thermal conductivity and specific heat capacity of biomass as a function of temperature, and convective heat transfer coefficient as a function of Reynolds number and Prandtl number. The above anomaly has been rectified in the model developed by Babu and Chaurasia (2003 a), which is used in the present study. The effect of particle size, orders of reaction, thermal and thermodynamic properties, shrinkage, heat of reaction, reactor temperature, etc., have already been discussed by the present authors in their earlier studies (Babu and Chaurasia, 2002 a, b; 2003 b, c, d, e, f, g, h, i; Chaurasia and Babu, 2003; and Chaurasia et al., 2003).

3. Problem formulation

In the present study, the influence of product yield, density, heating conditions and conversion on pyrolysis of biomass is examined for different geometries (slab, cylinder and sphere).

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The kinetic scheme as given by Babu and Chaurasia (2003 b) is utilized. The simultaneous chemical kinetics and heat transfer model (Babu and Chaurasia, 2003 a; 2003 c) is used to predict the effects of above properties on the convective-radiant pyrolysis of biomass fuels. Finite difference pure implicit scheme utilizing the Tri-Diagonal Matrix Algorithm (TDMA) is employed for solving the heat transfer model equation. Runge-Kutta 4th order method is used for solving the chemical kinetics model equations. Simulations are carried out for different geometries (slab, cylinder and sphere) considering the equivalent radius ranging from 0.0000125 m to 0.011 m, and the temperature ranging from 303 K to 2100 K.

4. Results and Discussion

The influence of average product yield and conversion time as functions of particle thickness with slab, cylinder and sphere geometries is shown in Fig. 1. It is found that, the yield of $(\text{char})_1$ increases while the yield of $(\text{volatile \& gases})_1$ decreases as the particle thickness is increased. This is a consequence of the decrease in temperature at any radial position with respect to the increase in particle size. Therefore the charring reactions (favoring the char formation) are successively favored to more extent. The concentration of $(\text{volatile \& gases})_2$ increases up to a certain value and then decreases as the particle size is further increased. A significant increase in pyrolysis time is observed as the particle size is increased. A spherical particle has the shortest conversion time, as can be expected based on the higher surface-to-volume ratio. However, at small particle radius (typically less than 1 mm), the rate of reaction becomes dominant and the different particle shapes show nearly equal conversion times. A comparison of the product concentrations of primary and secondary pyrolysis reactions indicates that the activity of the primary reactions is significant as compared to the activity of secondary reactions.

Biomass density has been varied in the range of values between 400-1600 Kg/m^3. However, no dependence of this parameter on product yield has been observed. Fig. 2 reports the product yield and conversion time as functions of the biomass density for R=0.009 m with cylindrical geometry. No effect of density on both the primary and secondary reaction products is observed. The primary solid degradation rate, and thus the volatile release rate, depends on the both the temperature and solid density. Although on one hand, the temperature of primary degradation becomes lower leading to slower heating rates of volatile release, on the other hand, the increased

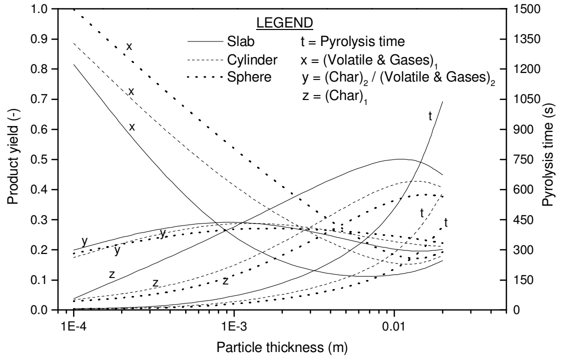

Figure 1: Average product yield and pyrolysis time as functions of particle radius (R) with slab, cylinder and sphere (T_0=303 K, T_f=900 K).

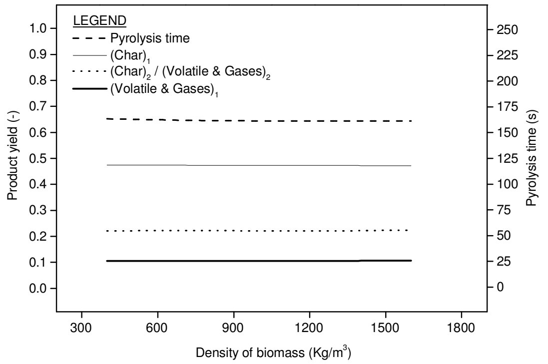

Figure 2: Average product yield and pyrolysis time as functions of density of biomass (ρ) with cylindrical pellet (R=0.009 m, T_0=303 K, T_f=900 K).

solid density makes the primary degradation rate faster. The two effects counteract with each other, resulting in an almost constant release rate of volatiles and char, as the density of biomass is increased. The conversion time does not depend on the density of biomass and is nearly constant (161 s).

The role played by heating rate, i.e., the final temperature (T_f) on the particle can be observed from Fig. 3, which reports the time evolution of the temperature at the sample centerline for R=0.01m with cylindrical pellet. A similarity in the curves can be seen, due to the existence of a flat zone, which becomes successively more evident as the heating rate (T_f) is made slower. The temperature of the flat zone decreases with T_f, because of the reduction in the gas overpressure. As expected, the complete conversion of pyrolysis occurs at successively shorter times as T_f is increased. For low heating rate (T_f=500 K), only 1.22 % of the pyrolysis completes even at t=900s while for high heating rate (T_f=900 K), the pyrolysis completes (100 %) at t=190 s itself.

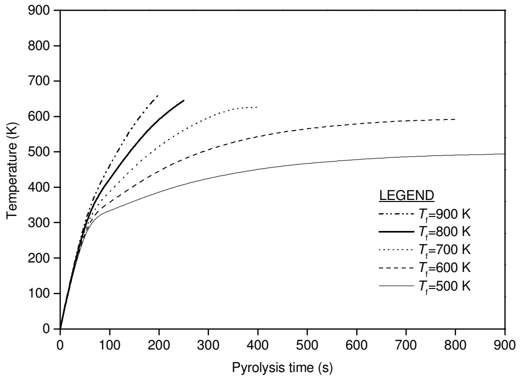

Figure 3: Temperature profile as functions of pyrolysis time (t) with cylindrical pellet at various values of final temperature (R=0.01 m, T_0=303 K, x=0.0).

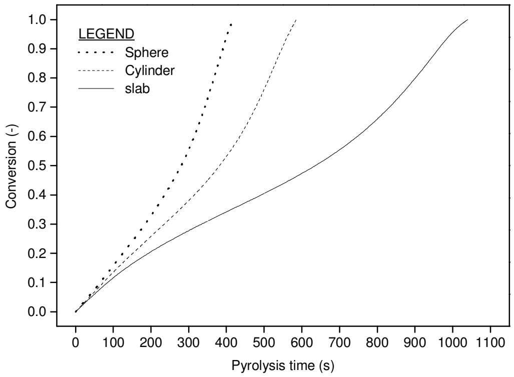

Figure 4: Conversion as functions of pyrolysis time (t) with slab, cylinder and sphere (R=0.02 m, T_0=303 K, T_f=900 K).

The conversion profile with slab, cylinder and sphere is shown in Fig. 4 for R=0.02 m. The radii of cylinder and sphere are taken as half the thickness of slab. The trends in the conversion profile are same for all the three geometries. The time required for complete conversion of pyrolysis (i.e. the initial concentration of biomass is zero) is highest for slab (1040 s) and lowest for sphere (417 s). This is due to the fact that surface-to-volume ratio is lowest for slab and highest for sphere. Geometrically, the sphere has got a more heat absorbing capacity as compared to cylinder and slab and it is the least for slab. Mathematically it is reflected in the value of parameter b (b=1, 2 and 3 for slab, cylinder and sphere respectively) in the model equation (Babu & Chaurasia, 2003a) and hence the observed trends in conversion profile. Similar profiles were obtained for different geometries (slab, cylinder and sphere) considering the equivalent radius ranging from 0.0000125 m to 0.011 m, and temperature ranging from 303 K to 2100 K.

5. Conclusions

The yield of $(\text{char})_1$ increases while the yield of $(\text{volatile \& gases})_1$ decreases as the particle thickness is increased. There is no effect of density of biomass on both the primary and secondary reaction products. The conversion time does not depend on density of biomass and is nearly constant for complete conversion. Complete conversion of pyrolysis occurs at successively shorter times as the heating rate (T_f) is increased. The time required for complete conversion of pyrolysis is the highest for the slab and lowest for the sphere. The results discussed above have a lot of practical importance and physical significance in industrial pyrolysis applications. The results are also important and useful for design of biomass gasifiers, reactors, etc.

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