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Modeling of beech wood pellet pyrolysis under concentrated solar radiation

Kuo Zeng [a], José Soria [b], Daniel Gauthier [a], Germán Mazza [b], Gilles Flamant [a, *]

[a] Processes Materials and Solar Energy Laboratory, PROMES-CNRS, 7 Rue du Four Solaire, 66120, Odeillo Font Romeu, France
[b] Institute for Research and Development in Process Engineering, Biotechnology and Alternative Energies (PROBIEN, CONICET – UNCo), 1400 Buenos Aires St., 8300, Neuquén, Argentina

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ABSTRACT

A two-dimensional, unsteady CFD (Computational Fluid Dynamics) single particle model was developed and used to simulate the solar pyrolysis process of beech wood pellets (10 mm in diameter and 5 mm in height). Pseudo-stoichiometric coefficients about the mass fraction of primary tar converted by the reaction into gas and secondary tar were determined at different temperatures and heating rates for the first time. The 2D model predictions were successfully validated with tests performed at 600 °C to 2000 °C final temperature, with 10 and 50 °C/s heating rates. The evolution of the final products and mass losses of pyrolyzed biomass are enhanced with temperature and heating rate. Moreover, the higher the temperature and heating rate, the higher the gas yield. This emphasizes the intra-particle tar secondary reaction into gas for pyrolysis of large size sample under high temperature and heating rate.

1. Introduction

Sustainable heat and power generation from renewable energy sources such as biomass and solar attract more and more attention owing to the continuous diminution of fossil fuels and the intensifying environmental problems. Between 2010 and 2040 significant developments in renewable energy production are expected in biomass energy (from 45217.4 to 136950.2 PJ) and solar energy (from 184.2 to 55768.2 PJ) [1].

However, the low energy density is the biggest obstacle to the biomass usage. Solar energy utilization is impacted by its diluted, intermittent and unequally distributed features. These drawbacks can be overcome by converting biomass and solar energy into solar fuels. Hybrid solar/biomass endothermic process in which biomass is used as chemical reactants and solar energy as the process heat is a good strategy. Indeed in such a process, concentrated solar radiation is the energy source of high-temperature process heat for biomass pyrolysis reactions [2]. There are three main advantages from this combination [3]: (1) Gas pollutants discharge is avoided. (2) The feedstock calorific value is upgraded. (3) The intermittent solar energy is chemically stored in the form of solar fuels. In the 1980s, Beatie et al. [4] obtained a maximum gas yield of 31 mmol/g coal from direct solar pyrolysis at flux level of 1 MW/m^2. Recently, bio-char [5], bio-gas [6–8] and bio-oil [9,10] with potential use were produced through solar pyrolysis process.

Solar pyrolysis is carried out under concentrated solar radiation. Some effort has been expended experimentally and theoretically for the better understanding of the complex mechanisms in biomass pyrolysis under simulated solar radiation in image furnace. The image furnace consists in a xenon lamp (light source) associated to a set of concentrating mirrors, which can be adjusted to the required concentrated radiant flux. Reviewing biomass pyrolysis modeling reveals the comprehensive chemical and physical processes [11]. The theoretical and experimental study of cellulose pellets flash pyrolysis submitted to concentrated radiation validated the simple kinetic pathways derived from “Broido-Shafizadeh” model [12]. The three-parallel reaction scheme just considering char, tar and gas was used for biomass pyrolysis in image furnace [13,14]. Both Eulerian and Lagrangian modeling approaches agreed well with the experimental results obtained with oak pellets' fast pyrolysis in an image furnace. They showed that the liquid yield (approximately 62%) did not change with the heat flux density (from 0.3 to 0.8 MW/m^2), whereas the gas and char yields

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* Corresponding author.
E-mail address: gilles.flamant@promes.cnrs.fr (G. Flamant).

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Nomenclature

Latin letters

A	Pre-exponential factor, 1/s
a	Stoichiometric coefficient to gas, –
B	Permeability, m^2
b	Stoichiometric coefficient to secondary tar, –
C_p	Heat capacity, J/kg/K
D	Diffusion coefficient, m^2/s
d_{pore}	Pore diameter, m
E	Activation energy, J/mol
F	Momentum source term, Pa/m
e	Emissivity, –
g	Gravity, m/s^2
k	Reaction rate constant, 1/s
L	Length, m
M	Molar mass, kg/mol
m	Mass, kg
P	Pressure, Pa
Q	Heat generation, W/m^3
R	Radius, m
R_g	Ideal gas constant, J/mol/K
x	Cylindrical coordinate (heating direction), m
r	Cylindrical coordinate (radius direction), m
S	Source term, $kg/m^3/s$
T	Temperature, K
t	Time, s
v	Velocity, m/s

Greek letters

Δh	Reaction heat, J/kg
ΔT	Temperature difference, K
Δt	Time difference, s
ε	Porosity, –
λ	Thermal conductivity, W/m/K
μ	Viscosity, Pa s
ρ	Apparent density, kg/m^3
$\widehat{\rho}$	Intrinsic density, kg/m^3
η	Pyrolysis degree, –

Subscripts

S	Solid
i	Component (w, c, is)
Ar	Argon
c	Char
cond	Conductive
g	Gas
is	Intermediate solid
r	Radial direction
rad	Radiative
t1	Primary tar
t2	Secondary tar
V	Volatiles (g, t1, t2)
w	Wood
x	X direction

increased and decreased, respectively [13]. A single particle model predicting the evolution of products and mass losses of biomass pellets submitted to concentrated radiation was developed [14]. In such image furnaces, condensable vapors and gases released from the biomass samples were quenched immediately. Tar secondary reactions were not considered in all above models. Actually, primary pyrolysis products (vapors and gases) must diffuse out of the pellets through the hot temperature char layer. Thus, chemical processes of biomass pyrolysis may be described through a primary stage and a secondary stage [15–17]. Chan et al. [15] developed a mathematical wood pyrolysis model inclusive of water release, tar cracking and char deposition chemical reactions, which can be used for predicting the ultimate product distribution and can aid in process optimization to either maximize or minimize the tar production. A coupled transport and reaction model of biomass pyrolysis including shrinkage has been developed by Di Blasi et al. [16]. The experimental and simulation results of wooden particles subjected to an assigned external radiation reveal that the tar secondary reaction is enhanced with the heat flux. Grønli et al. presented a competitive reaction model including a secondary tar cracking step, which can be used to predict the effects of heat flux on the product distribution for biomass pyrolysis [17]. Recently, a few researchers developed models to study the effect of process parameters, such as radiant heat flux, on the product distribution from biomass pyrolysis [18,19]. However, there is no modeling investigation validated experimentally by biomass pyrolysis using a real solar furnace. Up to now, the pyrolysis parameters' influence on product distribution in real solar reactor was only reported in our previous studies [6–8]. Both temperature and heating rate can be used to influence and determine the proportions of the main products of solar pyrolysis process and their characteristics.

Most previous models were developed on the basis of the experimental results obtained by pellet pyrolysis under low heating rates [13,15–19]. Actually, solar pyrolysis has the advantage of high temperature and fast heating rate. The reaction rate constant depends on the heating rate [20]. So a kinetics selection based on fast heating rate experimental tests has been done for modeling solar pyrolysis under severe conditions (heating rate up to 450 °C/s and temperature up to 2000 °C). For wood pellet exposed to concentrated solar radiation, a char layer close to the exposed surface is formed. The pyrolyzing zone propagates into the pellet interior with heat transport. The secondary tar reaction may occur when the interior primary tar flows out through the high temperature char layer. Therefore, it is essential to take into account intra-particle heat and mass transfer and tar secondary reaction in solar pyrolysis model.

Kinetic parameters of biomass pyrolysis depend on the heating rate and final temperature reached [21–23]. They play an important role in determining the pyrolysis product distribution [24–26]. The understanding of kinetics of pyrolysis process and accurate prediction of pyrolysis rates are very much important for optimal design of pyrolysis reactor. Some kinetic models have already been developed to study how these two parameters affecting the pyrolysis chemical and physical processes in conventional reactors [27,28]. For this reason, a two-dimensional, unsteady single particle model, was developed and used to simulate the solar pyrolysis of beech wood pellets under various temperatures and heating rates. The model describes the transport phenomena along with the kinetics that take place in a biomass pellet during solar pyrolysis. The formulated model should allow a deeper understanding of the behavior of intra-particle heat/mass transfer processes and of the tar secondary reactions effects.