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Parametric analysis of pyrolysis process on the product yields in a bubbling fluidized bed reactor

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ABSTRACT

This paper presents a numerical study of operating factors on the product yields of a fast pyrolysis process in a 2-D standard lab-scale bubbling fluidized bed reactor. In a fast pyrolysis process, oxygen-free thermal decomposition of biomass occurs to produce solid biochar, condensable vapours and non-condensable gases. This process also involves complex transport phenomena and therefore the Euler-Euler approach with a multi-fluid model is applied. The eleven species taking part in the process are grouped into a solid reacting phase, condensable/non-condensable phase, and non-reacting solid phase (the heat carrier). The biomass decomposition is simplified to ten reaction mechanisms based on the thermal decomposition of lignocellulosic biomass. For coupling of multi-fluid model and reaction rates, the time-splitting method is used. The developed model is validated first using available experimental data and is then employed to conduct the parametric study. Based on the simulation results, the impact of different operating factors on the product yields are presented. The results for operating temperature (both sidewall and carrier gas temperature) show that the optimum temperature for the production of bio-oil is in the range of 500–525 °C. The higher the nitrogen velocity, the lower the residence time and less chance for the secondary crack of condensable vapours to non-condensable gases and consequently higher bio-oil yield. Similarly, when the height of the biomass injector was raised, the yields of condensable increased and non-condensable decreased due to the lower residence time of biomass. Biomass flow rate of 1.3 kg/h can produce favourable results. When larger biomass particle sizes are used, the intraparticle temperature gradient increases and leads to more accumulated unreacted biomass inside the reactor and the products' yield decreases accordingly. The simulation indicated that the larger sand particles accompanied by higher carrier gas velocity are favourable for bio-oil production. Providing a net heat equivalent of 6.52 W to the virgin biomass prior to entering the reactor bed leads to 7.5% higher bio-oil yields whereas other products' yields stay steady. Results from different feedstock material show that the sum of cellulose and hemicellulose content is favourable for the production of bio-oil whereas the biochar yield is directly related to the lignin content.

1. Introduction

Environmental issues and the unsustainability of fossil fuels has motivated many researchers to seek alternative energy sources [1,2]. Biomass can be used as a sustainable and eco-friendly source of energy due to its abundance and formation process [3]. All organic material such as agricultural products and its waste, forest residue, land and aquatic animals can be classified as biomass [4–6]. Lignocellulosic biomass contains high energy organics in the form of cellulose, hemicellulose, and lignin which are available in agricultural waste, forest and harvesting crop residues such as corn stover, switchgrass, bagasse etc. [7,8]. Extracted energy from biomass is greener and more sustainable in comparison to conventional fossil fuels since it has lower emissions of sulfur dioxides (SO_2) and particulate matter (PM) [9]. Carbon neutrality is another benefit of biomass which means that due to the life cycle of biomass, the photosynthesis process is able to recycle the released carbon dioxide (CO_2) into the environment [9,10]. Conversion of biomass to an upgraded quality fuel such as a liquid or more homogenous solid is also achievable [11,12]. The possible routes are thermochemical conversions which are mainly; provision of heat via

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Nomenclature

List of symbols

A_i	Arrhenius constant, s^{-1}
C_p	Heat capacity, J/kg K
d_s	Particle diameter, m
Ea_i	The activation energy of reaction *i*, J/mole
g	Gravity acceleration, m/s^2
Δh	Heat release, kJ/kg
k	Thermal conductivity, J/kg K
k_i	Arrhenius rate constant of reaction *i*, dimensionless
MW	Molecular weight, kg/kmole
R	Gas constant, J/mole K
T	Temperature, Kelvin
U_{mf}	Minimum fluidization velocity, m/s
Y	Mass fraction

Greek symbols

α	The initial mass composition of cellulose in the feedstock, dimensionless
β	The initial mass composition of hemicellulose in the feedstock, dimensionless
γ	The initial mass composition of lignin in the feedstock, dimensionless
ρ	Density, kg/m^3
μ	Dynamic viscosity, kg/m.s
η	Product yield
ε_i	Volume fraction of phase *i*, dimensionless
ε_{mf}	Minimum gas volume fraction, dimensionless

direct combustion, a synthesis gas generation by gasification; production of bio-oil, char, and non-condensable gas through pyrolysis process [10]. The generated products of biomass pyrolysis are beneficial for some applications including bio-oil for liquid fuel as a source of high-value chemicals; solid biochar (e.g. sustainable source for adsorbent, soil amendment, or catalyst); and biogas for energy recovery [13,14]. Pyrolysis is categorized into three different groups; slow, fast, and flash pyrolysis. Char is the primary product of slow pyrolysis whereas the primary product of fast and flash pyrolysis is the liquid bio-oil. The produced bio-oil can be used for co-generation of heat and power in boilers, gas turbines, and diesel engines, or it can be upgraded to a higher quality fuel after refining [15–17].

In recent years, numerous experimental [3,18–23] and numerical [24–35] studies have investigated the biomass pyrolysis process. Although performing an experimental test is inevitable for finalizing the design and optimization of the pyrolysis process, it is very costly and time-consuming. In addition, a detailed understanding of complex physical phenomena such as multiphase flow dynamics, heat and mass transfers, and chemical kinetics that take place simultaneously inside the reactors, is challenging. Computational Fluid Dynamic (CFD) modelling techniques can be used as a tool in a better understanding of these types of systems. Moreover, CFD can model the internal temperature and pressure changes that are hard to measure in the harsh conditions of the reactor environment. CFD simulations can provide an insight into transport phenomena by giving an indication of the product yields of the pyrolysis process in reactors. In CFD simulations different reaction mechanisms can be exchanged in and out depending on feedstock and pyrolysis conditions/reactors. The heterogeneity of the biomass and the multiphase flow make the reaction mechanism complex, however global reaction rates have been proposed by various researchers e.g. [30,31]. Typically, global reactions are assumed where the biomass is converted through a series of primary and secondary reactions [36]. The reaction rates are typically derived in reactors where heat and mass transfer resistances are minimized. To properly model a pilot or commercial scale reactor, these resistances must be included in the form of transport equations.

Widespread applications of fluidized bed reactors (FBR) have prompted the use of CFD simulations as a tool in design [27–34,37–41], to investigate impacts such as nitrogen and sidewall temperature, sand particle size, biomass feed rate and particle size, feedstock material,

Table 1
CFD studies of typical reacting multiphase flow.

Author(s)	Reactor type	Process type	Dimension	Major findings
Cardoso et al. [25]	BFBR	Gasification	2-D	• Tendency of biomass particles is to be in the middle and upper regions of the bed whereas sand particles accumulate at the middle and bottom of the bed. • Lighter biomass particles move towards the top of the bed, and heavier biomass particles mixed with the sand particles. • Increased superficial gas velocity improved the binary mixing. • Biomass particles move upwards across the bed at the reactor's centreline and downwards in the near-wall region. • Smaller biomass particles allowed for a better heat transfer.
Eri et al. [44]	BFBR	Fast pyrolysis	2-D	• Cellulose-rich biomass produces more bio-oil than other biomass types. • The content of lignin has a close relationship with char production.
Kulkami et al. [45]	Vortex reactor	Fast pyrolysis	3-D	• Segregation of unwanted char particles towards the exhaust leads to lower undesirable gas-char contact, which resulted in more convective heat transfer coefficient between gas-solid and eventually higher yield of bio-oil.
Peng et al. [46]	BFBR	Fast pyrolysis	2-D	• The product yields and reaction rates are a strong function of pyrolysis temperature • Cellulose had the strongest ability to produce bio-oil, while lignin had the strongest ability to produce char.
Zhong et al. [47]	BFBR	Fast pyrolysis	2-D	• The particle shrinkage effect is applied to the complex pyrolysis mechanism. • The scheme has little impact on volume fraction and temperature distribution but influential impact on velocity distribution, mass fraction, diameter, and density, which finally effects the product yields.
Lathouwers and Bellan [48,49]	FBR	Fast pyrolysis	2-D	• The most influential factor on the bio-oil yield is the operating temperature.
Aramideh et al. [50,51]	Auger reactor	Fast pyrolysis	3-D	• The optimal wall temperature for maximum bio-oil production is about 823 K. • Increased pre-treatment temperature of biomass led to lower bio-oil yield. • Higher nitrogen flow rate resulted in higher bio-oil whereas increased biomass feed rate led to lower bio-oil yield.