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Original Research Paper

Numerical study of hydrodynamics with surface heat transfer in a bubbling fluidized-bed reactor applied to fast pyrolysis of rice husk

Cong-Binh Dinh [a], Chun-Chung Liao [b], Shu-San Hsiau [a,*]

[a] Department of Mechanical Engineering, National Central University, Jhongli City, Taoyuan County 32001, Taiwan, Republic of China
[b] Department of Mold and Die Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung 80778, Taiwan, Republic of China

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ABSTRACT

The present study investigates the hydrodynamics and heat transfer phenomena that occur during the biomass fast pyrolysis process. A numerical approach that combines a two-dimensional Eulerian multi-fluid model and the kinetic theory of granular flow has been applied to simulate the gas-solid flow in a bubbling fluidized-bed reactor. In this study, rice husk and quartz sand with specified properties were used as biomass and inert material, respectively. Our model was first validated the feasibility using previous findings, then an extensive parametric study was conducted to determine the effects of the major variables, especially the size of rice husk particles, on the flow distribution and the heat transfer between the phases. The concept of standard deviation attributed to the dispersion of solid volume fraction was used to calculate the intensity of segregation. The simulated results indicated that the mixing of binary mixture was strongly affected by different sizes of rice husk particles. The heat transfer occurring inside the fluidized bed was described by the distribution of solids temperature, the variation of surface heat flux and heat transfer coefficient. Both heat transfer quantities were observed to be dominant in the dense bed regions as they strongly depend on the solids concentration in the fluidized bed. The increasing inlet gas velocity promoted the mixing of solid particles, thus resulted in the effective heat transfer from wall to particles and between the particles.

1. Introduction

When the need for reducing fossil fuels consumption and carbon dioxide emission is considered, modernized bioenergy systems are expected to be important contributors to future sustainable energy systems in both developed and developing countries. Thermo-chemical processes, such as combustion, pyrolysis and gasification, are currently the most common techniques by which various energy products can be produced from raw biomass feedstock for different applications. As bio-oil attributed to high energy density could be stored and transported to anywhere, fast pyrolysis has been widely studied in recent years. Biomass fast pyrolysis is known as the rapid thermal decomposition of organic materials at elevated temperatures in the absence of oxygen to produce syngas, bio-oil and bio-char [1].

Among various types of reactors chosen for fast pyrolysis process, fluidized bed reactor (FBR) is a very popular choice of design as they offer many advantages, such as simple construction and operation, effective fluid-solid contact, high heat transfer rates, and the ability of handling various materials [2]. Fluidized beds often involve in the mixtures of solid particles with different sizes, shapes, and densities, which usually tend to separate during fluidization. The mixing/segregation behavior of these mixtures in a fluidized bed is greatly important for both industries and research since it has specific influences on bed expansion, chemical reactions, heat transfer and mass transfer characteristics [3,4]. Various papers in the literature have been reported in that subject from different aspects of fluidization conditions and particle properties. Rowe and Nienow [5] were among the first researchers who investigated the segregation of binary mixtures of different particle densities and sizes in a bubbling fluidized bed (BFB). They proposed the terms "flotsam" and "jetsam" to represent the particles occupying the upper and the lower of the bed, respectively [6]. The

Abbreviations: 2-D, two-dimensional; AMG, algebraic multigrid; BFB, bubbling fluidized bed; CFD, computational fluid dynamics; FBR, fluidized bed reactor; HTC, heat transfer coefficient; KTGF, kinetic theory of granular flow; MFM, multi-fluid model; SIMPLE, semi-implicit method for pressure-linked equations.

* Corresponding author. Fax: +886 3 425 4501.
E-mail address: sshsiau@cc.ncu.edu.tw (S.-S. Hsiau).

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Nomenclature

C_p	specific heat capacity, J/(kg·K)
d	particle diameter, m
D	bed width, m
e_{ss}	restitution coefficient, dimensionless
g	gravitational acceleration (=9.81 m/s^2), m/s^2
h_i	specific enthalpy, J/kg
h_{surface}	surface heat transfer coefficient, W/(m^2·K)
h_{gs}	volumetric heat transfer coefficient, W/(m^2·K)
H	bed height, m
k	thermal conductivity, W/(m·K)
k	turbulent kinetic energy, m^2/s^2
M	mixing index, dimensionless
n	number of nodes, nodes
Nu	Nusselt number, dimensionless
p	pressure, Pa
Pr	Prandtl number, dimensionless
q''	surface heat flux, W/m^2
Q_{gs}	quantity of interphase heat transfer, W/m^2
Re	Reynolds number, dimensionless
S	segregation index, dimensionless
t	time, s
T	temperature, K
V, v	velocity, m/s

Greek letters

α	volume fraction, dimensionless
β	drag force coefficient, dimensionless
Δp	pressure drop, Pa
ε	turbulent dissipation rate, m^2/s^3
ρ	density, kg/m^3
μ	dynamic viscosity, shear viscosity, Pa·s = N·s/m^2
φ	specularity coefficient, dimensionless
τ	shear stress, N/m^2

Subscripts

0	initial value at $t = 0$
bio	biomass phase
bulk	bulk phase
g	gas
i	general index
mf	minimum fluidization
s	solid
sand	sand phase
w	wall

homogeneity or mixing behavior of binary mixture of solids has generally been characterized by the mixing index or segregation index. To date, various expressions of mixing index have been proposed by many authors [5–8].

A large number of experiments have been made to characterize the segregation/mixing of solid mixtures in gas-solid fluidized beds [9–13]. Oliveira et al. [13] investigated the effect of particle size on the hydrodynamics of binary mixtures composed of different types of biomass and sand. They reported that the higher diameter ratios of sand/biomass led to more noticeable bed segregation or the reduction in the fluidization quality. Besides experimental researches, various numerical studies on the hydrodynamics of multiphase FBRs have been performed [3,4,7,14–17]. The major emphasis of those studies was put on elucidating the segregation and mixing mechanisms of solid particles in dense gas fluidized beds. Gibilaro and Rowe [14] were the pioneers who developed a simple model (G-R model) describing the particle segregation in a binary mixture of solids. Accordingly, Bilbao et al. [15] adapted the G-R model to predict the hydrodynamics of a non-steady fluidized bed consisting of sand and straw. Sun et al. [16] applied a multi-fluid model (MFM) based on the kinetic theory of granular flow (KTGF) to investigate the flow behavior of a binary mixture of sand/rice husk particles in a BFB. They found that the superficial gas velocity, the particle size and the mass fraction of sand particles had considerable influences on the segregating behavior of rice husk particles. Sharma et al. [17] used both two-dimensional (2-D) and three-dimensional Eulerian MFMs to describe the hydrodynamics of a biomass/bio-char mixture in a BFB. They found that an increasing of superficial gas velocities resulted in the better mixing of the solid phases in the fluidized bed.

In relation to momentum transport, the heat transfer in fluidized beds has also been an important aspect of concern in this field. Three main thermal processes in gas-solid fluidized beds referred to wall-to-bed, gas-to-particle and particle-to-particle heat transfer, have been widely studied over the years for different cases, using different approaches. Schmidt and Renz [18] used both the Eulerian approach and the KTGF to predict the fluid dynamics and the influence of bubbles on the heat transfer in a gas-solid fluidized bed. Their results showed a strong relation between the local distribution of solid volume fraction and heat transfer coefficient (HTC). Armstrong et al. [19] conducted an extensive parametric study for different restitution coefficients, particle sizes and inlet velocities in a heated wall bubbling fluidized bed (BFB) using the two-fluid Eulerian model coupled with the KTGF. Two drag models, namely Gidaspow model and Syamlal-O'Brien model, were compared to determine its effects on the particle distribution and the wall-to-bed heat transfer. In addition, heat transfer and hydrodynamics of an unsteady gas-solid flow at different superficial gas velocities were described by the Eulerian MFM, incorporated with the KTGF and the standard $k-\varepsilon$ turbulence model [20–22]. A series of investigations based on the dynamics of biomass particles in BFB reactor were performed by using a combination of an Euler approach for the nitrogen gas and sand phases and a Lagrange approach for the biomass particle [2,23,24]. Accordingly, the fluid-particle interaction and the influences of biomass particle size, shape and heat transfer conditions on pyrolysis of biomass in a laboratory-scale FBR were reported.

Because of the lack of comprehensive understanding, the design of industrial FBRs for the biomass pyrolysis was primarily based on empirical correlations and experiments in laboratory and pilot-scale units. Whereas the measurement of important physical variables in either reactive or non-reactive fluidized beds is still a challenge due to the dense flow of particles and extremely high temperature, a well-defined multiphase flow model should be an alternative technique for investigating the role of the key parameters in our processes of concern.

The main objective of this study was to provide a better understanding of biomass pyrolysis with an emphasis on the solid particles behavior and associated heat transfer mechanisms that occur during pyrolysis process. In addition, an extensive parametric study was carried out for a variety of the major influences, such as inlet gas velocity, drag models, mixture composition, and biomass/sand size ratio to determine their effects on the flow distribution and hence the heat transfer performance. These works were mainly based on