Available online at www.sciencedirect.com
SCIENCE DIRECT
Fuel 84 (2005) 1739–1748
FUEL
www.fuelfirst.com

Simulation and experiment of segregating/mixing of rice husk–sand mixture in a bubbling fluidized bed

Sun Qiaoqun[a], Lu Huilin[a,*], Liu Wentie[a], He Yurong[a], Yang Lidan[a], Dimitri Gidaspow[b]

[a]*Department of Power Engineering, Harbin Institute of Technology, School of Energy Science and Engineering, Harbin 150001, China*
[b]*Department of Chemical and Environmental Engineering, Illinois Institute of Technology, IL 60616, USA*

Received 28 May 2003; accepted 30 September 2004
Available online 8 December 2004

Abstract

The fluidization behavior of rice husk–sand mixture in the gas bubbling fluidized bed is experimentally and theoretically studied. The relevancy of the pressure drop profile of rice husk–sand mixture to the definition of its minimum fluidization velocity is discussed, and the minimum fluidization velocity of rice husk–sand binary mixture is determined. The distributions of mass fraction of rice husk particles along the bed height are measured, and the profiles of the mean particle diameter of mixture are determined. A multi-fluid gas–solid flow model is presented where equations are derived from the kinetic theory of granular flow. Separate transport equations are constructed for each of the particle classes, allowing for the interaction between particle classes, as well as the momentum and energy are exchanged between the respective classes and the carrier gas. The distributions of the mass fraction of rice husk particles and the mean particle diameter of binary mixture are predicted. The numerical results are analyzed, and compared with experimental data.

Keywords: Sand-rice husk mixture; Kinetic theory of granular flow; Segregation; Fluidization

1. Introduction

Biomass is an important renewable energy resource. It not only has a wide distribution, but also abounds in quantity [1,2]. Gasification of biomass-agriculture and forest residues in fluidized bed-reactors is widely used for obtaining producer gas, synthesis gas and chemicals like methanol, etc. [3–5]. The rice husk is the outer cover of the rice and on average it accounts for 20% of the paddy produced, on weight basis. Experimental results indicate that fluidized bed combustion technology seems to be the suitable technology for converting a wide range of agricultural residues into energy due to its inherent advantages of fuel flexibility, low operating temperature and isothermal operating condition [6]. The fluidization characteristics of biomass materials are very important for the modeling and design of the reactors. However, biomass cannot be easily fluidized alone due to their peculiar shapes, sizes and densities. For proper fluidization and processing in the reactor, a second solid, usually an inert material like silica sand, alumina, calcite, etc. is used to facilitate fluidization of biomass. It also acts as a heat transfer medium in the reactor. The fluidization of sand and biomass mixtures is characterized by particles of different shapes, sizes, densities and compositions. Rao et al. [7] studied on the fluidization of mixtures of sands and biomass of rice husk, sawdust and groundnut shell powder to determine the minimum fluidization velocity in a fluidized bed. These experimental results show that, in general, it is difficult to fluidize rice husk, and its fluidization behavior improves when it is mixed with other solid particles.

Mixtures of solid particles of different size and/or different density tend to separate in vertical direction under fluidized conditions. The nonuniform distribution of the different solid components is caused by a competitive action of mixing and segregation mechanisms. The component that tends to sink at the air distributor is referred to as a jetsam, while the component that tends to float on

* Corresponding author. Tel.: +86 10 0451 8641 2258; fax: +86 10 0451 8622 1048.
E-mail address: huilin@hit.edu.cn (L. Huilin).

0016-2361/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.fuel.2004.09.026

Nomenclature

C_d	drag coefficient
d	particle diameter
e	restitution coefficient
$\mathbf{g}$	gravity
g_{sn}	binary radial distribution function
H	bed height
$\mathbf{I}$	unit tensor
L	height
m	mass of a particle
$\mathbf{n}$	normal direction
p	fluid pressure
p_s	solid pressure
q	fluctuating energy flux
Re	Reynolds number
t	time
u	velocity

Greek letters

τ_g	gas stress tensor
τ_s	particle stress tensor
Δh	segment height
θ	granular temperature
μ_g	gas viscosity
μ_s	shear viscosity
ξ_s	bulk viscosity
ε_g	porosity
ε_s	volume fraction of particles
ρ_s	particle density
γ_s	energy dissipation
β	drag coefficient

Subscripts

av	average
dil	dilute
g	gas phase
lam	laminar flow
m	solid phase
max	maximum packing
r	rice husk particles
s	sand particles, silica sand particles

the fluidized bed surface is referred to as a flotsam. Hence, in typical biomass combustion systems with a small amount of biomass fuel particles in a bed of sand particles, the sand will be the jetsam component, and the biomass fuel particles is the flotsam component. Segregation behavior of biomass fuel is of practical importance because the vertical location of biomass fuel influences the in-bed combustion efficiency of volatile matter.

Segregation behavior and minimum fluidization velocity of binary mixture were experimentally studied in bubbling fluidized beds [8–10]. Nienow et al. [11] and Rowe et al. [12] studied the segregation in the bubbling fluidized bed consisting of binary mixtures for both different particle size and density. Ekinci et al. [13] experimented the density and size segregation behavior determined from temperature distributions. Pilar et al. [14] have thoroughly reviewed several investigations reported on the fluidization of mixtures of solids with different particle sizes as well as mixtures of particles of different sizes and densities. Hoffmann et al. [15] experimented the segregation of the different particle sizes and densities of binary mixture in the bubbling fluidized bed. Wang et al. [16] investigated the particle concentration profiles and minimum fluidizing velocity of ternary mixtures. Wu et al. [17] studied the behavior of segregation of particles consisting of equal density, but different sizes. Mohammad et al. [18] reported expermental results of different binary mixtures in a gas bubbling fluidized bed. Marzocchella et al. [19] tested the particle size distribution in the equal density and dissimilar size of binary mixture in a bubbling fluidized bed. Manfred et al. [20] studied the mixing and segregation behavior of spherical solids in a bubbling fluidized bed of silica sand, and the time average segregation patterns of the solid mixtures were obtained from single particle trajectories measured by the particle detection system based on an electromagnetic principle. Formisani et al. [21] reported an experimental study of the fluidization behavior of mixtures of glass beads particles differing in size at various average compositions.

Theoretical analyses of multicomponent particles are available based on extensions of kinetic theory of dense gases, appropriately modified to include the effect of energy dissipations due to inelasticity [22,23]. In all of the aforementioned models, the equipartition of granular energy (the mean kinetic energy due to particle velocity fluctuations) of the respective particle classes is assumed in the derivation of kinetic energy equation of particles. However, this assumption is hold for molecular systems where dissipative effects are absent, and when the mass ratio of the respective particles is moderate. For granular flow of particle mixture, this assumption is inappropriate due to the dissipation associated with the inelasticity of particle collisions. Gidaspow et al. [24] extended the kinetic theory of dense gases to binary granular mixture with unequal granular temperature between the particle phases. The hydrodynamics of binary mixture with different sizes were studied by Mathiesen et al. using a CFD model, and predicted the axial and radial velocity and particle concentrations in a riser [25]. Goldschmidt et al. [26] studied the influence of the restitution coefficient on the segregation behavior of dense gas-fluidized beds based on a multi-fluid Eulerian model. Wachem et al. [27] simulated the flow behavior of gas-fluidized bed with a bimodal particle mixture using a computational fluid dynamics