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Mixing Behaviors of Wet Granular Materials in Gas Fluidized Beds

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***Abstract*—**The mixing behaviors of dry and wet granular materials in gas fluidized bed systems were investigated computationally using the combined Computational Fluid Dynamics and Discrete Element Method (CFD-DEM). Dry particles were observed to mix fairly rapidly during the fluidization process due to vigorous relative motions between particles induced by the flow of gas. In contrast, due to the presence of strong cohesive forces arising from capillary liquid bridges between wet particles, the mixing efficiencies of wet granular materials under similar operating conditions were observed to be reduced significantly.

***Keywords*—**Computational Fluid Dynamics, Discrete Element Method, Gas Fluidization, Mixing, Wet particles

I. Introduction

BIOMASS and coal can be used to generate power and gas, potentially without causing global environmental problems because biomass, unlike conventional fossil fuels, is a carbon-neutral resource. Biomass gasification is the process of converting carbonaceous materials or biomass into gases, such as carbon monoxide and hydrogen through high temperature reactions with steam or oxygen. The gas mixture produced is usually referred to as synthesis gas and can be burnt directly as fuel, converted to methanol and hydrogen or into synthetic fuel. The advantage of biomass gasification is that the synthesis gas produced can be utilized in a more efficient way than burning the original fuel. The reaction is usually carried out in a fluidized bed reactor in the presence of fine catalyst particles and at temperatures of more than 700^{o}C. Apart from using biomass as a carbon source for gasification reactions, various other types of organic compounds can also be used. These include organic waste such as horticultural waste, sewage sludge, municipal waste and even fossil fuels such as coal. Although most gasification reactions are normally carried out using one carbon source, it has been speculated by several researchers that the use of mixtures of carbon sources for gasification reactions may result in synergistic effects that may lead to higher reaction yields and lower production of the by-product known as tar in such processes [1-6].

In co-gasification processes, fluidization of at least two different types of solid particles (such as biomass and coal in the presence or absence of catalyst particles) in a fluidized bed reactor is necessary. Due to differences in sizes and material properties of the different types of solid particles, the fluidization behavior is expected to be different and much more complex than single-species fluidization. This has strong implications for actual co-gasification operations as good contacting and mixing between the various types of particles is essential for efficient chemical reactions.

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A good understanding of the fluidization behavior of such mixtures will be instrumental for optimization of the operating conditions used in such fluidized bed reactors and is important for industrial scale implementations of such operations. In addition, drying operations are also necessary as part of the feed pre-processing stage. This is especially the case with feedstock such as low rank coal, horticultural waste, domestic waste or sewage sludge which contains large quantities of moisture.

In this study, the method of combining Computational Fluid Dynamics (CFD) with the Discrete Element Method (DEM) was used to carry out investigations of the effects of various operating parameters and material properties on mixing behaviors of dry and wet granular materials in a gas fluidized bed. CFD-DEM is a particle-level simulation technique which has been shown to be a useful methodology for simulating various types of granular and multiphase flow processes [7-15]. It resolves motion and forces at the particle level by applying the fundamental Newton's laws of motion to individual particles and thus may provide a mechanistic understanding of complex particulate processes at a more fundamental level. In the following section, the CFD-DEM model applied and physical system of interest will be described.

II. Mathematical Model

A. Discrete Element Method

The molecular dynamics approach to modeling of granular systems, otherwise known as the Discrete Element Method (DEM), has been applied extensively for studies of various aspects of granular behavior. The translational and rotational motions of individual solid particles are governed by Newton's laws of motion:

$$m_i \frac{dv_i}{dt} = \sum_{j=1}^{N} \left(f_{c,ij} + f_{d,ij} \right) + m_i g + f_{f,i} + f_{cap,ij} \quad (1)$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{N} T_{ij} \quad (2)$$

where m_i and v_i are the mass and velocity of i^{th} particle respectively, N is the number of particles in contact with i^{th} particle, $f_{c,ij}$ and $f_{d,ij}$ are the contact and viscous contact damping forces respectively, $f_{f,i}$ is the fluid drag force due to an interstitial fluid, $f_{cap,i}$ is the capillary liquid bridge force between wet particles, I_i is the moment of inertia of i^{th} particle, ω_i is its angular velocity and T_{ij} is the torque arising from contact forces which causes the particle to rotate.

Contact and damping forces have to be calculated using force-displacement models that relate such forces to the relative positions, velocities and angular velocities of the

colliding particles. Following previous studies, a linear spring-and-dashpot model was implemented for the calculation of these collision forces. With such a closure, interparticle collisions are modeled as compressions of a perfectly elastic spring while the inelasticities associated with such collisions are modeled by the damping of energy in the dashpot component of the model. Collisions between particles and a wall may be handled in a similar manner but with the latter not incurring any change in its momentum. In other words, a wall at the point of contact with a particle may be treated as another particle but with an infinite amount of inertia. The normal ($f_{cn,ij}$, $f_{dn,ij}$) and tangential ($f_{ct,ij}$, $f_{dt,ij}$) components of the contact and damping forces are calculated according to the following equations:

$$f_{cn,ij} = -\left(\kappa_{n,i}\delta_{n,ij}\right)n_i \quad (3)$$

$$f_{ct,ij} = -\left(\kappa_{t,i}\delta_{t,ij}\right)t_i \quad (4)$$

$$f_{dn,ij} = -\eta_{n,i}\left(v_r \cdot n_i\right)n_i \quad (5)$$

$$f_{dt,ij} = -\eta_{t,i}\left\{\left(v_r \cdot t_i\right)t_i + \left(\omega_i \times R_i - \omega_j \times R_j\right)\right\} \quad (6)$$

where $\kappa_{n,i}$, $\delta_{n,ij}$, n_i, $\eta_{n,i}$ and $\kappa_{t,i}$, $\delta_{t,ij}$, t_i, $\eta_{t,i}$ are the spring constants, displacements between particles, unit vectors and viscous contact damping coefficients in the normal and tangential directions respectively, v_r is the relative velocity between particles and R_i and R_j are the radii of particles i and j respectively. If $\left|f_{ct,ij}\right| > \left|f_{cn,ij}\right|\tan\phi$, then 'slippage' between two contacting surfaces is simulated based on Coulomb-type friction law, i.e. $\left|f_{ct,ij}\right| = \left|f_{cn,ij}\right|\tan\phi$, where tan ϕ is analogous to the coefficient of friction.

B. Computational Fluid Dynamics

The motion of the continuum gas phase is governed by the Navier-Stokes equations with interphase interactions taken into account as an additional source term in the momentum equation. According to the local averaging technique, the continuity and momentum equations are expressed in terms of local mean variables over each computational cell:

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot \left(\varepsilon u\right) = 0 \quad (7)$$

$$\frac{\partial\left(\rho_f \varepsilon u\right)}{\partial t} + \nabla \cdot \left(\rho_f \varepsilon u u\right) = -\varepsilon \nabla P + \nabla \cdot \left(\mu_f \varepsilon \nabla u\right) + \rho_f \varepsilon g - F \quad (8)$$

where u is the velocity vector, ε is the local average porosity, P is the fluid pressure and F is the source term due to fluid-particle interaction.

C. Fluid Drag Force

In a multiphase system, interactions between the two phases take the form of fluid drag forces on the solid particles exerted by the interstitial fluid and arise from velocity differences between the two phases. In this study, the model due to Di Felice [16] which is applicable over a wide range of particle Reynolds numbers was used for evaluating the fluid drag force:

$$f_{f,i} = f_{f0,i}\varepsilon_i^{-(\chi+1)} \quad (9)$$

$$f_{f0,i} = 0.5 c_{d0,i}\rho_f \pi R_i^2 \varepsilon_i^2 \left|u_i - v_i\right|\left(u_i - v_i\right) \quad (10)$$

$$\chi = 3.7 - 0.65\exp\left[-\frac{\left(1.5 - \log_{10} \mathrm{Re}_{p,i}\right)^2}{2}\right] \quad (11)$$

$$c_{d0,i} = \left(0.63 + \frac{4.8}{\mathrm{Re}_{p,i}^{0.5}}\right)^2 \quad (12)$$

$$\mathrm{Re}_{p,i} = \frac{2\rho_f R_i \varepsilon_i \left|u_i - v_i\right|}{\mu_f} \quad (13)$$

where $f_{f0,i}$ is the fluid drag force on particle i in the absence of other particles, χ is an empirical parameter, ε_i is the local average porosity in the vicinity of particle i, $c_{d0,i}$ is the drag coefficient, $\mathrm{Re}_{p,i}$ is the Reynolds number based on particle diameter, ρ_f is the fluid density, μ_f is the fluid viscosity and u_i is the fluid velocity of the computational cell in which particle i is located.

D. Liquid Bridge Force

Following Mikami et al. [17], the capillary liquid bridge force between wet particles is calculated according to the following equations:

$$\hat{f}_{cap,ij} = \exp\left(A\hat{h}_c + B\right) + C \quad (14)$$

For particle-particle liquid bridge force,

$$\hat{h}_c = \left(0.62\theta + 0.99\right)\hat{V}^{0.34} \quad (15)$$

$$A = -1.1\hat{V}^{-0.53} \quad (16)$$

$$B = \left(-0.34\ln\hat{V} - 0.96\right)\theta^2 - 0.019\ln\hat{V} + 0.48 \quad (17)$$

$$C = 0.0042\ln\hat{V} + 0.078 \quad (18)$$

For particle-wall liquid bridge force,

$$\hat{h}_c = \left(0.22\theta + 0.95\right)\hat{V}^{0.32} \quad (19)$$

$$A = -1.9\hat{V}^{-0.51} \quad (20)$$

$$B = \left(-0.016\ln\hat{V} - 0.76\right)\theta^2 - 0.12\ln\hat{V} + 1.2 \quad (21)$$

$$C = 0.013\ln\hat{V} + 0.18 \quad (22)$$

where $\hat{h}_c = h_c/R_i$, $\hat{V} = V/\pi R_i^3$, $\hat{f}_{cap,ij} = f_{cap,ij}/\pi R_i \gamma$, h_c is the critical rupture distance between particles, V is the liquid bridge volume, γ is the surface tension and θ is the contact angle.

E. Simulation Conditions

The geometry of the computational domain considered in this study was a fluidized bed with a rectangular base measuring 64 mm × 8 mm and height of 800 mm. The granular materials consisted of 25000 spherical particles with diameter 1.0 mm and density 2500 kg m^{-3}. Other pertinent simulation parameters are presented in Table 1. In all simulations performed, particles were first allowed to settle freely under

gravity for 0.5 s and form a packing at the bottom of the container before fluidizing air was initiated. A uniform fluidization gas velocity was applied at the base of the computational domain to simulate a uniform gas distribution.

III. Results and Discussion

Fig. 1 shows the result of a computer simulation conducted using the CFD-DEM approach to investigate mixing behaviors during fluidization of dry solid particles. The particles were segregated into two layers by their initial positions within the bed and differentiated by their colors in the simulation snapshots.

TABLE I
MATERIAL PROPERTIES AND SYSTEM PARAMETERS

Number of particles	25000
Particle diameter	1.0 mm
Particle density	2500 kg m^{-3}
Coefficient of restitution	0.9
Coefficient of friction	0.3
Surface tension, γ	0.073 N m^{-1}
Contact angle, θ	0 rad
Gas density	1.205 kg m^{-3}
Gas viscosity	1.8×10^{-5} N s m^{-2}
Simulation time step	10^{-6} s

It may be observed that at the particular fluidizing velocity of 1.6 m s^{-1} applied, the two layers of particles were re-distributed rapidly and good mixing was achieved after a short period of fluidization. Such behaviors may be attributed to the presence of vigorous relative motions between particles that were induced by the flow of gas through the granular bed.

In contrast, Fig. 2 shows that mixing efficiencies were significantly reduced in the presence of a small amount of wetness. Due to the formation of large agglomerates of wet particles within which relative motions between individual particles were severely limited by the presence of strongly cohesive capillary forces, mobility of individual particles throughout the entire fluidized bed that was fundamentally important for mixing to occur became reduced significantly. This will have important implications for the eventual designs of fluidized bed systems for co-gasification processes whose feedstock comprise mixtures of wet granular materials.

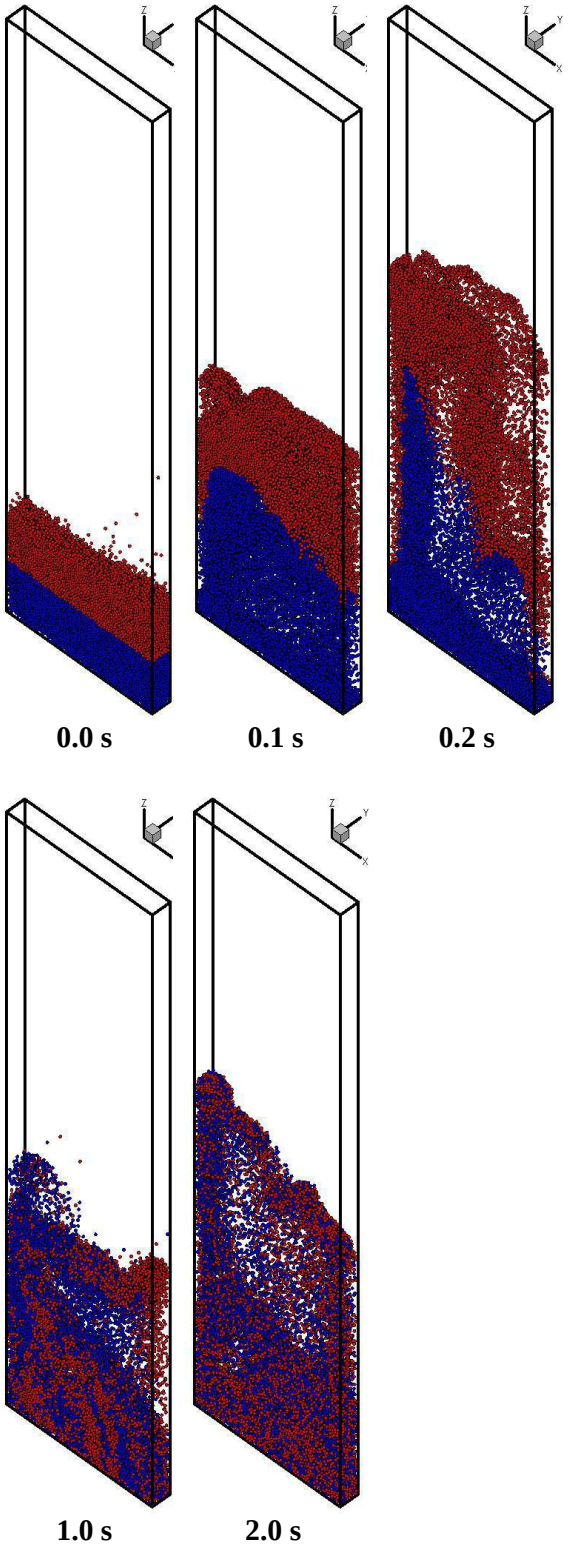

Fig. 1 Mixing behavior of dry particles in a gas fluidized bed. The fluidization velocity applied was 1.6 m s^{-1}

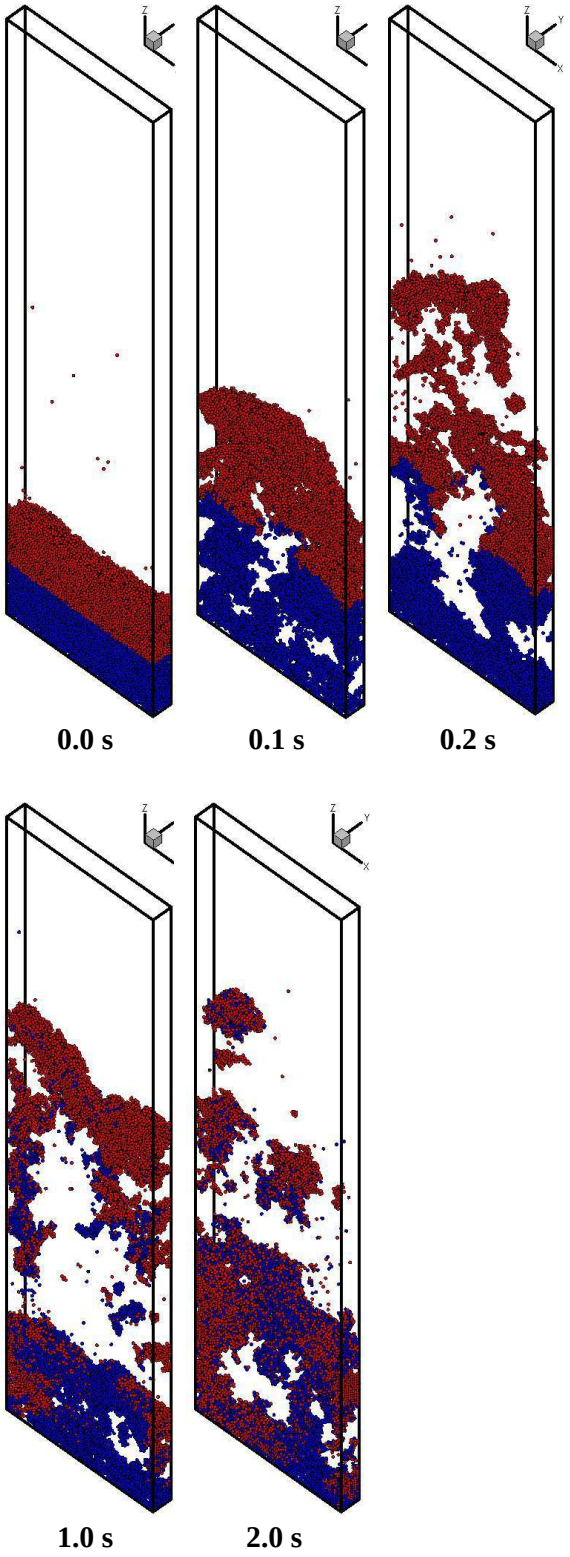

Fig. 2 Mixing behavior of wet particles in a gas fluidized bed. The fluidization velocity applied was 1.6 m s^{-1}

IV. Conclusions

Computational studies of mixing behaviors of both dry and wet granular materials in gas fluidized bed systems were conducted in this study. It was observed that mixing efficiencies of wet particles were reduced significantly in comparison with those of dry particles due to the presence of strong capillary forces which impeded relative motions between particles. Methods of improving mixing efficiencies in such systems, such as through different methods of air injection and varying the geometry of the fluidized bed system are possible subjects of future studies.

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