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# Hydrodynamic characteristics of gas-irregular particle two-phase flow in a bubbling fluidized bed: An experimental and numerical study

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ABSTRACT

In practical applications, the particles in a bubbling fluidized bed are usually irregularly shaped. The gas–solid flow behavior of black millet particles with ellipsoidal shape was numerically and experimentally investigated. In the present work, a two-fluid model with a modified Gidaspow drag model has been built in a gas–solid bubbling bed to investigate the flow behavior of particles with irregular shape. Particle sphericities are taken into account in the Gidaspow drag model, which is a significant factor affecting the flow behavior of irregularly shaped particles. Particle concentration and velocity distribution were studied at various inlet superficial gas velocities and initial bed heights. Numerical results were compared with experimental results obtained by PIV (Particle Image Velocimetry). It is shown that the simulation results using the modified Gidaspow drag model are in better agreement with the experimental results than using the original one, which indicates that the modified Gidaspow model is better suited for irregularly shaped particles.

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## 1. Introduction

Fluidized beds have a wide application in the fields of petroleum, chemical engineering, energy, environmental protection, pharmacy, food processing and so on. Whether in practical applications or theoretical research, the bubbling bed has been one of the most important research points for those involved in the field. In practical applications, the particles in a bubbling fluidized bed usually are irregularly shaped. Compared with regularly shaped particles, irregularly shaped particles can affect the gas–solid flow behavior of a bubbling fluidized bed. Therefore, research on the hydrodynamics of irregularly shaped particles in a bubbling fluidized bed is meaningful.

Computational fluid dynamics (CFDs), which is a powerful and efficient tool in investigating the gas–solid flow characteristics in a fluidized bed, has been adopted, studied and improved by a number of researchers [1–7]. The two-fluid model (TFM) and the discrete element method (DEM) are the two major approaches. Simulations applying DEM can provide dynamic information that is difficult to obtain by conventional experimental techniques, such as the trajectories of and transient forces acting on individual particles [8,9]. DEM, therefore, is especially prevalent among investigators [10]. With the development of theory and application, more and more attention is paid to the hydrodynamics of irregularly shaped particles in particulate systems with the adoption of DEM.

By comparison with a fluidized bed of spherical particles, Hilton et al. [11] presented the effect of grain shape on the dynamics of a fluidized bed, including increased pressure gradients within the bed and lower fluidization velocities. Applying three dimensional CFD and DEM, Ren et al. [12] investigated the flow of corn-shaped particles in a cylindrical spouted bed with a conical base. Gas–solid flow patterns, pressure drop, particle velocity and particle concentration at various spouting gas velocity were studied. Zhou et al. [13] extended the CFD–DEM approach to consider the fluidization of ellipsoidal particles. Particles with aspect ratios ranging from 0.25 to 3.5, which represented cylinder-type and disk-type shape particles, were used in the simulation. The effect of the aspect ratio on the flow pattern, the relationship between pressure drop and gas superficial velocity, and microscopic parameters such as coordination number, particle orientation and force structure were investigated. Favier et al. [14] put forward a new method of representing non-spherical, smooth-surfaced, axi-symmetrical particles in DEM using model particles comprising overlapping spheres of arbitrary size whose centers are fixed in position relative to each other along the major axis of symmetry of the particle. Chung et al. [15] investigated the convection behavior of non-spherical particles in a vibrating bed using DEM. The proposed DEM adopted the Hertz–Mindlin no slip contact force model to model particle collisions and used the multi-sphere method to exactly represent the shape of paired particles. Moreover, the simulation results were validated with experimental results. Oschmann et al. [16] carried out a numerical investigation of mixing in a model type fluidized bed, which was based on three-dimensional DEM coupled with CFD. Various elongated particle shapes were researched including cylinders, plates and cuboids. What is more, comparisons to spherical particles were conducted.

DEM is capable of providing micro-scale information of complex interactions and reproducing the macro-scale dynamic flow behavior

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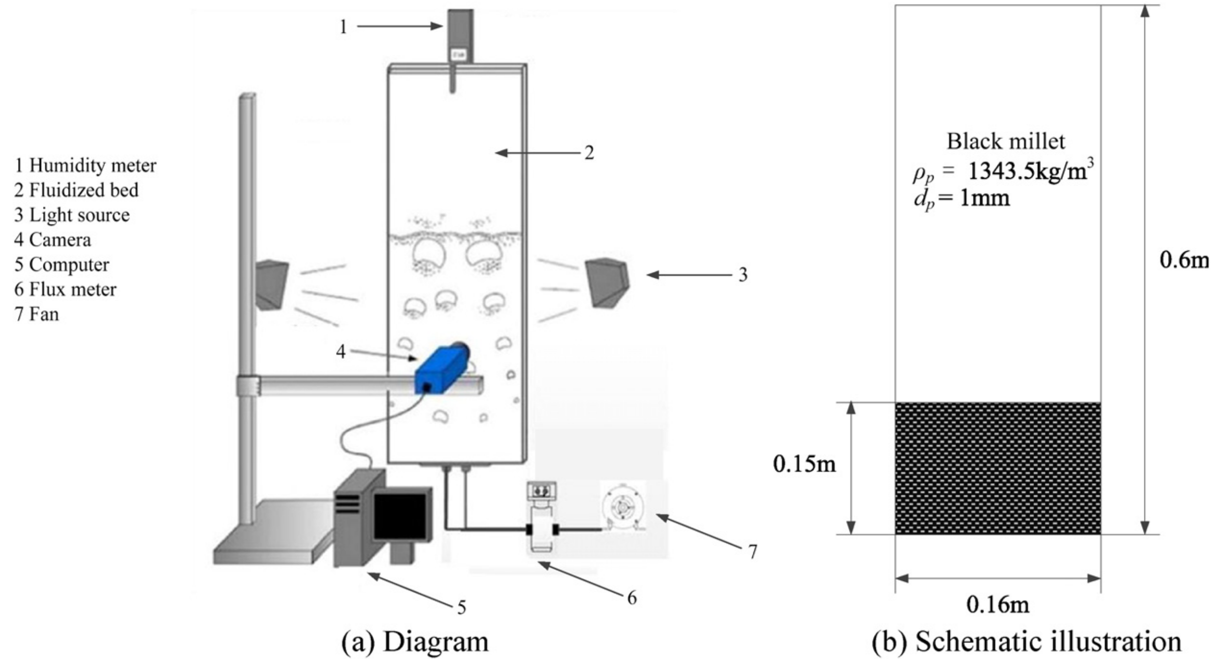


**Fig. 1.** Photograph and schematic illustration of the bubbling fluidized bed.

and is extensively applied in investigations on gas flows. High computational demands are often needed considering the complexity of particle collision models [17–27]. In contrast, TFM is not limited by the particle number and requires less computational demands, and so becomes a more natural choice for hydrodynamic modeling of engineering scale systems [28–30]. To our knowledge, very few investigations on non-spherical particles of gas–solid fluidized beds using TFM have been presented. Marques et al. [31] investigated experimentally the air–carton mixtures flow dynamics in conical spouted beds (CSBs) and presented comparisons with characteristic fluid dynamics obtained by using TFM. The flow behavior of air–carton disks is experimentally investigated by analyzing data of bed pressure drop, air velocity and fountain height. Sau et al. [32] carried out experimental and numerical studies for the hydrodynamics in a gas–solid tapered fluidized bed. Glass beads (spherical) of 2.0 mm and dolomites (non-spherical particles) of 2.215 mm in diameter were used in the work. Experimental results were compared with simulation results applying TFM. Bed pressure drop, bed expansion ratio and solid volume fraction were mainly discussed. Hence, it is of great significance to investigate the influence of particle shape on the hydrodynamics of gas–solid fluidized beds with the adoption of TFM.

In this work, we studied the flow behavior characteristics of black millet particles in a bubbling bed, such as velocity, granular temperature, concentration distribution and so on. The bubble properties including bubble diameter and velocity were also investigated. In the end, we studied the frequency and power spectral magnitude of bed voidage and made a wavelet multi-scale analysis of particle concentration pulsation. After this Introduction, the paper is structured as follows: second part, Experimental method; third part, Numerical method; fourth part, Results and discussion; fifth part, Conclusions; sixth part, Acknowledgments.

## 2. Experimental method

### 2.1. Experimental setup

In a pseudo two-dimensional bubbling fluidized bed constructed of plexiglass ($W \times D \times H = 0.16$ m $\times$ 0.03 m $\times$ 0.6 m), irregularly shaped black millet particles with a density of 1343.5 kg/m$^3$, an average diameter of 1 mm, and particle sphericity of 0.96 were fluidized with air at a superficial gas velocity of 0.6 m/s, 0.7 m/s, 0.8 m/s, 0.9 m/s and 1.0 m/s. Considering the electrostatic interaction between particles and walls of the fluidized bed, the air entering into the bed needed to be humidified. The air was humidified up to a relative humidity of 50–60%. Moreover, we conducted a series of experiments to measure the particle–particle and particle–wall restitution coefficients. The experiments are performed with and without humidified air. The surface of the particles was covered with water by humidifying the air to a relative humidity 50–60%. It was found that the restitution coefficients under the two conditions are nearly the same. So we assume that the effect of water is small in the simulation. Fig. 1a and b gives a diagram and a schematic illustration of the experimental setup used in this work. To ensure the quality of the obtained images, a light with a direct-current power supply was utilized to illuminate the bed. A high-speed digital camera was used to record the images of the bed. Further details of the experimental setup are listed in Table 1.

### 2.2. Particle velocity measurements

A nonintrusive technique, particle image velocimetry (PIV), is applied for the measurement of an instantaneous velocity field in one plane of a flow in a bubbling fluidized bed. No additional tracer particles are needed in gas–particle flows since the discrete particles can readily be distinguished to visualize the particle movement. The flow on the front of the bed is illuminated using a light source. A high-speed digital camera was used to record images of the particles for the illuminated front plane. Two subsequent images of the flow, separated by a short

**Table 1**
Details of the PIV experimental setup.

| | |
|---|---|
| Camera | FlowSense 4M camera |
| Camera frame rate | 15 Hz |
| Pixel pitch | 7.40 μm |
| Camera resolution | 2048 × 2048 pixels$^2$ |
| Particle–particle collision | |
| Restitution | 0.70 ± 0.01 |
| Particle–wall collision | |
| Restitution | 0.70 ± 0.01 |

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