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The characteristics of the near field of the granular jet

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HIGHLIGHTS

- Characteristics of granular jet in quiescent air are investigated.
- Superficial velocity plays an important role in those characteristics.
- Width of jet and thickness of boundary layer linearly grow at first and then remains a constant.
- Vertical velocity profile of boundary layer is agree with parabolic distribution.

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ABSTRACT

This paper investigates the characteristics of the near field of the granular jet (e.g., diameter of granular jet core d_c, width of dispersed jet d, and thickness of boundary layer δ). Through image analysis, we find that particle superficial velocity has an important influence on those characteristics. In addition, d and δ linearly grow with the distance from the nozzle exit at first and then remain constant; this phenomenon differs from that in a single-phase jet. The vertical velocity field of the two sides of the jet core is directly obtained by particle image velocimetry. The calculation results suggest that the velocity profile of the boundary layer near the nozzle exit is a parabolic distribution.

1. Introduction

Entrained-bed pulverized coal gasification technology is a promising coal gasification technology for integrated coal gasification cycle combination. One of the most crucial issues in the pulverized coal gasification process is dense particle dispersion. Research on dense particle jet or granular jet is of great importance to guide the design of gasifiers and other industries [1–5].

Properties of granular materials are often different from those of conventional solids, liquids, and gases because of the dissipative nature of forces acting on interacting grains, including inelastic collisions and friction [6–8]. Granular flows can have a liquid-like appearance in many situations, such as the falling of granular jets under the influence of gravity [9,10]. Earlier studies on granular jet offer useful insight into the nature of granular flows, and understanding of the interactions between grains and other influencing factors can guide equipment design [11,12].

Experiments and molecular-dynamics simulations have been carried out to capture the flow characteristics of granular jet [10,13–15]. Surface tension can drive the instability of liquid jets and formation of drops. Experimental evidence proves that clusters similar to the drops can be found in granular jet falling without surface tension [16]. This observation may be driven by an unknown factor; an effective granular surface tension was used to illustrate capillary instability and other instabilities [13,17]. Amarouchene et al. [13] and Duran [17] pointed out that interstitial air is the origin of "surface tension." Although ambient air plays an important role in capillary instability, Möbius [14] found that clustering is observed even when the ambient pressure is 1/5000th atm. Their observation proved that ambient air is not necessary for the formation of clusters in granular jets. Royer et al. [10] observed the full evolution of cluster instability. They used a high-speed camera to capture the characteristics of free-falling granular jet and employed an atomic force microscope to measure the cohesive forces between grains. Their experimental results revealed that cohesive forces, including Van der Waals and liquid bridge forces, are the origin of cluster formation.

Analogous to liquid, the granular jet has been studied by many researchers as reviewed above. It has been investigated as a

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dispersed medium [1,11,12]. When a particle stream is free falling in quiescent air, particles will be entrained into the surrounding air to form a "boundary layer" caused by air turbulence and the relative velocity between particles and air [11]. Dispersion of granular jet by a coaxial air stream, in which the interaction between the granular jet and air is intense, has been investigated in our previous work [2,3]. However, fundamental research in this field is still limited, especially on the dispersion of granular jet in quiescent air. To bridge this research gap and to provide reference to future works, we investigate granular jet in quiescent air by using analogy with pressured atomization. Understanding of the interactions between the particle phase and quiescent air, especially its characteristics, are important to ensure proper design and optimization of the gasifier nozzle.

In the present work, the dispersion of granular jet in quiescent air is investigated using a high-speed camera and Dantec particle image velocimetry (PIV) software. Characteristics of the granular jet, such as granular jet core diameter, width of dispersed jet, thickness of the boundary layer, and vertical velocity of particles in the boundary layer, are investigated. The paper is organized as follows. Section 2 describes the experimental setup and air supply system. Image analysis is presented in Section 3, which gives a comprehensive understanding of the image pre-processing. After describing the image analysis method, experimental results and discussion are presented in Section 4. Finally, conclusions of this study are presented in Section 5.

2. Experimental setup and procedure

A schematic diagram of the experimental arrangement is shown in Fig. 1. The experimental setup consists of an air supply system, a nozzle, a high-speed camera, and a particle feeder. A cylinder provides high-pressure dry air that flows into the particle feeder filled with glass beads. The flux and pressure of dry air are also measured. In the experiments, the glass beads in the feed hopper flow out steadily with air from the nozzle, the structure of which is shown in Fig. 1. This particle-injecting method is similar to that presented by other researchers [18,19]. The diameter of the nozzle is $D = 4.95$ mm. Using a high-speed camera, 1000 images/s are taken (Fastcam, Photron Limited, up to 250,000 images/s and 10^{-6} s exposure time) to record the jet falling. The exposure time of each image is 1×10^{-5} s. MatLab and its Image Processing Toolbox are used to analyze the images.

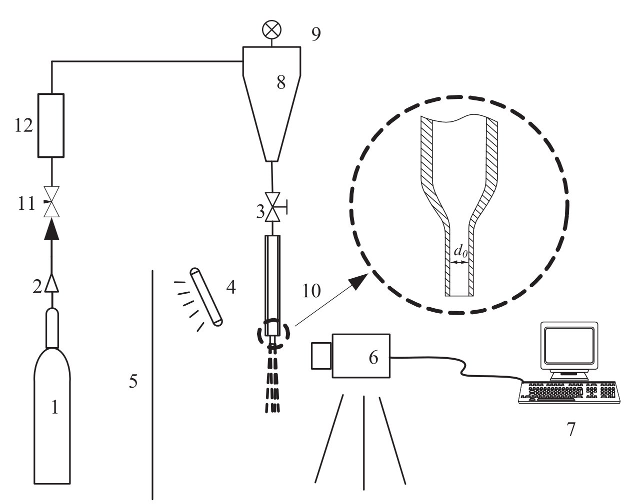

Fig. 1. Flow chart of experimental system. 1 – Steel cylinder; 2 – pressure – relief valves; 3 – valve; 4 – light; 5 – background board; 6 – high-speed camera; 7 – computer; 8 – Feed tank; 9 – pressure gauge; 10 – nozzle; 11 – neddle valve; and 12 – flow meter.

All experiments are performed with quasi-monodisperse $d_p = 125$ μm spherical glass beads (density $\rho_p = 2490$ kg/m^3, bulk density $\rho_b = 1450$ kg/m^3). To minimize the effects of humidity, the samples are dried in an oven. The granular jet mass flow rate in our experiments are $\dot{m} = 5.82,\ 8.56,\ 10.76$ g/s, which correspond to the granular superficial velocities $u_{p0} = 0.21$, 0.31, 0.39 m/s, respectively.

3. Image analysis

Moseler and Landman [20] modeled the evaporation of water molecules from the surface of liquid jet with molecular simulation. Fig. 2 presents the granular jet falling into an open surrounding. As shown in Fig. 2(a), a similar phenomenon, in which air entrainment results in particle dispersion, is also found in granular jet. A Cartesian coordinate axis is established, and the center of the nozzle exit is set as the original point. The diameter of the granular jet core d_c, the width of the dispersed jet d, and the thickness of the boundary layer δ are measured to characterize the particle dispersion for different granular superficial velocities (Fig. 2(b)). The method used to determine the corresponding values of d_c, d, and δ is described as follows.

Each set of images corresponds to 100 pictures taken at a frequency of 1000 Hz. Fig. 3(a) gives an example of a raw picture and the value of gradient in a certain sectional plane. As broad diffused light is used, the granular jet (liquid phase) appears dark, whereas the grain–poor region (gas phase) appears brighter. The value of gradient changes significantly in some regions. The above observation gives new insight to obtain the width of the dispersed jet; the value of the gradient of intensity fluctuates intensely in the grain–poor region but not or only weakly fluctuates in the liquid phase. To simplify the algorithm with a constant gradient threshold, the width of the dispersed jet can easily be calculated. The gradient threshold of 0.02 is used, which is applicable to all test cases. Given the dispersion of particles, the diameter of the granular jet core is difficult to identify (Fig. 2(a)). A phase discrimination algorithm [21] that employs a second-order intensity gradient to identify the boundary of the granular jet core is used. This method is more efficient for distinguishing granular jet core than that using the one-order gradient of image intensity. At the onset, to avoid the erroneous phase discrimination, a Gaussian blur can be applied to each image prior to computation of derivatives. We use an 8-bit integer 5-point blur:

$$I_{i,j}^{new} = \frac{1}{c+4}(cI_{i-1,j} + I_{i+1,j} + I_{i,j} + I_{i,j-1} + I_{i,j+1}), \quad (1)$$

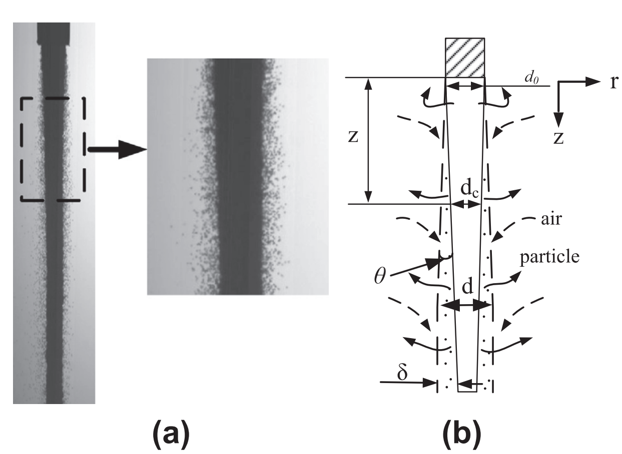

Fig. 2. The near field of the granular jet.