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Experimental investigation on vertical plug formation of coarse particles by a non-mechanical feeder

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ABSTRACT

Plug flow receives attention due to its advantages of low particle attrition, low pipeline wear and low energy consumption. A novel non-mechanical draft tube type feeder (DTF) for plug formation has been proposed in our previous study for vertical plug conveying of coarse particles. We further investigate the influence of key geometry parameter of the DTF on plug formation for different particle diameter. Furthermore, we attempt to extend the application of PIV technique to evaluate plug velocity in pneumatic plug conveying. Experiments for vertical plug formation are conducted with glass beads of three kinds of particle diameter (i.e. 6 mm, 4 mm and 2 mm). Plug formation characteristics are examined in terms of flow pattern in riser pipe, solids mass flowrate and pressure fluctuation. The experimental results show that four main features of plug flow pattern in the riser pipe are observed. Solids mass flowrate displays good linear relation to superficial gas velocity forthe same particle diameter in the plug flow regime, even with different relative entrainment height. Some interesting phenomena are observed for the pressure fluctuation. Plug velocity is successfully obtained by PIV technique with high temporal resolution. The present study provides a further understanding of the flow pattern and dynamic behavior of coarse particles in vertical plug formation with the draft tube type feeder.

1. Introduction

Granular materials are ubiquitous and play an important role in our daily life and in industrial applications [1–3]. The presence of interstitial fluid significantly complicates the dynamics of granular materials [3,4]. Of particular interest here is the particle plugs conveying in a pipeline by air, which may also be regarded as a kind of density waves of granular materials. Low-velocity plug conveying receives continuous interests in recent years, owing to the advantages of low particle attrition, low pipeline wear and low energy consumption [5,6].

Previous studies of plug conveying mainly focused on pressure drop(see e.g.,[7–10]), stress and friction force (see e.g.,[11–14]), plug motion behavior (see e.g., [15–18]), and transport boundaries (see e.g., [19,20]). Little attention was paid to the process of plug formation.

More recently, a novel non-mechanical draft tube type feeder (DTF) for plug formation has been proposed for vertical plug conveying of coarse particles in our previous work [21], which might be used to decrease particle attrition in vertical conveying of absorber spheres in the pebble-bed High Temperature Gas-Cooled Reactor (HTR or HTGR). The concept of the DTF is based on the combination of draft tube technique and local fluidization principle. Particles in the feeder are entrained by gas stream through a draft tube directly into the bottom of the riser for vertical conveying. Plug formation characteristics with a draft tube type feeder were preliminarily investigated by experiments with $d_p = 4$ mm glass beads, including the typical plug flow patterns, solids mass flowrate, pressure fluctuation and stochastic plug length [21]. Detailed particle motion behaviors and plug formation mechanisms in a draft tube type feeder are investigated with $d_p = 6$ mm glass beads by CFD-DEM (Computational Fluid Dynamics - Discrete Element Method) coupling simulation [22]. We have preliminarily discussed the influence of structure parameters, particle properties, and gas phase properties on the DTF performance in our previous work [21]. Due to the complex interaction between particle and fluid, the influence of key parameter of the DTF geometry (i.e. the relative entrainment height) and the effect of particle diameter on plug formation with this non-mechanical feeder are yet unclear. In this study, we further investigate the influence of these two factors on gas-solid flow behaviors during plug formation by experiments.

Plug velocity is a key parameter in pneumatic plug conveying, which plays important roles in pressure drop, flow pattern and particle

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attrition in plug flow. There are only a few experimental data of plug velocity reported in the open publications. The measurement techniques usually used are the tracer particles method [11,23–25] and the camera image method with a common frequency [15,26,27], which only estimate the average plug velocity at a low temporal resolution.

PIV technique is originally used for fluid velocity measurement, which can evaluate the statistical average velocity of particles in an interrogation window at a high temporal resolution [28–30]. In recent years, PIV technique has been extended to evaluate the particle velocities in two-dimensional granular flows [31–34], two-dimensionalgas-solid flows [35–38] and the strain in granular flow [39,40]. However, application of PIV technique to evaluate particle velocity in pneumatic conveying are comparatively few.

Yan and Rinoshika [41] applied high-speedPIV to measure the time-averaged axial particle velocity in a horizontal pneumatic conveying with dune model. Polyethylene particles with diameters of 2.3 and 3.3 mm were used as conveying materials. Ahigh-intensity continuous light source was used to illuminate the light sheet of width 5 mm at the center plane of a pipeline. Rinoshika etal. [42] further employed PIV to measure the distribution of particle fluctuation velocity near the minimum conveying velocity in the acceleration and fully developed regimes in a horizontal pneumatic conveying. Zhang etal. [43] used PIV analysis to obtain the profile of axial particle velocity in a 45°inclined conveying pipe during pneumatic transport of granular matter. The particles used were 2.80 mm polypropylene. The laser light sheet produced by an Nd: YAG laser was introduced from the top of the wall or sidewall to illuminate the granules at the center plane. Nied etal. [44] applied PIV analysis to measure particle velocity in proximity to the wall in horizontal plug conveying with image frames in the range of 120 fps to 160 fps, in which the measurement of temporal and spatial void fraction profiles and to reveal the inner structure of particle plugs by using electrical capacitance tomography were the research focus.

The main purpose of this study is to investigate the influence of the key geometry parameter, i.e. the relative entrainment height, of the draft tube type feeder on vertical plug formation of coarse particles for different particle diameter. Moreover, we attempt to apply PIV technique to evaluate plug velocity with high temporal resolution in vertical plug flow of coarse particles.

2. Experimental

2.1. Experimental apparatus

The experimental system (Fig.1) has been used to investigate the vertical plug formation of coarse particles in our previous work [21]. The gas flowrate is adjusted by electric control valves and bypass pipeline. The gas pressure, temperature and volumetric flowrate before the feeder gas inlet are measured and recorded in a computer by a data acquisition system with a sampling interval of 0.5 s. The superficial gas velocity in the riser (u_g) is converted to 101,325 Pa and 20 °C. It should be pointed out that the flowmeter was calibrated before the experiments, but the display values ($u_{g,dis}$, in unit m/s) were improperly used in the previous work [21]. The superficial gas velocity reported in that work should be corrected to the calibrated one ($u_{g,cal}$, in unit m/s) with $u_{g,cal} = 0.944\ u_{g,dis} - 0.1257$. We noticed this and used the calibrated superficial velocity after that work.

The draft tube type feeder is mainly made of plexiglass for visualization. The internal diameter of the riser pipe (D_r) is 50 mm. The depth from the inside bottom of DTF cylinder to the riser inlet and to the draft tube gas outlet are denoted as H and h, respectively. To investigate the effect of the relative entrainment height ($\Delta h = h - H$) on DTFperformance for plug formation, three values of H at 120 mm, 100 mm and 80 mm (denoted as H120, H100 and H80, respectively) are considered with the h fixed at 150 mm. It corresponds to the relative entrainment height Δh of 30 mm, 50 mm and 70 mm, respectively. The riser pipe consists of two parts. A screw connection is designed to adjust the depth H by replacing the lower part of the riser pipe, while the upper part of the riser pipe is identical (length 0.5 m). The length of the riser pipe (H_r) is 0.93 m, 0.95 m and 0.97 m, respectively.

The coarse particles used in the experiments are smooth glass beads (monodispersed), with particle diameter $d_p = 6$ mm, 4 mm and 2 mm, respectively. The particle density, determined by buoyancy method with an electronic balance (minimum mark 0.0001 g), is 2503 kg/m^3 for each of the three particle diameters. It is in accordance with the particle density of 2518 kg/m^3 measured for $d_p = 4$ mm [21] and 6mm [22] glass beads in the previous work. The particles discharge from an airtight hopper through a pipe into the DTF. The discharge pipe consists of a vertical section, a bend (bend radius 0.3 m) and an inclined section,

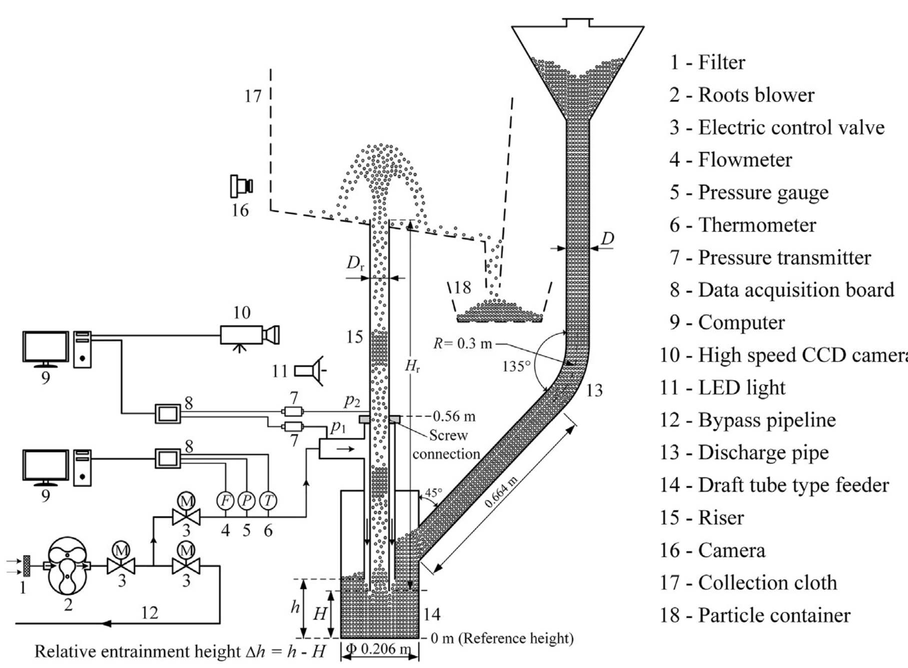

Fig.1. Schematic diagram of the experimental system.