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Experimental study on plug formation characteristics of a novel draft tube type feeder for vertical pneumatic conveying of coarse particles

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ABSTRACT

Plug flow receives attention because of its advantage to reduce particle attrition, pipe wear and energy consumption. A novel non-mechanical draft tube type feeder (DTF) for plug formation is proposed in this study for vertical plug conveying of coarse particles. Particles in the feeder are entrained by gas stream through draft tube direct into the bottom of riser pipe. The plug formation experiments with coarse particles (glass beads particle diameter 4.0 mm) are conducted with this novel feeder. Plug formation characteristics are investigated by solids mass flowrate, high frequency pressure fluctuations and high-speed camera measurements. Power spectral density analysis is used to characterize frequency distribution of the high frequency pressure fluctuations. The experimental results show that natural plug formation is successfully achieved by the DTF for the superficial gas velocity u_g in the range of 4.86 to 10.16 m/s. A "particle cloud" is initially formed by particles entrainment effect in the bottom of riser, then its porosity decreases and length increases by further particles entrainment and pickup to form a plug. The solids mass flowrate shows a good linear relation to the gas mass flowrate. The plug length shows to be stochastic in a certain range around 0.11 m, which is mainly attributed to the natural plug formation characteristics of the DTF. This study provides a natural plug formation feeder for vertical plug conveying of coarse particles. The feeder might be used for high temperature and/or high pressure operation environment in which high reliability is required. It might also be used to simplify the feeding device for vertical plug conveying of coarse particles.

1. Introduction

Pneumatic conveying has been successfully used for industrial loading, unloading and internal transport of bulk solids for many years. The phase diagram depend on gas velocity, particle diameter, geometry of the pipes and mass load of the conveying system [1]. The dilute phase conveying is predominantly used, in which particles are fully suspended in the gas flow. This has the advantage of low pressure fluctuations and high stability, but also suffers from high product degradation, high pipeline wear and high power consumption as a result of high gas velocity. Plug conveying is reached at low gas velocity with high pressure gradient [2,3]. Low-velocity plug conveying has received considerable attention over the last few years, because it causes low particle attrition, low pipeline wear and low energy consumption. The main issues concerned are pressure drop [4–10], friction force [4,11–17], plug motion behavior [18–22] and transport boundaries [23–25].

Solids feeder for plug formation is a key device in pneumatic plug conveying. The pressurized hopper with air knife [2,26,27], the rotary valve [2,8,23,25,27,28] or the screw feeder [12] is generally used to feed solids into the pipeline to form plug. These solids feeders for plug formation usually include mechanical component (e.g. solenoid valve or rotary valve), which is not suitable for application with high reliability requirement. Furthermore, solids feeder for plug formation is usually achieved in horizontal pipe. The development of non-mechanical plug formation device for vertical plug conveying is important for application with high reliability requirement, especially for high temperature and/or high pressure operation environment.

High Temperature Gas-Cooled Reactor (HTR or HTGR) is the Generation IV advanced nuclear reactor, which has the advantages of inherent safety, high efficiency and multiple purpose application potential [29,30]. Absorber sphere pneumatic conveying in pebble-bed HTR is a special application of pneumatic conveying technique in nuclear engineering [31]. It is featured with coarse particles, vertical conveying, high pressure helium gas used as conveying gas and high temperature environment for feeder operation. Our group has studied absorber sphere pneumatic conveying for many years [32]. It is important to decrease particle attrition of absorber spheres during pneumatic conveying process in pebble-bed HTR to decrease maintenance costs. This decrease of absorber sphere attrition might be achieved through low-velocity plug conveying. The high reliability requirements for

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high temperature and high pressure operation environment of absorber sphere conveying in pebble-bed HTR promote the development of non-mechanical feeder for vertical plug conveying of coarse particles.

A new type of non-mechanical plug formation device is proposed in this study for vertical plug conveying of coarse particles. The concept of this plug formation device is based on the combination of draft tube technique and local fluidization principle. Particles in the feeder are entrained by gas stream through draft tube direct into the bottom of riser for vertical conveying. It is named as draft tube type feeder (DTF) in the present paper for convenience.

The main purpose of this study is to investigate the plug formation characteristics for vertical pneumatic conveying of coarse particles by this novel draft tube type feeder. Experiments for plug formation with glass beads of particle diameter $d_p = 4.0$ mm are conducted with this novel draft tube type feeder. The characteristics of solids mass flowrate, pressure fluctuation and plug length are obtained. This type of feeder for plug formation might be used for high temperature and/or high pressure operation environment in which high reliability is required. It might also be used to simplify the feeding device for vertical plug conveying of coarse particles.

2. Experimental

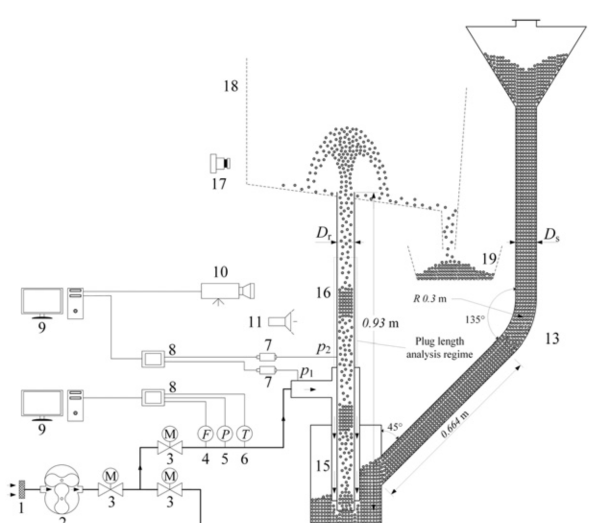
Fig. 1 shows the schematic diagram of the experimental setup. The source gas supplying system has been used to test feeder performance and pressure drop characteristics of dilute phase vertical conveying of coarse particles in our previous work [33,34]. The ambient air is filtrated and blown by the Roots blower to be used as the gas stream for plug formation in this study. The gas flowrate is adjusted by electric control valves and bypass pipeline. The DTF is mainly made of plexiglass for visualization.

The glass beads with particle diameter $d_p = 4.0$ mm and particle density 2518 kg/m^3 are used in the experiments. Particles are discharged from the air-tight hopper through a pipe into the DTF. The discharging pipe is consisted of a vertical section, a bend and an inclined section. The internal diameter of the discharging pipe (D_s) and the riser pipe (D_r) is 60 and 50 mm, respectively. The length of the riser pipe is 0.93 m. The internal diameter of the DTF column is 206 mm. The distance from the bottom of the DTF to the riser inlet and the draft tube gas outlet is 120 mm and 150 mm, respectively. Other main structure parameters of the experimental setup are also given in Fig. 1.

The glass beads are initially loaded into the DTF through flange at the top of the hopper. The total mass of glass beads is 42.3 kg in each loading. The glass beads are collected and weighted after leaving the riser top during stable plug formation. The whole process for particles leaving the top of the riser pipe is recorded by a camera (30 fps). The corresponding time for the collected glass beads is obtained by finding the starting and ending images from the camera record. The mass flowrate of the coarse particles (m_s) is then obtained. The gas pressure, temperature and volumetric flowrate before the feeder gas inlet are measured and recorded in the computer by the data acquisition system with a sampling interval of 500 ms. The gas mass flowrate of the feeder gas inlet (m_g) is then obtained. The superficial gas velocity in the riser (u_g) is converted to 101,325 Pa and 20 °C.

Another high frequency data acquisition system is used to measure the gauge pressure at feeder gas inlet (p_1) and the gauge pressure near the middle of the riser (p_2) with a sampling frequency of 2.5 kHz for each channel. The sampling time is 10 s. Power spectral density (PSD) analysis has been used by Pahk and Klinzing [35] to investigate the relation between pressure fluctuations and various flow regimes in dilute phase pneumatic conveying of polymer pellets. This method is used to characterize frequency distribution of the high frequency pressure fluctuations of the plug formation by the DTF in the present study.

Images of plug flow at the upper section of the riser are recorded by a high speed CCD camera with 1000 fps for the image analysis. The high speed CCD camera and high frequency pressure are simultaneously triggered with hands of one person in the image collection experiments. This is convenient for the subsequent analysis of the relation between pressure fluctuations and plug motion behavior. The camera provides 500 pixel × 1024 pixel resolution at 1000 fps and can continuously record for 5.1 s for these parameters. A centimeter rule is attached near the riser pipe in order to measure the plug length. The flow field of the recorded section is illuminated by a 150 W LED light from the front of the DTF.



1- Filter; 2- Roots blower; 3- Electric control valve; 4- Flowmeter; 5- Pressure gauge; 6- Thermometer; 7- Pressure transmitter; 8- Data acquisition board; 9- Computer; 10- High speed CCD camera; 11- LED light; 12- Bypass pipeline; 13- Discharging pipe; 14- Draft tube type feeder (DTF); 15- Draft tube; 16- Riser; 17- Camera; 18- Collection cloth; 19- Particle container

Fig. 1. Schematic diagram of the experimental setup.