Powder Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Experimental and numerical study of particle velocity distribution in the vertical pipe after a 90° elbow

Yong Lu [a,*], Zhenbo Tong [a], Donald H. Glass [b], William J. Easson [b], Mao Ye [c]

[a] Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, School of Energy and Environment, Southeast University, Nanjing 210096, China
[b] Institute for Materials and Processes, School of Engineering and Electronics, The University of Edinburgh, EH9 3FB Edinburgh, UK
[c] Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, China

ARTICLE INFO

Article history:
Received 28 July 2016
Received in revised form 3 November 2016
Accepted 29 November 2016
Available online xxxx

Keywords:
Pneumatic conveying
Roping
Particle velocity
Laser Doppler Anemometry

ABSTRACT

A major problem of utilizing co-firing technique is controllably distributing fuel mixtures of pulverized coal and granular biomass in a common pipeline. This research related into particle velocity distribution in the vertical pipe after a right angle elbow was undertaken using the Laser Doppler Anemometry (LDA) technique and a coupled computational fluid dynamics (CFD)-discrete element method (DEM) simulation. According to the similarity criterion of Stokes Number, three types of glass beads were used to model the dilute gas-solid flow of pulverized coal or biomass pellets. In the vertical pipe after an elbow (R/D = 1.3, R is the bend radius as 100 mm and D is pipe diameter as 75 mm), a horseshoe shape feature has been found on cross-sectional distributions of the axial particle velocity for all three types of glass beads on the first section which is 15 mm away from the blend exit. At the further downstream sections, the horseshoe-shaped feature is gradually distorted until it completely disappears. The distance for total disintegration is about 300 mm away from the first section for the first type of glass beads, 150 mm away for the second type and 75 mm away for the third one. As for particle number rate, its cross-sectional distribution on the first section shows that a rope is formed at the pipe outer wall where the maximum particle number rate occurs. On the whole, the rope formed by the first type of glass beads can be still observed at the section which is 450 mm away from the first section. For the second type of glass beads, the rope will disintegrate from the section (300 mm away) according to the cross-sectional distributions of the dimensional value of particle axial velocity divided by air conveying velocity. Overall, the roping characteristic is not obviously shown in the gas-solid flow of the third type of glass beads after the first section. All of these indicate that ropes formed from larger particles disperse more easily, for reasons perhaps related to their higher inertia. In addition, CFD-DEM analysis was employed to determine the particle characteristics to confirm this assumption. The numerical results indicated that the flow pattern has the highest axial velocity near the elbow to form the 'horseshoe' pattern. As the particles with lower Stokes Number were easier to follow the air flow, this is the reason why the horseshoe pattern of smaller particles was more obvious than larger particles.

1. Introduction

In co-firing applications, not only is biomass utilized as a sustainable alternative energy source which saves the usage of fossil fuel, but also CO_2 emission can be reduced through keeping the net amount of CO_2 from the biomass neutral or zero-emission in the atmosphere [1,2]. Co-firing biomass with coal in the same installation has been proved to be an important renewables technology, and it has the great economic advantage of re-using the existing infrastructure of power stations. There has been remarkably rapid progress over the past 5–10 years in the development of the co-utilization of biomass materials in coal-fired boiler plants. Biomass co-firing has been successfully demonstrated in over 228 installations worldwide for most combinations of fuels and boiler types in the range 50–700 MW. Among them, more than a hundred of these were in Europe, and there have been over 40 commercial demonstrations in the United States [3–5].

Before burning in a furnace, the mixed fuel of pulverized coal and biomass should be transported by a kind a pneumatic conveying system which uses air to convey granular materials through a pipeline and has been used commercially to transport the pulverized coal for many years in coal-fired power stations. The current existing pneumatic conveying systems should be retrofitted to be suitable for transporting the fuel blend. These modifications include fuel handling, storage and feed systems [6,7].

Since biomass granules have significantly different characteristics from pulverized coal (for instance, biomass has less heating value than that of coals) and are also more fibrous and less dense, these differences

* Corresponding author.
E-mail address: luyong@seu.edu.cn (Y. Lu).

http://dx.doi.org/10.1016/j.powtec.2016.11.050
0032-5910/© 2016 Published by Elsevier B.V.

in properties mean that there are potential problems in storage, bulk handling, feeding, combustion, slagging, corrosion and gaseous emissions. According to their air retention properties, Geldart (1973) classified granular materials into four distinct groups A, B, C and D by using density and mean particle size in his fluidization research. The experimental results of Mills [8] confirmed that the materials in group A have very good retention properties and are suitable to be pneumatically transported either in the dense or dilute phase. Biomass density varies from 100 kg/m^3 for straw to 700 kg/m^3 for forest hard wood and coal density ranges from 1100 kg/m^3 for low-rank coal to 2330 kg/m^3 for high density pyrolytic graphite [9]. The pulverized coal used in modern pulverized coal-fired power stations is normally <110 μm in size. However, the granular biomass consumed in many demonstration co-firing power plants is usually filtered to be <3 mm by a 6 mesh sieve before transportation (NETBIOCOF, 2006) [10]. Considering the blockage risk due to transporting oversize granular biomass mixed with pulverized coal in a common pipe, a more suitable granular biomass should be <1 mm in size (equivalent diameter of a sphere) in case of its density around 300 kg/m^3. This kind of granular biomass can be classified in groups A particles and it is suitable for pneumatic conveying according to Mills (2004) investigation.

In research on co-firing applications, most previous studies focused on combustion issues such as combustion efficiency, pollutant formation, carbon conversion, ash management, corrosion, fuel chemistries associated with blending and other downstream impacts. The relevant literature which focuses on transporting the pulverized biomass and coal fuel supply is particularly sparse. Obviously, dilute pneumatic conveying systems are commonly applied to transport pulverized fuel in most coal-fired power plants and there are also numerous experimental and numerical published papers investigating phenomena like gravity setting, roping, erosion, attrition, pressure-wave propagation and gas-solid turbulence modulation etc. in pipes, understanding of the mechanism of pneumatic conveying is still under development due to its complexity. For example, it is still difficult to measure and control the mass flow rate of a solid phase in a pipe and to distribute gas-solid flow from a main pipe to several sub-pipes at an equal mass rate or a specific ratio (DTI, 2003) [11]. The roping phenomenon is also one of great interest in pneumatic conveying research. It occurs in a bend and results in particles being concentrated within a small portion of one pipe cross-section at the bend, as well as in the pipe downstream of the bend, due to particle inertia [12]. Consequently, it is very important to study the Rope disintegration processing after a bend before dual or triple branches are used to deliver particles in a controllable way to the various burners in a pulverized fuel (PF) boiler.

So far, three previous papers which experimentally study particle dynamics in a vertical pipe behind a pipe bend have been searched. Huber and Sommerfeld [13] who used PDA to study the degree of segregation of glass beads with mean size 40 μm under 14 and 21 m/s air conveying velocity with solid loading ratio 0.5 in a vertical pipe behind an elbow. Their experimental data of particle concentration profile displays the rope locating at the region close to the pipe outer wall and the minimum velocity at the pipe outer wall corresponds to the velocity of the dust rope sliding along the wall. They thought it might be caused by momentum losses from particle-wall and inter-particle collisions. Another two experiments [14,15] were done by using a fibre-optic probe to measure time-averaged local particle velocities, concentration and mass fluxes over cross-sections in a vertical pneumatic conveying line following a horizontal-to-vertical elbow under a range of conveying air velocities and solids mass loadings. The profiles of particle concentration show a high particle mass concentration close to the outer wall (along the x negative axis) for four different fluid conditions.

Therefore our research focuses on investigating the characteristics of transporting biomass/coal blends in a vertical pipe downstream of a 90° elbow by using Laser Doppler Anemometry (LDA). Since biomass particle commonly have more irregular shapes, much larger sizes and kinds of density, it is very complicated to define a biomass particle precisely. In order to in order to address the problem of controllable distribution in co-firing techniques and gain an improved understanding of pneumatic conveying mechanisms, three kinds of glass beads were selected to be simulate the dilute gas-solid flow of pulverized coal or biomass pellets according to the criterion of similarity of Stokes Number in our pilot and pioneer experiments.

2. Experimental setup and measurement

In order to characterize the cross-sectional characteristics of the solid phase in different pipe elements of a dilute pneumatic conveying systems, a pilot scale positive pressure dilute pneumatic conveying system was built which involved horizontal and vertical pipes connected by an elbow (R/D = 1.3). The schematic diagram of the experimental apparatus is shown in Fig. 1. The pipe inner diameter and outer diameter are ϕ75 and ϕ85 mm respectively. The effective length of the horizontal glass pipes is 4 m and the vertical is 2 m long. A T piece is used to connect a screw-feeder with the horizontal pipe and several plastic tubes are used to connect a centrifugal fan and a cyclone. This cyclone is used to separate particles from the air at the end of the system. Then particles separated from air are collected in a storage reservoir for recycling in further experiments. Additionally, every metal connector between the pipes is earthed to reduce electrostatic risk due to particle-wall collisions. Air flow is provided by a centrifugal fan with a maximum 0.05 m^3/s volume flowrate under against a 2.2 KPa back-pressure. Air conveying velocity can vary from 10 to 42 m/s by adjusting the pipe back-pressure and the butterfly valve at the inlet of the fan. The maximum particle mass flow rate of the feeder was experimentally determined to be 1.0×10^{-3} kg/s for glass beads with actual density 2550 kg/m^3 and bulk density 1559 kg/m^3.

Since granular biomass is usually lighter and larger than pulverized coal, the question whether they have any similar characteristic in pipe flow is investigated. Stokes Number (St) is defined as the ratio of particle inertia to fluid drag. It is known that a particle having a small Stokes Number has a good capability of following the fluid. We will use the Stokes Number to classify the similarity between pulverized coal and granular biomass characteristics in the direction of fluid flow and apply the terminal velocity (U_{pt}) for the dimensionless analysis of particle velocities in the gravity direction. The detailed equations for calculating the terminal velocity of a particle are listed in the book 'Processing of Particulate Solids' (Seville J.P.K et al., 1997) [16]. Table 1 shows values of St and U_{pt} for typical samples of pulverized coal, wood chips and glass beads.

Experiments were performed under the dilute flow regime with three different sizes of glass beads and smoke. Three types of glass beads were selected to be transported in pipes by air, which were to simulate the dilute gas-solid flow of pulverized coal or biomass pellets [17]. According to the similarity of Stokes Number among particles shown in Table 1, we assumed that the first type of glass beads (<50 μm) and the second (70– 110 μm) should correspond to pulverized coal within 0– 110 μm, as used in power stations. The third group (180– 300 μm) should represent wood-chips around 1 mm equivalent diameter. The data of their mass median particle size are (39, 96, 267) μm respectively according to the data sheet of glass beads provided by the company Worf Glaskugeln GmbH. In addition, smoke was also used to track the air phase of the flow in the LDA experiments.

The instrument of LDA used to measure three dimensional velocity in experiments is a 3D Dantec LDA system [18] which includes two FibreFlow probes with a front lens of f = 800 mm. One probe combines two pairs of beams with wavelengths of 488 nm (blue) and 514.5 nm (green) respectively. The planes produced by the different colored beams are perpendicular to each other. Another probe was integrated with one pair of 476.5 nm beams (violet). As a result, the 3D particle velocity could be measured simultaneously by using these two probes when three pairs of beams focus on the same point. A 40 M shifting Hz frequency of a Bragg cell is selected to determine the particle velocity

Please cite this article as: Y. Lu, et al., Experimental and numerical study of particle velocity distribution in the vertical pipe after a 90° elbow, Powder Technol. (2016), http://dx.doi.org/10.1016/j.powtec.2016.11.050