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Comparison of pressure drops through different bends in dense-phase pneumatic conveying system at high pressure

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ABSTRACT

In order to investigate the effect material property, bend geometry and location on pressure drop through the bend, experiments of dense-phase pneumatic conveying are carried out at conveying facility with the pressure up to 4.0 MPa. Petroleum coke and anthracite powders with different particle sizes are applied to examine flow characteristics. The empirical correlations of pressure drop through the bend are obtained using Barth's additional pressure theory and multi-variable linear regression. Results show that pressure drop through vertical downward bend is the least, followed by pressure drop through horizontal bend, pressure drop through vertical upward bend is the largest. Powders with larger size need consume more energy than that with smaller size at the same solid loading ratio and conveying velocity as gas–solid mixture flows across the same radius bend. Flow characteristics of petroleum coke and anthracite are analyzed and compared. Pressure drop through the bend with the long radius is greater than that with the short radius. While to unit length, pressure drop of long radius bend is less than that of short radius bend. The empirical correlations of pressure drop through the bend are derived and predicted results agree well with the experimental results. The flow characteristics of the bend offer the theoretical support for design, control and operation of dense-phase pneumatic conveying at high pressure.

1. Introduction

Pneumatic conveying is an important process in the chemical, energy and pharmaceutical industry for transportation of granular particles [1–4]. The aim of these transport systems is to transfer particulate material between storage locations, or to feed different kinds of reactors. One of the advantages of using pneumatic conveying system to transport bulk particulate material, compared to other systems, is the flexibility in routing the pipeline. This often results in transport pipes with many bends, which considerably increase the difficulty in predicting the performance of the system. Bends and elbows play vital roles in giving pneumatic conveying systems considerable flexibility by allowing routing and distribution. Dense-phase pneumatic conveying at high pressure is one of the key technologies in gasification. Because of low velocity, high pressure and high solid concentration in transportation, gas–solid mixture across bend is very unsteady and complicated [5–14]. Pressure drop through bend is seriously affected by bend geometry, location, material property, etc.

The importance of the bend in the design of pneumatic transport systems has been noted by many researchers. Mason et al. [15] apply polyethylene pellets and cement to examine the performance envelope of the pneumatic conveying system and observe the flow regimes of the gas–solid mixture in the pipe. An analytical model is developed to determine the contribution of the solids to overall pressure drop in both straight pipes and bends. Levy and Mason [16] investigate the effect of bend on the distribution of particle in pipe cross section and segregation in pneumatic conveying system using three-dimension numerical simulation. Results show that the presence of a bend causes particles to concentrate around the pipe wall downstream of the bend. The effect of pipe diameter, bend radius ratio and different material properties on flow parameters is examined. Das and Meloy [17] study pressure drop in a close-coupled double bend in pneumatic conveying of fly ash. Pressure drop across two close-coupled 90-degree bends is compared to the pressure drop in an isolated single 90-degree bend. Resulting bend pressure drops are correlated to the corresponding phase density and superficial air velocity at the bend inlet. Under similar flow conditions, the pressure drop in a close-coupled double bend is less than double of that in a single bend. This shows that pressure drop through a close-coupled double bend conveying solid material is not equivalent to the cumulative effect of two single bends. The power correlation relating the pressure drop with superficial air

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Nomenclature

D	internal diameter of pipe, m
d_p	particle mean diameter, m
e	the natural constant, $e = 2.718$
Fr	Froude number
G	mass flow rate, kg/h
g	acceleration of gravity, m/s^2
L	pipe length, m
R	bend radius, m
P_2	receiving tank pressure, MPa
Δp	pressure drop through the bend, kPa
Δp_g	pressure drop due to gas friction, kPa
Δp_s	additional pressure drop caused by solids, kPa
Δp_{sa}	pressure drop due to accelerating the solids, kPa
Δp_{sf}	pressure drop due to solid friction and impact, kPa
Δp_{sh}	pressure drop due to raising and suspending the solids, kPa
Δp_{sh1}	pressure drop due to suspending solid particles, kPa
Δp_{sh2}	pressure drop due to raising solid particles, kPa
Re	Reynolds number
U	superficial gas velocity, m/s

Greek letters

λ_g	resistance coefficient of gas phase
λ_s	resistance coefficient of additional solid phase
μ	solid loading ratio
ρ_g	gas density, kg/m^3
ρ_s	solid density, kg/m^3

velocity and solid loading ratio shows a reasonable agreement with test data. Lee et al. [18] apply polypropylene beads and glass beads to study solid concentration and velocity distribution determination through 90° bend in the pneumatic conveying system. The experimental results show a constant frequency pulsating flow for polypropylene beads in the dense-phase flow regime. For dilute-phase flow regime, both polypropylene and glass beads show a continuous annulus flow structure. Numerical simulation using the Euler–Euler method is also conducted using computational fluid dynamics and the fluid and particle flow characteristics are compared with the experimental data. Wadke et al. [19] use the numerical simulation and experiment to describe variation of aerodynamic forces and particle motion in a dilute horizontal pipe. It is found that the bend causes an increase in mean particle velocity compared with a horizontal pipe. Results show that the number of impacts in the bend decreases as the velocity of the particle increases. The results from the simulation agree closely with the experimental time-of-flight measurements. Mcglinchey et al. [20] develop a model to predict the pressure drop across a 90° bend both in a horizontal plane and in a vertical plane for an extended range of conveying conditions. The model results presented are compared with experimental data gathered from an industrial-scale pneumatic conveying test system. Broad qualitative agreement in trends and flow patterns are found. Chu and Yu [21] use three-dimensional combined continuum and discrete model to investigate flow characteristics in bend. The applicability of the approach is first qualitatively verified by comparing the simulated results with the observations in the literature in terms of typical flow features in bends such as roping, particle segregation, particle velocity reduction, particle recirculation, and pressure fluctuation. The gas–solid, particle–particle and particle–wall interaction forces are then analyzed to understand their roles in governing the complicated flow. Zhou et al. [22] carry out dense-phase pneumatic conveying experiments to reveal pressure drop through the bend. Effects of operating parameters on the pressure drops are examined in dense-phase pneumatic conveying at high pressure. Hanley et al. [23] use macro-scale model to examine the breakage of particles at a 90° bend during dilute phase pneumatic transport. Breakage results if the impact force between the particle and pipe bend exceeds the intrinsic strength of the particle. The latter is taken to be distributed according to the Weibull distribution. Impact force depends on impact velocity and this relationship is obtained by a two-phase structural model of the particle, based on the widely used Kelvin-Voigt model. The impact velocity is distributed as a result of a distribution in particle velocity and in impact angle, though the variability in the latter is shown to be the significant component. Rinoshika [24] studies the effect of the dune model and soft fins in horizontal pneumatic conveying involving a 90° bend. At the upstream of bend and in the bend, the particle velocity of using the dune model is evidently higher than that of the conventional pneumatic conveying and using soft fins. However, the effect of soft fins and dune model on the particle velocity is maintained downstream of the bend. Hidayat and Rasmuson [25] investigate the effects of particle diameter, particle density, particle volume fraction, gas velocity and bend radius ratio on relevant quantities in engineering applications in a U-bend. A small bend radius ratio will produce a faster dispersion of particles, which benefits drying, but on the other hand, will increase the total pressure drop. Thus, optimizing gas velocity and bend radius ratio is important in reducing energy consumption. Laín and Sommerfeld [26] apply Euler/Lagrange approach in connection with the k–ε turbulence model accounting for full two-way coupling to simulate the pneumatic conveying. The structure of the secondary flow developing in the bend is investigated and the influence of the particles as well as inter-particle collisions on the secondary flow structure and intensity is addressed. A detailed analysis of the segregation phenomena occurring in the bend and the influence of the particle phase on the flow structure can be performed by the calculations. Despite numerous studies, both experimental and numerical, have been conducted on different pneumatic conveying systems to characterize the flow behaviors of the solids in bend, most of those researches are mainly carried out to dilute-phase pneumatic conveying at low pressure. Effect of material property, bend geometry and location on the pressure drop through the bend in dense-phase pneumatic conveying is not fully understood at high pressure.

This paper presents a comprehensive study of effect of material property, bend geometry and location on pressure drop through the bend in dense-phase pneumatic conveying at high pressure. A series of cases with powders of different particle sizes and material categories are performed at different gas velocities. Pressure drops through horizontal bend, vertical upward bend and vertical downward bend are examined and compared. Empirical correlations of pressure drop through the bend are derived and analyzed. The findings should be useful not only for establishing a comprehensive understand about the effect of material property, bend geometry and location but also for designing and controlling pneumatic conveying systems.