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Experimental study of the blockage boundary for dense-phase pneumatic conveying of powders through a horizontal slit

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ABSTRACT

The estimation of the blockage boundary for pneumatic conveying through a slit is of significant importance. In this paper, we investigate the characteristics for blockage of powder (48 μm average diameter) through a horizontal slit (1.6 m × 0.05 m × 0.002 m). The results show that the required critical solid mass flow rate increases as the superficial air velocity increases superficial air velocity. The solid loading ratio and superficial air velocity displayed a decreasing power law relationship. This finding agrees with existing theory and experimental results. However, a minimum inlet solid loading ratio exists. When the air velocity is greater than the corresponding air velocity of the minimum solid loading ratio, the solid loading ratio exhibits an increasing trend in power law. We also found that when the inlet conveying pressure increased, the critical solid mass flow rate required for blockage, the inlet solid loading ratio, and the minimum inlet solid loading ratio increased.

Introduction

Blockage is a significant phenomenon in particulate flow (Dai & Grace, 2010). Severe problems may result once blockage occurs, and these can be difficult to alleviate. Therefore, the study of blockage has raised widespread interest (Bharti, Chhabra, & Eswaran, 2007; Chen & Liou, 2011; Maheshwari, Chhabra, & Biswas, 2006; Salama & El-Morshedy, 2012; Umekage, Yuu, Shinkai, & Abe, 1998), especially in the field of pneumatic conveying. Pneumatic conveying is generally divided into two categories, i.e. dense- and lean-phase conveying (Konrad, 1986). Dense-phase conveying is for fine material transportation because of its lower power consumption (Behera, Agarwal, Jones, & Williams, 2012). It is, however, far from perfect, as it may lead to unstable flows, such as slug and dune flow. These unstable flows often result in flow blockage (Rinoshika & Suzuki, 2010). Thus, specific operating conditions for blockage prevention are crucial to ensure the robust running of dense-phase pneumatic conveying systems (Klinzing, Marcus, Rizk, & Leung, 1997).

Many studies have been conducted on unstable flows (Jaworski & Dyakowski, 2007; Li et al., 2005; Lu et al., 2013; McGlinchey, Cowell, & Ryan, 2012). Recently, the minimum transporting boundary for dense-phase pneumatic conveying has attracted substantial attention. Rinoshika, Yan, and Kikuchi (2012) examined the distribution of the particulate fluctuation velocity near the minimum conveying velocity in dense-phase pneumatic conveying. Zheng, Rinoshika, and Yan (2012) performed experiments to investigate the multi-scale features of particulate fluctuation velocity at an air velocity with minimum pressure drop in the acceleration and fully developed regimes. Mills (2004) presented a map of conveying line inlet air velocity versus solids loading ratio to describe the minimum conveying conditions for given materials. Wypych and Yi (2003) proposed a set of models to predict blockage or an unstable boundary based on powder mechanics for the low-velocity slug-flow of granular materials. Mallick and Wypych (2009) initiated a unified set of criteria for scale-up of unstable boundaries for the dense-phase pneumatic conveying of powders. Setia, Mallick, Wypych, and Pan (2013) established a model to predict blockage conditions by using the solid loading ratio and the Froude number at pipe inlet conditions as model parameters. These prior

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Nomenclature

A	slit cross-sectional area, m^2
B	slit width, m
D	equivalent slit diameter, m
g	gravitational acceleration, m/s^2
H	slit height, m
V_s	superficial air velocity, m/s
Fr_i	Froude number, $Fr_i = V_s/\sqrt{gD}$
m_f	air mass flow rate, kg/s
m_s	solids mass flow rate, kg/s
m^*	inlet solid loading ratio, $m^* = m_s/m_f$
P_t	inlet conveying pressure, MPa
$V_{s,min}$	superficial air velocity when the inlet solid loading ratio reaches the minimum.

Greek letter

ρ	air density, kg/m^3

Subscripts

exp	experimental
min	minimum

investigations have contributed substantially to the blockage boundary study of pneumatic conveying systems. However, few studies have reported on blockage problems in the dense-phase conveying of fine material through slits.

Draining gas in gassy coal seams possesses three obvious benefits: it can improve the health and safety of underground workers, it can reduce the impact of gas on the environment, and it can produce a relatively clean-burning energy source (Bibler, Marshall, & Pilcher, 1998; Cheng, Wang, & Zhang, 2011; Karacan, Ruiz, Cotè, & Phipps, 2011; Keim, Luxbacher, & Karmis, 2011). However, in most Chinese coalmines, the methane concentration for drainage is lower than 30% (Wang & Cheng, 2012). Because low-concentration methane cannot be utilized, it is usually released. This study was motivated by the problems of enhancing the methane concentration of underground methane drainage systems through pneumatic conveying technologies.

Because of the effects of borehole excavation, many macro-slits exist in coal seams around the boreholes (Bossart, Meier, Moeri, Trick, & Mayor, 2002; Hawkins, Swift, Hoch, & Wendling, 2011; Souley, Homand, Pepa, & Hoxha, 2001). Outside air passes through these slits into the boreholes and reduces the methane gas concentration. If powders could be transported to the slits using a pneumatic conveying system, the accumulation of powder could block the slits and the gas concentration in the boreholes could be increased (Hu, Zhou, Zhao, Gao, & Xu, 2012; Zhou et al., 2009; Zhou, Xia, Liu, Hu, & Liu, 2011).

Existing studies have focused mainly on the prevention of blockages in dense-phase pneumatic conveying systems. We, however, focus on how to block the slits efficiently. In this work, we have designed an experimental system for the dense-phase pneumatic conveying of fine powders through a horizontal slit. The dynamic powder blockage process was recorded using cameras. The influences of conveying pressure (P_t), superficial air velocity (V_s), and solid mass flow rate (m_s) on powder blockage in the slit have been investigated. The derived variable solid loading ratio (m^*) was also used to determine the blockage behavior in the experimental system. This work can contribute to the economical and efficient blockage of slits.

Experimental

Experimental apparatus

Though various types of rock slits cause blockage, the horizontal slit is the simplest and most common type that occurs in conveying systems. For visualization, Plexiglas plates are often used as fluid flow channels to simulate slits (Bauget & Fourar, 2008; Davies & Desai, 2008; Fourar & Bories, 1995; Qian, Chen, Zhan, & Luo, 2011). The dense-phase conveying system consists of a horizontal slit composed mainly of Plexiglas, as shown in Fig. 1. The horizontal slit is 50 mm high, 2 mm wide, and 1600 mm long. The experimental system also consists of a high-pressure vessel, a pressure regulator, a pressure transmitter, a flow transmitter, a screw feeder, and a dust collector. The high-pressure vessel provides dry air of a certain pressure for the experimental system. The pressure reducer reduces the working pressure in the channel. The pressure of the air source can be reduced to a required degree and the outlet pressure can be stabilized by adjusting the pressure reducer. The throttle valve controls the gas flow by adjusting the throttle section. The pressure gauge and rotor flow meter measure the air supply pressure and gas flow in the channel, respectively. The screw feeder consists of a rotating screw, a coupling component, a drive shaft, and a geared motor. The controlling cabinet controls the speed of the motor, which determines the solid mass flow rate. Table 1 shows the main characteristics of the rosy bentonite powder that was used in this study.

Experimental procedure

In dense-phase pneumatic conveying at an engineering site, the controllable parameters are mainly the inlet conveying pressure (P_t), the superficial air velocity before the entry of a particle (superficial air velocity) (V_s), the solid mass flow rate (m_s), and the inlet solid loading ratio (m^*). In this paper, we focus on the influence of these parameters on powder blockage and provide some guidelines for technological parameters in engineering practice. Because of the limitations of the experimental system, too high or too low a solid mass flow rate will be difficult to control. The range of experimental operating parameters is shown in Table 2. The experimental procedure is as follows:

(1) Close ball valve II, open ball valve I and adjust the pressure reducer so that pressure gauge I indicates the required conveying pressure. Open ball valve II, adjust the throttle valve so that the rotor flow meter indicates the required gas flow rate, and convert the gas flow into the corresponding superficial air velocity. Adjust the control cabinet to start the geared motor at the required velocity and convert the rotating speed into the

Table 1
Material physical properties.

Average particle size (μm)	Particle density (kg/m^3)	Bulk density (kg/m^3)	Moisture (%)	Angle of repose (°)
48	2156	970	6.3	42

Table 2
Range of operating parameters.

Conveying pressure (g) (MPa)	Superficial air velocity (m/s)	Solids mass flow rate (kg/s)	Solids loading ratio
0.06–0.14	4.17–13.89	0.029–0.140	33–106