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Impact of continuous particle size distribution width and particle sphericity on minimum pickup velocity in gas–solid pneumatic conveying

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HIGHLIGHTS

- Three Geldart Group B materials investigated for minimum pickup velocity (U_{pu}).
- As particle size distribution (PSD) width increases, U_{pu} decreases then increases.
- Lower particle sphericity accentuates non-monotonic trend between U_{pu} and PSD width.
- Disagreement with correlations highlights need to understand these two effects.

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ABSTRACT

The minimum pickup velocity (U_{pu}) for pneumatic conveying is analogous to the minimum fluidization velocity (U_{mf}) in fluidization systems in that both dictate the minimum gas velocity required and have important implications in gas–solid flows. However, U_{pu} is not as well-understood as U_{mf}. In this work, the impact of the width of lognormal particle size distributions (PSDs) and particle sphericity (φ) on U_{pu} was determined by the modified weight loss method. Three Geldart Group B materials (namely, glass, aluminum oxide and plastic), with various PSD widths and different particle sphericities (φ), were investigated. Two observations are worth highlighting: (i) as PSD width increases, U_{pu} surprisingly exhibits a non-monotonic behavior (namely, decreases then increases), and (ii) the lower the particle sphericity (φ) is, the greater the extent of the non-monotonic behavior becomes. The discrepancy between the U_{pu} values of the experimental data here and values predicted by available correlations underscores the non-negligible impact of PSD width and particle sphericity, which thereby warrants more understanding and the incorporation of such effects to improve the predictive capability of gas–solid pneumatic conveying.

1. Introduction

Pneumatic conveying is prevalent in operations involving particle transport, because of the operational simplicity, and low capital and operational cost. Pneumatic conveying is employed in various industries like pharmaceutical, oil and gas, and agro-processing. Although pneumatic conveying is an established application in industry, the equipment is often run based on empirical correlations and rules-of-thumb based on experience, rather than scientific principles. Having a mechanistic understanding of minimum pickup velocity (U_{pu}) will allow for more efficient processes to be designed and operated. In addition, attrition and fragmentation of particles are significant problems in industrial pneumatic conveying lines. Hence, if the transport velocity is kept minimum based on knowledge of U_{pu}, particle breakage can be reduced considerably in dilute phase transport systems (Kalman, 2000; Salman et al., 2002). Two notes are worth highlighting: (1) U_{pu} needs to be distinguished from minimum saltation velocity (Zenz, 1964) in that the initial position of the particles is different, although an understanding of both is needed in predicting minimum conveying velocity (Rabinovich and Kalman, 2008). Specifically, the former relates to particles initially at rest, whereas the latter relates to particles initially suspended. Despite the saltation velocity being the more commonly used critical velocity in pneumatic conveying, knowledge of U_{pu} is needed for example in these situations: (i) in dilute flows, whereby a velocity higher than saltation velocity is required, (ii) if particles settle at the pipe bottom

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in cases of process upsets, and (iii) in hydraulic conveying (Rabinovich and Kalman, 2008); and (2) U_{pu} for pneumatic conveying is analogous to the minimum fluidization velocity (U_{mf}) in fluidization systems (Babu et al., 1978; Bourgeis and Grenier, 1968; Ergun, 1952; Saxena and Vogel, 1977; Thonglimp et al., 1984; Wen and Yu, 1966) in that both dictate the minimum gas velocity required and have important implications in gas–solid flows, but the former is not as well-understood as the latter.

Studies on pneumatic conveying systems span characterization of pneumatic flow into various flow modes and its dependence on material properties (Pan, 1999), analysis of axial and radial swirling (Li and Tomita, 2000), transport limitations (Wypych and Yi, 2003), simulations involving shear rate (Stevenson et al., 2002), and comparison of the aptitude of various models (namely, Eulerian, Lagrangian and hybrid) in simulating pneumatic conveying (Pirker et al., 2010). The focus of this work is on the minimum pickup velocity (U_{pu}), which is defined as the gas velocity required to initiate the rolling motion of (Hallow, 1973) or suspend (Kalman et al., 2005) the particle initially at rest on a surface. U_{pu} has been relatively less studied but is an important parameter in the operation of such systems. A semi-empirical correlation was developed by Cabrejos and Klinzing (1992) to predict U_{pu}. Expectedly, the relationship between U_{pu} and particle sizes was observed to be non-monotonic (namely, decreases then increases), because U_{pu} is elevated for small particles whereby cohesive forces dominate and also elevated for large particles whereby inertial forces dominate. Cabrejos and Klinzing (1994) then further developed a U_{pu} correlation as a function of particle size (d_p), particle Reynolds number (Re_p), particle density (ρ_p) and gas density (ρ_g) using dimensional analysis. About a decade later, Hayden et al. (2003) investigated monodisperse Geldart Groups A and C (Geldart, 1973) particles, and observed (i) similarly a minimum in the plot of U_{pu} versus d_p, depending on the relative dominance of cohesive and inertial forces, (ii) that electrostatic forces play an important role for smaller particles (with diameters of 20–40 μm), resulting in an increase in U_{pu}, particularly for the insulating glass particles rather than the conducting stainless steel particles, and (iii) that non-spherical particles in general have greater U_{pu} values than spherical particles, although detailed investigation on the effect of particle sphericity was not reported. Correspondingly, to concentrate on the effects of continuous PSD width and particle sphericity (φ), Geldart Group B particles were investigated in this work.

Subsequently, Kalman et al. (2005) compiled new experimental data along with that found in literature, and defined three zones (I, II and III) for classifying the particles according to different pickup characteristics, which closely correspond to the Geldart classification of particles into four groups (A, B, C and D) according to varying behaviors in bubbling fluidized beds (Geldart, 1973). The zones are classified based on the relationship between the Archimedes number (Ar) and the particle Reynolds number (Re_p^* modified to account for differences in pipe diameters). The resulting curve of Re_p^* versus Ar has been termed the master curve for U_{pu} (Rabinovich and Kalman, 2008). Specifically, particles are classified into the three zones as follows (Kalman et al., 2005):

$$\text{Zone I}: Re_p^* = 5\,Ar^{\frac{3}{7}} \text{ for } Ar \geq 16.5 \tag{1}$$

$$\text{Zone II}: Re_p^* = 16.7 \text{ for } 0.45 < Ar < 16.5 \tag{2}$$

$$\text{Zone III}: Re_p^* = 21.8Ar^{\frac{1}{3}} \text{ for } Ar \leq 0.45 \tag{3}$$

where Re_p^* is the particle Reynolds number modified to account for different pipe diameters (Kalman et al., 2005)

$$Re_p^* = \frac{\rho_f d_p U_{pu}}{\mu_f\left(1.4 - 0.8e^{-\frac{D/D_{ref}}{1.5}}\right)} \tag{4}$$

and

$$Ar = \frac{g\rho_f\left(\rho_p - \rho_f\right)d_p^3}{\mu_f^2} \tag{5}$$

where D_{ref} is the reference pipe diameter of 50 mm. Approximately, Zone I corresponds to the larger Geldart Group B and D particles, Zone II to Geldart Group A, while Zone III to the highly cohesive Geldart Group C.

Earlier U_{pu} work has largely focused on monodisperse particles, or rather has assumed monodispersity and/or has only reported particle size ranges but not the exact particle size distribution (PSD) investigated. However, practical operations are typically polydisperse. More recently, Goy et al. (2011) investigated the effects of binary mixtures of particles belonging to different zones on U_{pu}. For binary mixtures involving only Zone I particles, U_{pu} increases as the mass fraction of the larger particles increases. On the other hand, for binary mixtures of Zones I and II particles, the cohesive effects of the smaller Zone II particles become more dominant and the trend of U_{pu} with respect to mass fraction of each species depends on the particle diameter ratio of the two species. Furthermore, Tay et al. (2012) investigated the effects of ternary mixtures (i.e., three particle species) on U_{pu} and hypothesized that, up to a limit of 20% by mass of the smallest particles, the smallest particles aid entrainment of the larger particles by occupying the interstitial spaces thereby enhancing the interstitial velocity. A new Re_p^* versus Ar master curve for binary and ternary mixtures was developed based on the Sauter-mean of the mixtures (Tay et al., 2012)

$$Re_p^* = 20Ar^{\frac{1}{4}} \text{ for } 20 \leq Ar_{mixture} \leq 2500 \tag{6}$$

In particular, due to inter-particle interactions, especially the acknowledged inter-particle momentum transfer effects such that smaller particles ease the entrainment of larger particles (Chew et al., 2013; Geldart et al., 1979), U_{pu} is likely a function of a representative particle size. Because Tay et al. have ascertained that the Sauter-mean diameter (Fan and Zhu, 1998; Rhodes, 1998; Yang, 2003), as opposed to other weightings of the mean diameter, is the most relevant parameter in the development of their correlation for binary and ternary mixtures, the work here has also adopted the Sauter-mean diameter in the analyses.

Despite the advances on U_{pu} to date, Gomes and Mesquita (2014) very recently compared various U_{pu} correlations and detected contradictory U_{pu} predictions, which signals the need for improved mechanistic understanding. Hence, this experimental effort aims at revealing the impact of two prevalent and important parameters on U_{pu}, namely (a) the width of continuous (lognormal) particle size distribution (PSD) and (b) particle sphericity (φ). Particles categorized as Geldart Group B were used to avoid the complication of inter-particle cohesive forces, the more extensive effects in smaller (Geldart Groups A and C) particles of which gives rise to the observation of increasing U_{pu} values with decreasing particle size (Goy et al., 2011; Hayden et al., 2003; Kalman et al., 2005). Notably, the development of a new model is beyond the scope of the current effort, whose key focus is instead in experimentally providing new physical insights for the validation of mechanistic models, in order to reduce reliance on empirical correlations. With regards to (a), in view of the prevalence of lognormal PSD and the gap in the knowledge base in this respect, this work investigated the effects of varying widths of continuous (lognormal) PSD of Geldart Group B (Geldart, 1973) particles on U_{pu}. Although previous efforts have investigated polydisperse systems in terms of binary (Goy et al., 2011) and ternary (Tay et al., 2012) particle mixtures, different behaviors have been observed between binary mixtures and continuous PSDs (Chew et al., 2011a, 2011b, 2012, 2013, 2010); hence an understanding on the impact of continuous PSDs on U_{pu} is necessary. Experimental results here reveal a surprising non-