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Impact of particle diameter, density and sphericity on minimum pickup velocity of binary mixtures in gas-solid pneumatic conveying

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ABSTRACT

The impacts of particle diameter (d_p), particle density (ρ_p) and particle sphericity (φ) on the minimum pickup velocity (U_{pu}) of binary mixtures of Geldart group B particles were investigated. Three types of binary mixtures were tested, whereby the two constituents vary in (i) only d_p (i.e., binary-size), (ii) only ρ_p (i.e., binary-density), and (iii) both d_p and ρ_p (i.e., binary-size-density). Notably, there is a lack of data on the pickup characteristics of the latter two types of binary mixtures, although behavioral differences are acknowledged. The minimum pickup velocity, U_{pu}, was experimentally determined by the weight loss method and also derived using a force balance model developed here. The key results were: (1) d_p exerts a more dominant influence on U_{pu} than ρ_p; (2) particle sphericity (φ) has a non-negligible impact on U_{pu}; and (3) a drag and frictional force balance analysis accounting for particle sphericity gives reasonable predictions of U_{pu}, which in turn provides a mechanistic insight on U_{pu}.

1. Introduction

Gas-solid flow is employed in wide-ranging industrial processes, but such operations are still largely dependent on empirical correlations rather than on first principles. Empirical predictions have been found to vary by orders-of-magnitude, hence are limited in the scope of application [1,2]. In order to progress towards first-principles models, more understanding of the impact of polydispersity and particle sphericity is needed. The focus of the current effort is on the minimum pickup velocity (U_{pu}) in gas-solid pneumatic conveying, which has been relatively less studied compared to minimum fluidization velocity, despite its widespread applications spanning pharmaceutical, agro and food processing and petroleum refining industries.

Knowledge of U_{pu} is important in pneumatic conveying operations to minimize energy consumption without causing pipe blockage due to particle deposition on one hand, and reduce erosion and particle attrition or fragmentation on the other [3]. The two commonly used fluid velocities in conveying operations are the minimum pickup velocity (U_{pu}) and the minimum saltation velocity (U_{salt}) [4]. U_{pu} is the minimum fluid velocity required to initiate motion in a particle initially at rest [5], so it is associated with a particle initially at rest. U_{salt} is the critical velocity below which particles will sediment at the bottom of the pipe [6], hence it is associated with particles initially suspended in air [7]. In spite of U_{salt} being the more commonly used critical velocity in pneumatic conveying, it is still necessary to have a knowledge of U_{pu} in cases of process interruptions whereby the particles settle to the pipe bottom, or in hydraulic conveying or fine powder aerosol flow lines [7]. U_{pu} is also essential in other areas such as analyzing the movement of sand dunes and soil deposition in the river and ocean [8], understanding erosion of silt on river beds [9], and in dust control applications [10].

A review of the efforts on U_{pu} is given here in chronological order. One of the earlier efforts on U_{pu} was by Cabrejos and Klinzing [11] who proposed a technique based on visual observation to determine U_{pu}. Particles of diameter (d_p) between 10 and 800 μm were investigated and a semi-empirical correlation involving Reynolds (Re) and Archimedes (Ar) numbers was developed. Notably, U_{pu} was shown to first increase and then decrease with increasing d_p. This was attributed to decreasing inter-particle cohesion in the lower d_p range, and increasing inertial forces in the higher d_p range. Using dimensional analysis, Cabrejos and Klinzing [6] developed a correlation for U_{pu} as a function of particle size (d_p), particle Reynolds number ($\mathrm{Re_p}$), particle density (ρ_p) and gas density (ρ) using dimensional analysis:

$$\frac{U_{pu}}{\sqrt{gd_p}} = 0.0428\mathrm{Re_p^{0.175}}\left(\frac{D}{d_p}\right)^{0.25}\left(\frac{\rho_p}{\rho}\right)^{0.75}. \tag{1}$$

Subsequently, Hayden et al. [12] used Geldart groups A and C particles and studied the effects of particle size, density and shape, and

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electrostatics on U_{pu}. Three key observations were a non-monotonic relationship between U_{pu} and d_p, the effect of electrostatics was more dominant on the insulating glass particles than on the conducting stainless steel particles, and non-spherical particles generally have a greater U_{pu} than spherical particles. However, they did not conduct a detailed investigation on the effect of different particle sphericities (φ) on U_{pu}. Kalman et al. [8] further advanced U_{pu} by classifying particles into three zones, namely, Zones I, II and III, which correspond well with the Geldart classifications of particles in a bubbling fluidized bed [13]. Approximately, Zone I corresponds to Geldart groups B and D, Zone II corresponds to Geldart group A and Zone III corresponds to Geldart group C. The zones were classified based on empirical relationships between the Archimedes number, Ar, and a modified particle Reynolds number $\mathrm{Re_p}^*$

$$\text{Zone I}: \mathrm{Re}_\mathrm{p}^* = 5Ar^{\frac{3}{7}} \ \text{for} \ \mathrm{Ar} \geq 16.5 \tag{2}$$

$$\text{Zone II}: \mathrm{Re}_\mathrm{p}^* = 16.7 \ \text{for} \ 0.45 < \mathrm{Ar} < 16.5 \tag{3}$$

$$\text{Zone III}: \mathrm{Re}_\mathrm{p}^* = 21.8\mathrm{Ar}^{\frac{1}{3}} \ \text{for} \ \mathrm{Ar} \leq 0.45 \tag{4}$$

where $\mathrm{Re_p}^*$ is $\mathrm{Re_p}$ modified to account for the effect of pipe diameter in order to facilitate comparisons between systems with different pipe diameters [8]

$$\mathrm{Re}_\mathrm{p}^* = \frac{\rho d_p U_{pu}}{\mu_f \left(1.4 - 0.8 e^{-\frac{D/D_{ref}}{1.5}}\right)} \tag{5}$$

and Ar is defined as

$$\mathrm{Ar} = \frac{g\rho\left(\rho_p - \rho\right) d_p^3}{\mu_f^2} \tag{6}$$

where D_{ref} is the reference pipe diameter of 50 mm and μ_f is the dynamic viscosity of the fluid. This three-zone classification was later incorporated into a 'generalized master curve' encompassing all critical threshold velocities [14]. Kalman and Rabinovich [15] scrutinized the pickup phenomenon from particle deposits as opposed to pickup from a layer of particles, and noted that U_{pu} from deposits is strongly dependent on the height and shape of the particle heap.

Although particle systems are typically polydisperse in practice, much of the earlier efforts focused on monodisperse systems or only reported d_p ranges without specifying polydispersity. More recently Goy et al. [16] studied the effect of the composition of binary-size mixtures of spherical particles on U_{pu} using two particle species of the same particle density (ρ_p) but different particle diameter (d_p). It was observed that the U_{pu} of binary-size mixtures of particles belonging to the Zone I [8] increased as the composition of the larger species increased, whereas the U_{pu} of binary-size mixtures of particles belonging to different Zones depended on the ratio of the d_p of the constituent species. Tay et. al. [17] measured pickup velocities of ternary-size mixtures and found that the presence of smaller particles as the third species aided the entrainment of binary-size mixtures up to a limit of 20% by mass of the smaller particles. Even more recently, Anantharaman et al. [18], using the more practical lognormal particle size distribution (PSD), found that U_{pu} values were surprisingly non-monotonic (i.e., decreased then increased) with the increase in the width of the lognormal PSD. Collectively, the efforts on polydisperse systems have revealed interesting dynamics related to U_{pu}, but gaps in the knowledge base exist on binary mixtures consisting of non-spherical particles, and binary-density (i.e., the two constituents vary in only ρ_p) and binary-size-density (i.e., the two constituents vary in both d_p and ρ_p) mixtures. This is the focus of the current effort. It should be noted that binary-size and binary-density mixtures have been found to have different gas fluidization behaviors [19–22], hence a corresponding study for pneumatic conveying is warranted.

There is scarce information on the impact of particle sphericity (φ), on U_{pu}. Hayden et al. [12] presented one of the first efforts, which showed that non-spherical particles exhibited a greater U_{pu} than spherical particles. Kalman et al. [8] measured U_{pu} of non-spherical Geldart group D particles and observed discrepancies between the measured U_{pu} values and those predicted by the three-zone model of Eqs. (2), (3) and (4). To account for the effect of particle sphericity (φ), they defined a characteristic Archimedes number (Ar) by modifying Eq. (6) and found that non-spherical particles displayed a lower characteristic Ar than spherical ones. Anantharaman et al. [18] sought to understand the combined effects of varying particle sphericity (φ) and width of lognormal PSDs on U_{pu}, and found that the non-monotonic trend of U_{pu} with respect to PSD width was accentuated as φ increased, as a result of particle rotation and lift effects associated with non-spherical particles [23,24]. With the understanding that φ impacts U_{pu} in continuous PSD systems, this work aims to determine the effect of φ on U_{pu} in binary mixtures.

Gomes and Mesquita [10] took an analytical approach in developing a U_{pu} model. Its utility is, however, limited beyond the specific system investigated, because empirical coefficients (e.g., fractional powers of U) was used to improve the model prediction, and errors of >40% in the model prediction was observed even with their own data. The same authors [25] also recently reviewed all available U_{pu} correlations and found that their model predictions were contradictory. To bridge the gap in the knowledge base on U_{pu}, this study is targeted at investigating binary mixtures with constituents differing in particle diameter (d_p), particle density (ρ_p) and particle sphericity (φ).

2. Materials and experimental methods

2.1. Experimental setup

The experimental unit used, which was identical to that used in previous studies [18,26], is shown in Fig. 1. The unit was made of acrylic pipe of inner diameter 16 mm and it consisted of three horizontal removable sections. Air from a centralized compressed air supply with a maximum airflow rate of 0.001 m^3/s entered the test unit through Section A, while Section C was the outlet connected to a cyclone collector. Sections A and C were 91 cm and 83 cm long, respectively. Section B was 30 cm long and it was split into two semi-cylindrical halves; for the bottom half, a length of 27.5 cm was filled to the brim with a plasticine mold, while the remaining 2.5 cm served as a chamber in which the test particle sample was loaded. The particles were loaded such that the surface of the sample remained flat and of the same height as the plasticine mold. Such a setup ensured a constant cross-sectional area for the air flow throughout the run irrespective of the extent of particle entrainment, which is different from the variable cross-section arrangements used by Cabrejos and Klinzing [11] and Hayden et al. [12].

2.2. Materials

The solid particles used were glass, plastic and aluminum oxide from Abrasive Engineering Pte. Ltd., Singapore. Each particle type was carefully sieved to obtain the required particle diameter (d_p). Particles of three d_p values of each particle type was investigated. The particle sphericity (φ) was determined by the projected image technique, as detailed in an earlier work [18]. The particles in this study belonged to Geldart group B [13], and they were so chosen specifically to eliminate inter-particle cohesive effects. The particle properties, namely, particle diameter (d_p), particle density (ρ_p), and particle sphericity (φ), of the solids tested are given in Table 1. The measured minimum pickup velocity (U_{pu}) values are also provided. For easy reference glass, aluminum oxide and plastic are