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Effect of particle characteristics on particle pickup velocity

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Abstract

Particle entrainment is investigated by measuring the velocity required to pick up particles from rest, also known as pickup velocity. Pickup velocity is a function of individual particle characteristics and interparticle forces. Although 5–200 μm particles are investigated, the work presented here focuses on the pickup of particles in a pile in the size range of 5–35 μm. These smaller particle sizes are more typical for pharmaceutical and biomedical applications, such as dry powder inhalers (DPIs). Pickup velocities varied from 3.9 to 16.9 m/s for the range of particle sizes investigated.

There is a strong correlation between particle size and the dominating forces that determine the magnitude of the pickup velocity. Preliminary data investigating pickup velocity as a function of particle size indicate the existence of a minimum pickup velocity. For larger particle sizes, the mass of the particle demands a greater fluid velocity for entrainment, and for smaller particle sizes, greater fluid velocities are required to overcome particle–particle interactions. Pickup velocity remains relatively constant at very small particle diameters, specifically, less than 10 μm for glass spheres and 20 μm for nonspherical alumina powder. This can be attributed to the negligible changes in London–van der Waals forces due to a hypothesized decrease in interparticle spacing. At intermediate particle diameters, electrostatic forces are dominant.

Keywords: Particle; Pickup velocity; van der Waals forces

1. Introduction

Pickup velocity, or the velocity required to pick up a particle initially at rest, is an effective way to assess the conveying behavior of bulk particles. Pickup velocity is relevant in a wide range of applications. For example, some pharmaceutical areas are beginning to focus on dry powder inhalers for drug delivery. Dry powder inhalers (DPIs) do not require the use of aerosols as propellants. Instead, drug carrier particles are "picked up" from a stationary state by inhalation through a breathing tube. These particles typically have a size range of 30 – 90 μm [1–4]. Because it is necessary to use fine powders for inhalation, several problems must be solved to make drug delivery via DPIs more effective. Spray drying is a common method of producing carrier particles, but the combination of very small particle diameters and irregular particle shape generally leads to poor flow characteristics. Therefore, the successful delivery of drugs using DPIs is dependent upon understanding several physical properties, such as particle size, shape, surface roughness, and cohesiveness. By becoming aware of how these and other parameters affect the flow behavior of powder, the effectiveness of DPIs can be improved.

Pickup velocity is also important for large-scale processes involving the movement of bulk powder through pipelines. A good estimate of the minimum conveying velocity must be known in order to optimize any solid's conveying system. Conveying velocities above what is necessary can lead to wasted energy, particle attrition, and pipe erosion. Velocities that are too low can result in saltation and blockage of the pipeline. Likewise, pickup velocity is an important parameter in dust control applications. Knowledge of the minimum velocity associated with resuspending or preventing settling of dust particulates is essential when designing any dust control system. Other applications of pickup velocity include studying the movement of sand dunes and understanding erosion of silt on riverbeds.

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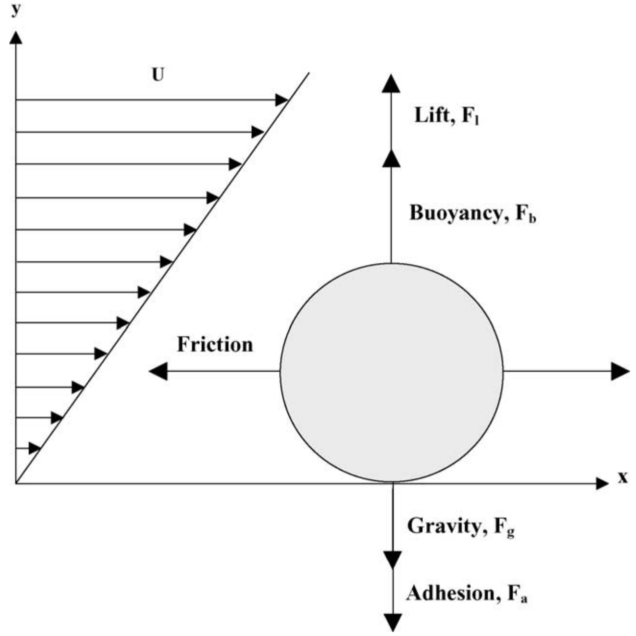


Fig. 1. Forces acting on a single particle in shear flow.

Schlichting and Gersten [5] determined boundary layer thickness, δ, over a flat plate in turbulent flow to be a function of plate length, x:

$$\delta = 5\sqrt{\frac{vx}{U_\infty}} \tag{1}$$

where v is the kinematic viscosity and U_∞ is the free-stream velocity. Particles completely submerged in this boundary layer ($d_p < \delta$) are exposed to a linear velocity profile, and hence experience a shear lifting force. The boundary layer thickness is approximately 2000 μm for the velocity range used for this work, which is much larger than all particle diameters studied. As a result, it is assumed that all particles used in this research experience a shear lifting force. Saffman [6] proposed the lift force, F_l, acting on a single spherical particle in a shear flow field to be:

$$F_l = \frac{Kvd_p^2\kappa^{\frac{1}{2}}\mu}{4v^{\frac{1}{2}}} \tag{2}$$

where v is the fluid velocity, d_p is the particle diameter, κ is the magnitude of the velocity gradient, K is a constant calculated to be 81.2, and μ and v are the fluid viscosity and kinematic viscosity, respectively.

Fig. 1 shows the dominant forces acting on a single particle resting on a flat plate in shear flow. Although Cabrejos [7] showed that horizontal movement occurs before vertical lift-off, pickup velocity is considered to be the velocity at which the particle becomes entrained in the moving fluid, which implies vertical movement. To achieve vertical pickup of the particle, the sum of the upward forces must equal the sum of the downward forces:

$$F_g + F_a = F_l + F_b \tag{3}$$

where F_g is the gravitational force, F_a is the force due to adhesion, F_l is the shear lift force, and F_b is the buoyancy force. For a pile of particles, F_a would represent all attractive forces (electrostatic forces, forces due to liquid bridging, surface forces, etc.) between particles.

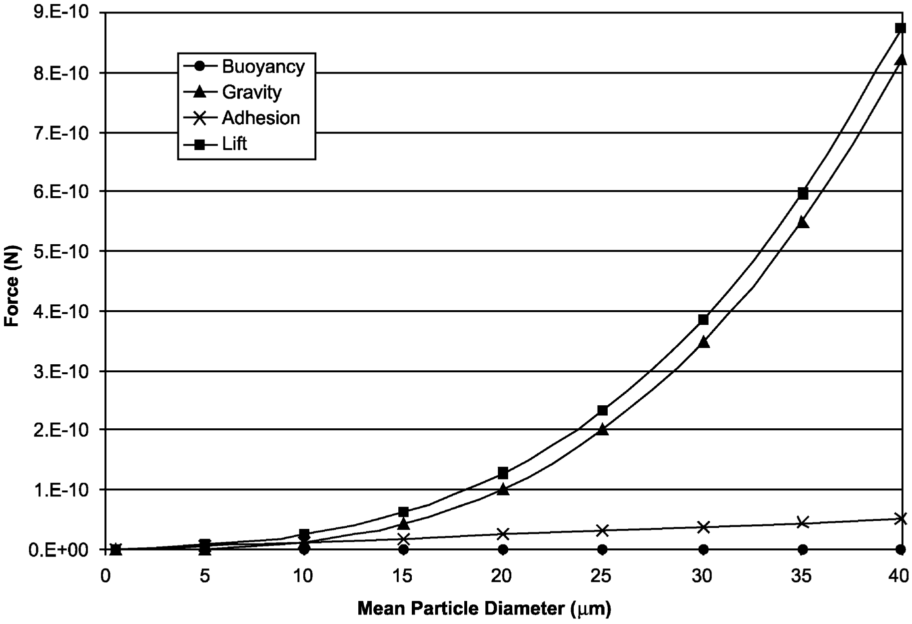


Fig. 2. Forces acting on a spherical glass particle at incipient motion.

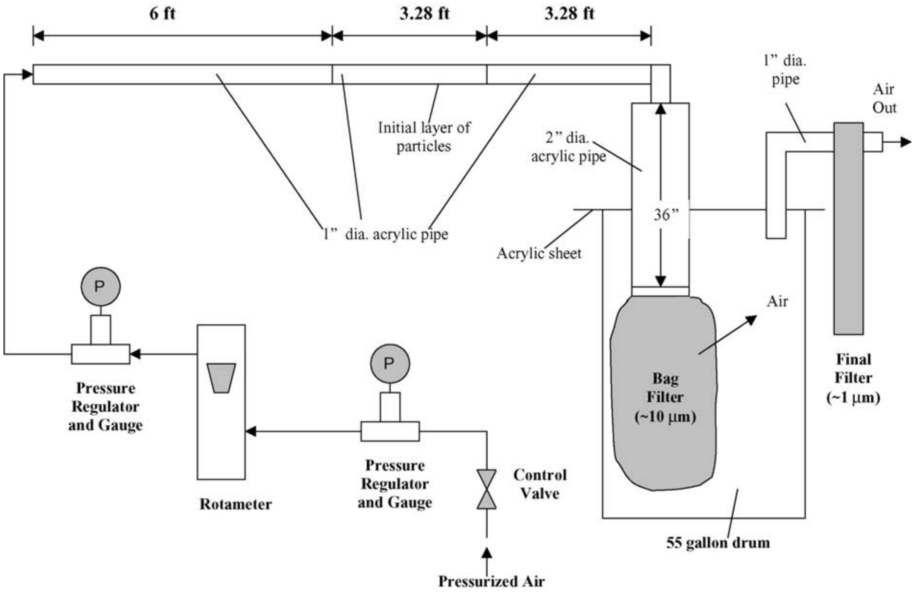


Fig. 3. Pickup velocity experimental set-up.

Rubinow and Keller [8] give the lift force due to rotation of a particle, F_r, to be:

$$F_r = \frac{\pi}{8} d_p^3 \rho_f \Omega x V \tag{4}$$

where ρ_f is the fluid density, Ω is the angular velocity of the particle, and V is the particle velocity. For spin lift to be the same order of magnitude as shear lift, the angular velocity of the particle must be of the order 10^5 s^{-1}. As angular velocities of this magnitude are not expected, the lift force due to particle spin is neglected in the force balance. For the case of a single particle resting on a flat surface, the adhesive force is taken to be the van der Waals attraction between a sphere and a flat plate:

$$F_a = \frac{A_H d_p}{12 s^2} \tag{5}$$

where A_H is the Hamaker constant and s is the spacing between the particle and the wall, estimated to be approximately 8×10^{-8} m [7].

Solving Eq. (3) for pickup velocity, U_{mf}, in this case:

$$U_{mf} = \frac{2.62 v^{\frac{13}{21}} D^{\frac{3}{21}}}{\mu^{\frac{8}{21}}} \left(\frac{\pi}{6} g(\rho_p - \rho_f) + \frac{1.302 \times 10^{-6}}{d_p^2} \right)^{\frac{8}{21}} \tag{6}$$

where D is the pipe diameter and ρ_p is the particle density. Fig. 2 shows the relative contributions to the balance of forces in Eq. (3). At small particle diameters, pickup velocity is primarily determined by the balance between attractive and lift forces. As expected, attractive forces become less significant as the particle diameter increases, and at a diameter of approximately 40 μm, the balance between gravity and lift forces dominates the pickup of the particle.

Previous research by Cabrejos [7,9],and Cabrejos and Klinzing [10,11] has investigated the effects of certain parameters on the pickup velocity of a pile of particles larger than 100 μm. The significance of particle size, particle density, gas density, and gas viscosity was studied, and correlations were developed to relate these factors with pickup velocity. Cabrejos concluded that pickup velocity is proportional to the square root of particle diameter and particle density to the three-fourths power. He also found that pickup velocity is inversely proportional to the square root of gas density, and is not greatly affected by gas viscosity.

Effects of particle shape were briefly mentioned, although no specific relationship with pickup velocity was determined. Investigation of the effects of particle size showed the existence of a minimum pickup velocity. Above this minimum, inertial effects require higher velocities to

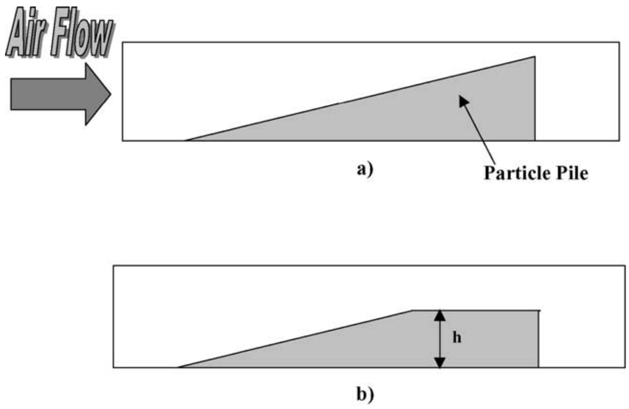


Fig. 4. Experimental method for measurement of pickup velocity.

Table 1
Materials used for pickup velocity experiments

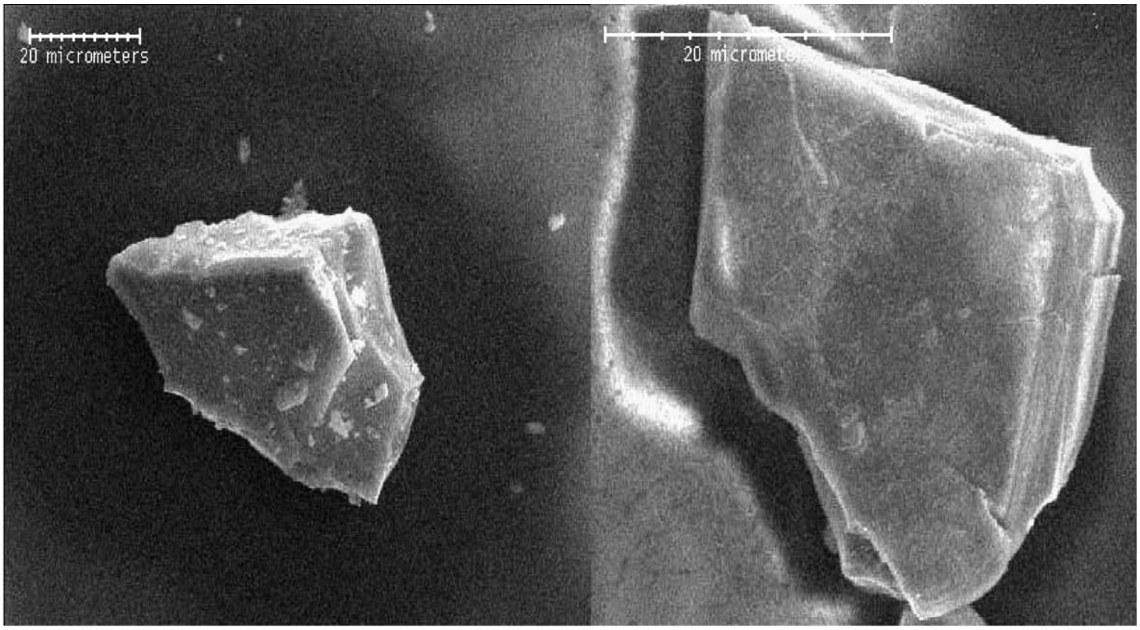
Particle type	Density (g/cm^3)	Linear fractal dimension	Mean diameter (μm)
Glass spheres	2.5	2.0	11 mean sizes from 4.6–500 μm
Crushed glass	2.5	2.1	7.5 22.5
Nonspherical calcined alumina	3.9	2.1–2.2	8 mean sizes from 0.53–31.0 μm
Stainless steel spheres	8.0	2.0	12.4 26.0
PVP spheres	0.7	2.0	11.0 15.0

pick up larger particles. Below this minimum, particle–particle interactions become more significant and higher velocities are required to separate individual particles. The work presented in this paper focuses on the correlation between particle characteristics and pickup velocity using particulates less than 35 μm in diameter. Shape, size, and density effects, as well as electrostatic forces, are investigated.

2. Experimental

A schematic representation of the equipment used for this project is shown in Fig. 3. The most important features of the set-up are three sections of acrylic pipe, 1 in. in diameter. These transparent pipes allow the experimentalist to observe the movement of particles within them in order to study the mechanism of pickup and to determine when steady state has been achieved. The first section of pipe has a length of 6 ft and exists to ensure fully developed flow. The middle section of acrylic pipe is approximately 40 in. in length and is used to hold the particles at the start of the experiment. The final portion of the pipe is necessary to minimize end effects. Existence of fully developed turbulent flow and negligible end effects was verified for a one-phase flow situation through the use of Fluent (Fluent Inc., Lebanon, NH), a computational fluid dynamics package. Various lengths and diameters of pipe were examined with these simulations, and the actual equipment was designed with two to three times the required pipe length upstream and downstream of the test section.

The experimental method used to measure pickup velocity begins with a stationary pile of particles placed in the center section of acrylic pipe. Previous research utilized a horizontal pile surface, but duning became a problem when smaller particles were used. As air flowed over the initial portion of the pile, particle spacing decreased due to strong surface forces, causing the air to erode the tail of the pile only. To remedy this, the pile is angled upward and away from the source of flow to encourage erosion in layers (Fig. 4a). Air flow is initiated at a constant volumetric flow rate through the pipe. As the free cross-sectional area of the pipe increases due to removal of particles, the air velocity decreases. Eventually, the velocity is no longer sufficient to entrain any additional particles, and the height of the flat portion of the pile (h) is measured (Fig. 4b). The cross-



a) b)

Fig. 5. SEM images of (a) crushed glass and (b) calcined alumina particles.

sectional area remaining in the pipe is calculated using geometric relationships [7], and pickup velocity is then calculated.

Table 1 lists the properties of the materials used in the investigation. The standard deviation (S.D.) of particle sizes is approximately 20% of the mean value reported in the table. Fig. 5 shows representative SEM images of crushed glass and alumina particles used in the experiments. All particles were dried for at least 3 days in a drying oven and stored in a dessicator to minimize the presence of moisture in the system. A dry bulb–wet bulb technique was used to verify a constant 14% relative humidity of the pressurized air, and a filter was placed upstream of the test pipe to remove any excess water or oil. In addition, the entire experimental apparatus was grounded to reduce electrostatic buildup. At least three trials with each particle type were performed.

3. Results and discussion

Experimental data collected from all particle types is shown in Fig. 6. The bars in all figures represent 1 S.D. from the mean value, and in some cases, are too close together to be seen in the plots. Investigation of pickup velocity as a function of particle size shows a minimum in the pickup velocity curve, which agrees with results from previous work [7,9]. In addition, a plateau exists at very small particle diameters where pickup velocity is not greatly affected by changes in particle size (<20 μm), particle shape, or intrinsic particle density (0.7–8.0 g/cm^3). None of these factors affect the magnitude of the pickup velocity because the relevant cohesive force is the attractive London–van der Waals forces between the particles in this size range, and pickup velocity is determined by a balance between the attractive force and the lift force. The London–van der Waals force is proportional to particle diameter and inversely proportional to particle spacing squared. We believe that compression of the pile at the pile surface occurs during pickup testing. It could be that this compression decreases the interparticle spacing and could offset the change in particle diameter, resulting in a small change in the van der Waals force and a fairly constant pickup velocity. The particle size range over which the pickup velocity is constant is greater with nonspherical particles than with spherical particles. Fig. 7 shows data collected from spherical glass and nonspherical alumina particles less than 35 μm in diameter. Perfect spheres always contact each other at a single point, while nonspherical particles may contact each other at a point, line, or plane. Therefore, the van der Waals forces act over a larger area between the nonspherical alumina particles, and with the potential of more particle interlocking, pickup velocity remains constant over a broader size range.

Deviations in pickup velocity measurements are more prominent at smaller particle sizes because van der Waals forces are dominant. Since the magnitude of the van der Waals forces depends on particle contact area, pickup velocity will vary with particle arrangement and packing at these small diameters. Also, deviations associated with spherical particles are significantly less than those associated with nonspherical particles at very small particle diameters. Numerous trials (>20) were performed with several small nonspherical particles with no noticeable

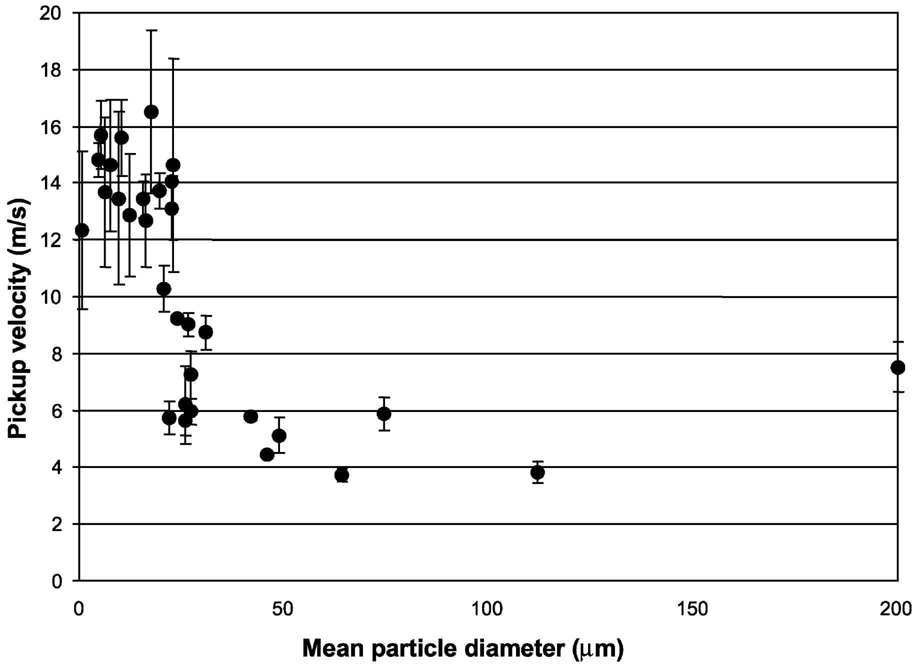


Fig. 6. Pickup velocity data for all particle types tested.

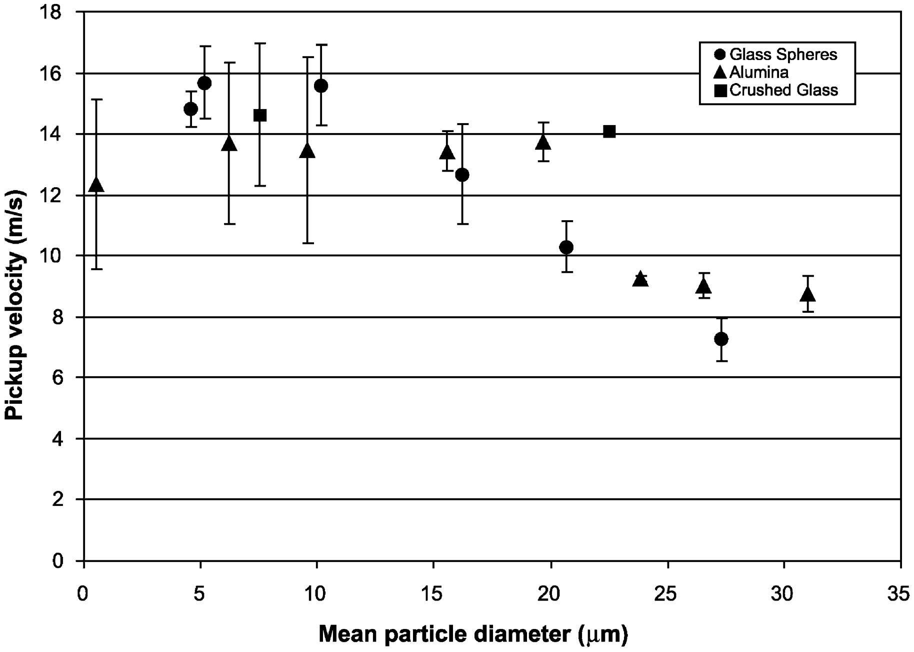


Fig. 7. Pickup velocity data for particles smaller than 35 μm.

decrease in deviation in pickup velocity. We hypothesize that this is also a result of particle packing. When spherical particles are tested, packing is more uniform and reproducible from trial to trial. Packing among nonspherical particles, however, is random and cannot be predicted. Results from experiments performed with spherical glass particles larger than 40 μm in diameter can be seen in Fig. 8. Data from earlier research have been included to show agreement with the upward trend seen in our results. The purpose of this comparison was to ensure the collected data were in the range of values reported in previous studies. Slight differences from previous data can be attributed to narrower particle size distributions used in the work presented here.

Fig. 7 also illustrates the effect of particle shape on pickup velocity. When crushed and spherical glass particles approximately 20 μm in diameter are compared, the result is

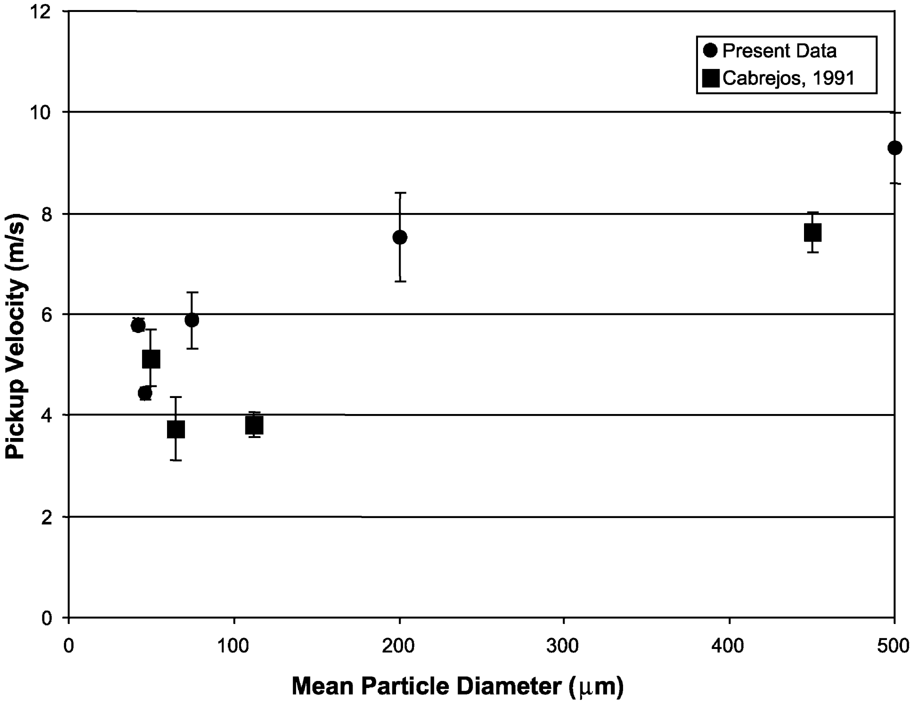


Fig. 8. Pickup velocity data for glass spheres larger than 40 μm.

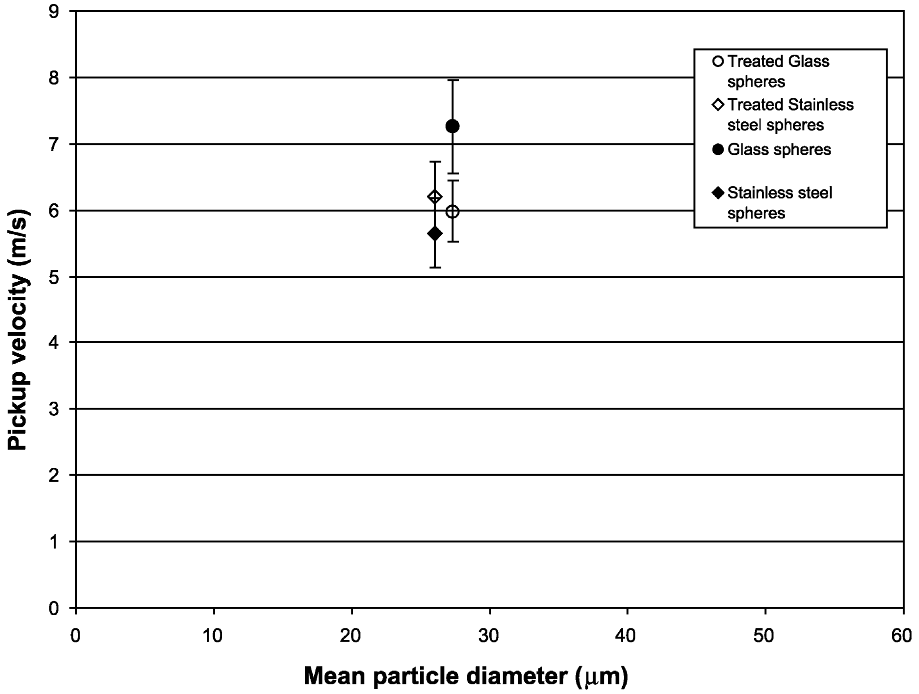


Fig. 9. Investigation of electrostatic effects.

a higher pickup velocity for the nonspherical material. Particle–particle interlocking occurs in nonspherical particles and necessitates a higher fluid velocity to separate and entrain them. These results agree with those found by previous research groups [7,9]. van der Waals forces are less important at this intermediate size than at the very small particle sizes. When van der Waals forces are dominant, nonspherical particles have a larger deviation in pickup velocity than spherical particles due to random packing effects. However, Fig. 7 shows that the deviation associated with the spherical glass particles is larger than that of the crushed glass, indicating that van der Waals forces are not dominant for particles of this average size.

Electrostatic effects play an important role in the attractive force between particles at intermediate particle sizes. Fig. 9 compares the pickup velocities for glass and stainless

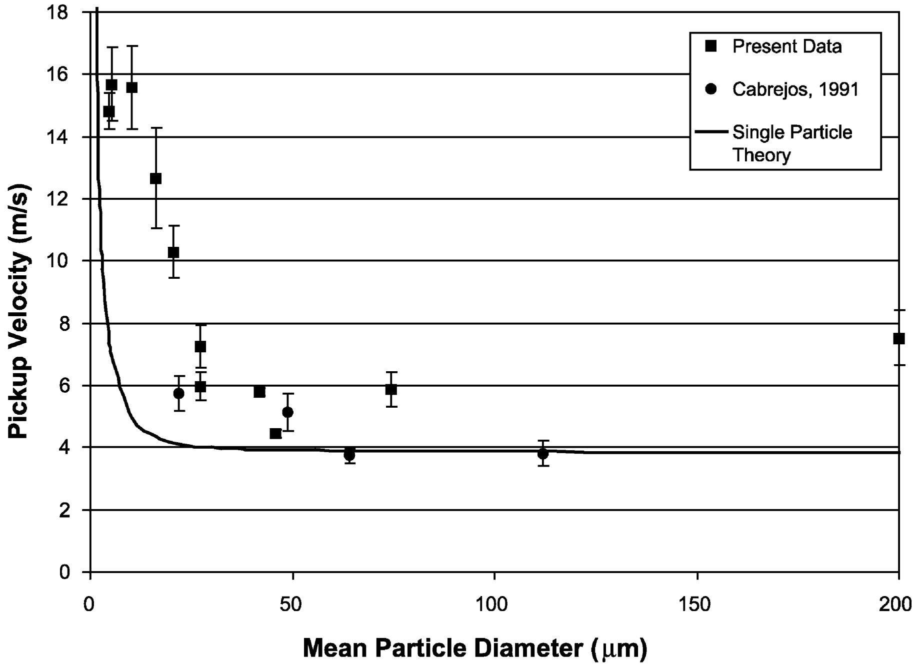


Fig. 10. Comparison of experimental data with theoretical analysis using glass spheres.

steel spheres at diameters of approximately 25 μm. Although the density of stainless steel is more than three times the density of glass, the pickup velocity for the stainless steel is lower. Hence, electrostatic forces are overcoming the weight of the particles. Glass is an insulating material, so charges produced by triboelectrification cannot be passed without the aid of an antistatic substance. Stainless steel, on the other hand, is conductive, so it will readily pass charge from one particle to another. To verify this hypothesis, an antistatic film (Larostat®, BASF) was used to coat the inside of the test pipe. When data were collected from these two types of particles in the treated environment, the pickup velocity of the stainless steel did not change significantly but the pickup velocity of glass decreased. The presence of the antistatic material enabled the glass spheres to pass some of the charge out of the system, so the electrostatic forces between them were reduced. However, there is evidence that some charge remained in the glass spheres because the pickup velocity for glass did not fall below that of the steel as was expected.

Fig. 10 compares experimental pickup velocities of glass spheres with the theoretical pickup velocity given in Eq. (6). The theoretical analysis curve lies below the experimental pickup velocity data at all particle diameters, which suggests the attractive forces are underestimated for the small and intermediate particle sizes. This agrees with the explanations made previously because electrostatic, shape, and multiple particle effects on the van der Waals force were not included in the analysis. At larger particle diameters, where the attractive forces are less important in determining pickup velocity, we anticipate that the description of the lift force is inadequate as the Saffman analysis is valid for $v/(\nu\kappa)^{1/2} \ll 1$. At particle diameters less than 10 μm, adhesive forces are greater than the force of gravity, supporting our argument that cohesion and lift, and not inertia, determine the magnitude of the pickup velocity for very small particle diameters.

4. Conclusions

Different forces dominate the magnitude of pickup velocity over particular ranges of particle size. For particles in the size range of 5–200 μm, a minimum in pickup velocity occurs. At the larger particle sizes, inertial effects dominate and require higher flow rates to entrain larger particles, and for the smaller particle sizes, particle–particle interactions are significant such that higher velocities are needed to separate smaller particles. Changes in pickup velocity are negligible at very small particle diameters (< 10–20 μm) due to relatively constant London–van der Waals forces. It is hypothesized that a decrease in particle separation due to compression is counteracted by the decrease in particle diameter, so the overall interaction force does not change appreciably. Electrostatic forces dominate at intermediate particle sizes (~ 20–40 μm). This was verified by reducing the amount of electrostatic forces present and observing the effect on conductive and insulating materials.

Particle shape influences the magnitude of deviation at very small diameters. Particle packing is more uniform for spheres, but is more random for nonspherical particles. As a result, nonspherical particles have a broader range of pickup velocity values at a particular diameter. In addition, pickup velocities for nonspherical particles are higher due to particle interlocking.

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