ON THE PREDICTION OF PICKUP AND SALTATION VELOCITIES IN PNEUMATIC CONVEYING

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Abstract - This paper presents a comparative study of the critical pickup and saltation velocities of particles in horizontal pipelines for pneumatic conveying design. A comparative study is performed using different existing correlations in the literature for the determination of the minimum velocity of transport as a function of the particle and pipe diameter, particle density, solid mass flow rate and particle sphericity. Their limitations and difficulties in predicting those critical velocities are analyzed. For the pickup velocity, an experimental study was also carried out in order to support the analysis. Recommendations are presented on the use of such correlations.
Keywords: Pickup velocity; Saltation velocity; Pneumatic conveying; Gas-solid flow.

INTRODUCTION

Pneumatic conveying is a process in which solid particulate materials are conveyed by gas flow through pipeline systems. Nowadays, this type of transport has become a popular technique in the field of particulate materials. Applications for pneumatic conveying systems can be found in many industrial areas, such as ore processing and in the chemical, pharmaceutical, agricultural and food processing industries.

A key parameter for successful operation of a pneumatic conveying system is the minimum velocity required for particle entrainment, also known as the pickup velocity. The minimum velocity to maintain the particulate flow is called the saltation velocity. The knowledge of these velocities is critical for an accurate design of a pneumatic conveying system. If the fluid velocity is much higher than is

necessary, the system is subjected to unnecessary energy losses, particle attrition and excessive pipe erosion. A fluid velocity below these critical velocities can result in clogged pipelines.

Both pickup and saltation velocities are functions of the particle properties, such as size, density and sphericity, fluid properties, such as density and viscosity, and the main process variable, the solid mass flow rate. Despite the existence of advanced modeling for turbulent gas-solid flows (Huilin *et al.*, 2003) and modern powerful numerical methods to solve this complex flow model (Chu and Yu, 2008; Pirker *et al.*, 2010), the empirical correlation for both pickup and saltation velocities still remains as a practical issue for industrial pneumatic conveying systems design

Several attempts have been made in the past to predict the minimum conveying velocity, but, unfortunately, the majority of existing approaches have

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several limitations and contradictions, as reviewed by Yi *et al.* (1998) and Rabinovich and Kalman (2008).

The goal of this paper is to provide a critical analysis of the pickup and saltation velocities, considering the influence of parameters such as particle and pipeline diameters, particle density and solids loading ratio. For the pickup velocity, an experimental study was also carried out to support the analysis. Thus, this paper presents recommendations on the limitations of the existing correlations.

LITERATURE REVIEW

The minimum transport velocity is defined as the lowest velocity at which particles can be transported inside a pipeline in a stable manner without deposition on the bottom of the pipe. The saltation velocity is defined as the gas velocity in a horizontal pipeline in which the particles begin to fall from their state of suspension and are deposited at the bottom of the pipeline.

The pickup velocity is defined as the gas velocity necessary to suspend the particles initially at rest in the bottom of the pipeline (see Figure 1), or it may be defined as the fluid velocity required to initiate a sliding motion, rolling and suspension of the particles.

(a)

(b)
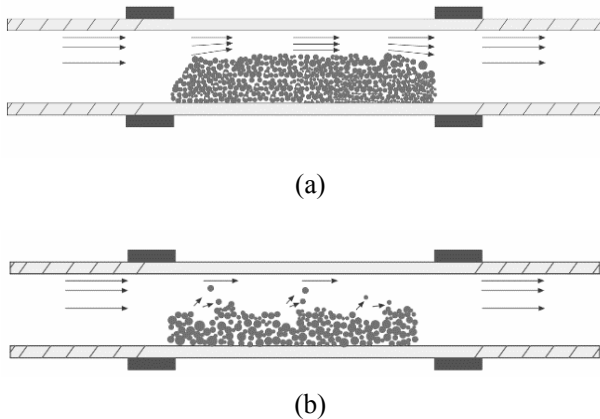
Figure 1: (a) Particles at rest in the bottom of the pipeline. Air velocity less than the pickup velocity. (b) Particles are dragged by the air stream. Air velocity equal to or greater than the pickup velocity.

The main correlations found in the literature that are used for predicting the critical pickup and saltation velocities are presented below. These correlations are analyzed in this work.

Main Correlations Used for Predicting Critical Saltation Velocity

Rizk (1976)

$$\zeta = \frac{W_S}{\rho_f U_S A} = \left(\frac{1}{10^d}\right) Fr_S^x \tag{1}$$

where:

$Fr_S = U_S / \sqrt{g D_T}$ (Froude number at the Saltation velocity), $d = 1.44 d_p + 1.96$, $x = 1.1 d_p + 2.5$, (d and x in mm), ζ is the solids loading ratio, W_S is the solids mass flow rate, d_p is the particle diameter, D_T is the pipe diameter, U_S is the saltation velocity, ρ_f is the fluid density, g is the acceleration of gravity and A is the cross-sectional area of pipe.

Matsumoto *et al.* (1977)

For:

$$d_p > 1.39 D_T \left(\frac{\rho_p}{\rho_f}\right)^{-0.74}$$

$$\zeta = 0.373 \left(\frac{\rho_p}{\rho_f}\right)^{1.06} \left(\frac{U_t}{10\sqrt{g d_p}}\right)^{-3.7} \left(\frac{U_{min}}{10\sqrt{g D_T}}\right)^{3.61} \tag{2}$$

For:

$$d_p < 1.39 D_T \left(\frac{\rho_p}{\rho_f}\right)^{-0.74}$$

$$\zeta = 5560 \left(\frac{d_p}{D_T}\right)^{1.43} \left(\frac{U_{min}}{10\sqrt{g D_T}}\right)^{3.61} \tag{3}$$

where ρ_p is the particle density, U_t is the terminal velocity and U_{min} is the minimum conveying velocity.

Schade (1987), apud Yi *et al.* (1998)

$$\frac{U_S}{\sqrt{g D_T}} = \zeta^{0.11} \left(\frac{D_T}{d_p}\right)^{0.025} \left(\frac{\rho_p}{\rho_f}\right)^{0.34} \tag{4}$$

Weber (1981)

For:

$$U_t \leq 3 \ m/s \tag{5}$$

$$Fr_{min} = \left(7 + \frac{8}{3}U_t\right)\zeta^{0.25}\left(\frac{d_p}{D_T}\right)^{0.1}$$

For:

$$U_t > 3 \ m/s \tag{6}$$

$$Fr_{min} = 15\zeta^{0.25}\left(\frac{d_p}{D_T}\right)^{0.1}$$

where Fr_{min} is the Froude number at the minimum conveying velocity.

Geldart and Ling (1992)

For:

$$\frac{G_s}{D_t} < 47000 \tag{7}$$

$$U_{min} = 1.5 G_s^{0.465} D_T^{-0.01} \mu^{0.55} \rho_f^{-0.42}$$

For:

$$\frac{G_s}{D_t} < 47000 \tag{8}$$

$$U_{min} = 8.7 G_s^{0.302} D_T^{0.153} \mu^{0.55} \rho_f^{-0.42}$$

where, μ (in kg/m.s) is the dynamic viscosity of the gas and G_s (in kg/m^2.s) is the solids flux.

Ochi (1991)

$$\frac{U_s}{\sqrt{gd_p}} = 1.05 f_s^{0.47}\left(\frac{U_t}{\sqrt{gd_p}}\right)^{0.82}\zeta^{0.25} \tag{9}$$

where f_s is the particle friction coefficient with the pipeline wall.

Cabrejos and Klinzing (1994)

$$\frac{U_S}{\sqrt{gd_p}} = \frac{U_{s0}}{\sqrt{gd_p}} + 0.00224\left(\frac{\rho_p}{\sqrt{\rho_f}}\right)^{1.25}\zeta^{0.5} \tag{10}$$

where, U_{s0} is the saltation velocity of a single particle.

Kalman and Rabinovich (2008)

For:

$$\left(1 + 30 C_V^{0.35}\right)^{2.33} Ar < 2450 \tag{11}$$

$$\frac{\rho_p d_p U_{mp}}{\mu} = 14.3\left(\left(1 + 30 C_V^{0.35}\right)^{2.33} Ar\right)^{0.1}$$

where, U_{mp} is the minimum pressure velocity and,

$$Ar = \frac{\rho_f\left(\rho_p - \rho_f\right)gd_p^3}{\mu^2}, \ \left(\text{Archimedes number}\right)$$

For,

$$\left(\left(\frac{1-\varepsilon}{\varepsilon}\right)^{0.1} + 30 C_V^{0.35}\right)^{2.33} Ar \tag{12}$$

$$\frac{\rho_f d_p U_{mp}}{\mu} = 1.1\left(\left(\left(\frac{1-\varepsilon}{\varepsilon}\right)^{0.1} + 30 C_V^{0.35}\right)^{2.33} Ar\right)^{3/7}$$

where,

$$C_V = \frac{\zeta\rho_f}{\rho_p + \zeta\rho_f}, \ \left(\text{solids volumetric concentration}\right)$$

Main Correlations Used for Predicting the Critical Pickup Velocity

Cabrejos and Klinzing (1992)

$$U_p = \left[1.27 \ Ar^{-1/3} + 0.036 \ Ar^{1/3} + 0.45\right] \tag{13}$$
$$\left[0.70 \ Ar^{-1/5} + 1\right] U_{p0}$$

where U_{p0} is the pickup velocity of a particle alone and,

$$U_{p0} = \frac{\pi}{8}\left[1 - \left(\frac{d_p}{D_r}\right)^{1.5}\right]\sqrt{\frac{4}{3}\frac{f_s gd_p}{C_D}\left(\frac{\rho_p - \rho_f}{\rho_f}\right)} \tag{14}$$

coarse particle

C_D is the drag coefficient of the particle.

$$1.54 \times 10^{-4} \left[1 - \left(\frac{d_p}{D_T} \right)^{1.5} \right]^{-2} C_D \rho_f d_p^4 \left(\frac{U_{po}^7}{v^3 D_T} \right)^{\frac{1}{2}}$$

$$= f_s \left[\frac{\pi}{6} g d_p^{\,3} \left(\rho_p - \rho_f \right) + 1.302 \times 10^{-6} d_p - 6.35 \times 10^{-3} \rho_f \, d_p^{\,3} \left(\frac{U_{po}^{21}}{v^5 D_T^{\,3}} \right)^{\frac{1}{8}} \right] \quad \text{(fine particle)} \tag{15}$$

v is the kinematic viscosity.

Cabrejos and Klinzing (1994)

$$\frac{U_p}{\sqrt{g d_p}} = 0.0428 \, Re_p^{\,0.175} \left(\frac{D_T}{d_p} \right)^{0.25} \left(\frac{\rho_p}{\rho_f} \right)^{0.75} \tag{16}$$

where Re_p is the particle Reynolds number.
Valid for:
$25 < Re_p < 5000$, $8 < (D_T/d_p) < 1340$ and $700 < (\rho_p/\rho_g) < 4240$.

Kalman *et al*. (2005)

First Zone:

$$Re_p^* = 5 Ar^{\frac{3}{7}}, \text{ for } Ar > 16.5 \tag{17}$$

Second Zone:

$$Re_p^* = 16.7 \text{ , for } 0.45 < Ar < 16.5$$

Third Zone:

$$Re_p^* = 21.8 \, Ar^{\frac{1}{3}}, \quad \text{for } Ar < 0.45$$

where,

$$Re_p^* = \frac{\rho_f \, U_p \, d_p}{\mu \left(1.4 - 0.8 e^{-\frac{D_T/D_{T50}}{1.5}} \right)}$$

where D_{T50} is a 50 mm pipe diameter.
Valid for:
$0.5 < Re_p^* < 5400$, $2 \times 10^{-5} < Ar < 8.7 \times 10^7$, $0.53 < d_p < 3675$ µm, $1119 < \rho_s < 8785$ kg/m^3 and $1.18 < \rho_g < 2.04$ kg/m^3.

Rabinovich and Kalman (2009)

Non-Spherical Coarse Particle (Drag)

$$\frac{n}{8} \pi C_D \, Re_p^{\,2} + 0.1 f_s \left(\frac{d_p}{D_T} \right)^{0.29}$$

$$Re^{2.02} - \frac{1}{6} \pi f_s Ar = 0 \tag{18}$$

Spherical Coarse Particle (Rolling)

$$\frac{n}{8} \pi C_D \, Re_p^{\,2} + 0.1 f_s \left(\frac{d_p}{D_T} \right)^{0.29}$$

$$Re^{2.02} - \frac{1}{6} \pi f_s Ar \frac{d_p}{2} = 0 \tag{19}$$

Fine particle

$$0.0277 n \, Re_{50}^{\,1.96} + 0.00635 \left(\frac{d_p}{D_T} \right)^{0.375}$$

$$Re^{2.625} = \frac{\pi}{6} Ar + \frac{1}{12} \frac{A_h \rho_f d_p}{s^2 \mu^2} \tag{20}$$

where A_H is the Hamaker constant, n is the wall effect coefficient, f_s is the friction coefficient and Re_{50} is the Reynolds number for the pickup velocity measured in a pipe of 50 mm in diameter.

COMPARISON OF CORRELATIONS FOR THE SALTATION VELOCITIES

In order to analyze the accuracy of the correlation in predicting the saltation velocities, numerical testing was carried out for all of the referenced correlations. In all simulations air was the transport

gas at ambient conditions (ρ = 1.18 kg/m^3). These analyses were designed to assess the influence of average particle diameter, pipeline diameter and solids mass flow rate at the saltation velocity, thus providing evidence for the indication of the best correlations in specific design situations.
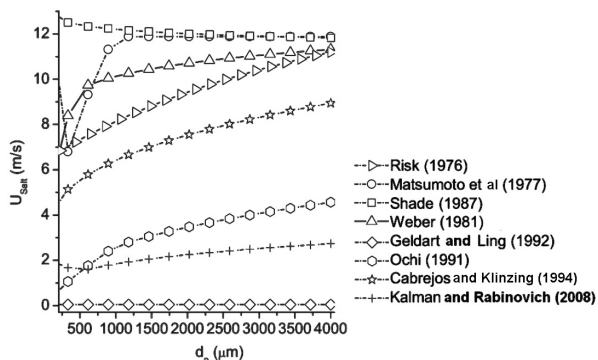
Influence of Particle Diameter

Figure 2 presents a plot of the saltation velocity as a function of the average diameter of fine particles (0-200 μm). The mass flow rate of solids (Ws = 350 kg/h) was kept constant in all simulations. An inner diameter of 50.4 mm for the horizontal pipeline was used. Sand particles were used (ρ_p = 2636 kg/m^3) in all simulations. The result indicate that only the Rizk (1976) correlation presented a variation with the increase of the average particle diameter, which suggests that all other correlations are not appropriate for predicting pickup velocity throughout a wide range of average particle diameters. It was also observed that the correlation of Rizk (1976) follows the physical behavior for the whole range of particle diameters, since for small particle sizes the effect of cohesive forces is higher, requiring a higher velocity for the particle entrainment (Cabrejos and Klinzing, 1994; Hayden *et al.* 2003; Rabinovich and Kalman, 2009).
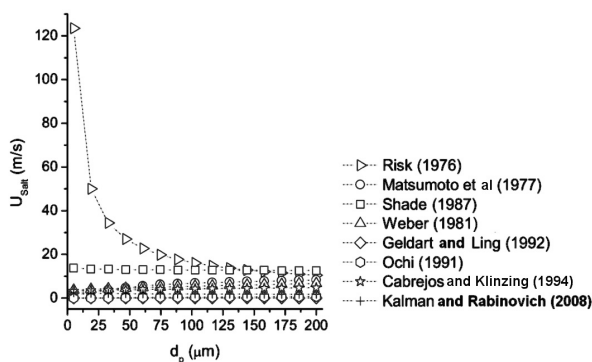
Figure 2: Velocity of deposition as a function of average particle size. d_p: 0 - 200 micrometers.

Figure 3 shows the plot of saltation velocity as a function of average particle diameter of 200-4000 μm. The mass flow rate of solids was maintained constant at 350 kg/h, and a horizontal pipeline with an inner diameter of 50.4 mm was used. The average particle diameter ranged from 100 to 4000 μm. Sand particles were used (ρ_p = 2636 kg/m^3) in all simulations. The data indicate that some correlation predict an almost constant saltation velocity (Geldart and Ling, 1992 and Kalman and Rabinovich, 2008), and others very low values for the range from 0 to

2.5 m/s. Other correlations (Rizk, 1976; Matsumoto *et al.*, 1977; Weber, 1981; Ochi, 1991; Cabrejos and Klinzing, 1994) showed an increase in the saltation velocity with the increase in average particle diameter. The results of Shade (1987) showed that the saltation velocity decreases with the increase of the average particle diameter, which is not in accordance with the real physical behavior. The comparison between the lowest and highest value of the saltation velocity results in a value of approximately 13 m/s.

Figure 3: Velocity of deposition as a function of average particle size. d_p: 200 - 4000 micrometers.

Influence of Pipeline Diameter

Figure 4 shows a plot of saltation velocity as a function of pipeline diameter. The simulations were made with sand particles (ρ_p = 2636 kg/m^3) with particle diameter (d_p = 200 μm) at a solid mass flow rate of 350 kg/s. A great discrepancy in the results was found. Some correlations provide a practically constant saltation velocity estimation (Geldart and Ling, 1992; Ochi, 1991), showing low values for the range from 0 to 1 m/s. Other correlations (Rizk, 1976; Shade, 1987; Matsumoto *et al.,* 1977; Cabrejos and Klinzing, 1994; Kalman *et al.*, 2005) show an increase with the diameter of the pipeline.
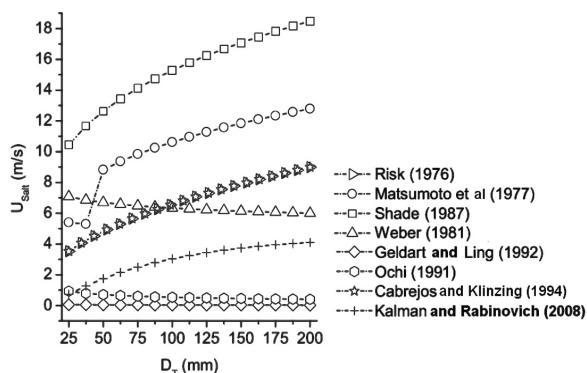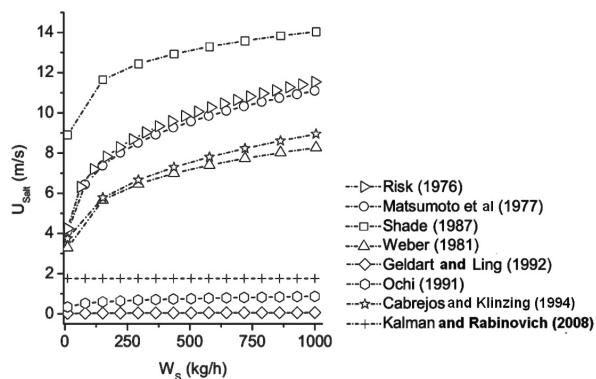

Figure 4: Saltation velocity as a function of pipeline diameter.

Conversely, other correlation (Weber, 1981; Ochi, 1991; Geldart and Ling, 1992) show a decrease in the saltation velocity when the pipeline diameter was increased. The difference between the highest and lowest saltation velocity value for a pipe diameter of 200 mm is approximately 19 m/s.

Influence of the Solids Mass Flow Rate

Figure 5 shows a plot of saltation velocity as a function of mass flow rate for solid particles of sand (ρ_p = 2636 kg/m^3). The simulations were carried out for particle and pipeline diameters of 200 μm and 50.4 mm, respectively. The range for the solid mass flow employed was from 50 to 1000 kg/s. Some correlations (Geldart and Ling, 1992; Ochi, 1991; Kalman *et al.*, 2008) remained constant in the range of very low saltation velocity values (between 0 and 2 m/s) and other correlations show growth with an increase in solid mass flow (Weber, 1981; Cabrejos and Klinzing, 1994; Matsumoto *et al.*, 1977; Rizk, 1976; Shade, 1987). The saltation velocity values are very divergent. The difference between the highest and lowest saltation velocity for the solid mass flow rate of 1000 kg/s was about 14 m/s.

**Figure 5:** Saltation velocity as a function of the solids mass flow rate.

COMPARISON OF THE PICKUP VELOCITY CORRELATIONS

For the determination of the pickup velocity, four significant correlations available in the literature were evaluated. In all simulations air was used (ρ_f = 1.18 kg/m^3) as the transporter gas. The goal of the simulations was to analyze the influence of the particle size, pipe diameter and particle density. This was accomplished by varying one parameter and keeping the others constant. In order to support this analysis, experimental work was also carried out. In

the following section the testing bench is described, as well the characteristics of the materials used.

The Experimental Setup

An experimental apparatus, see Figure 6, was developed to determine the pickup velocity, which consists basically a 1.5-meter-long, 50 mm diameter horizontal steel pipeline; three horizontal PVC pipelines (each 6 meters long and 50, 75 and 100 mm in diameter), with a butterfly valve at the end of each pipeline; three transparent sections (placed in the middle of the PVC pipelines, where the visual observations were carried out); a root blower (controlled by a frequency inverter), which provides the gas flow rate and pressure necessary for picking up the particles; and a solids collector with a paper filter bag placed on its top. A complete description of this experimental setup can be found in Gomes (2011). Experiments were carried out using air as the conveying gas at ambient conditions.
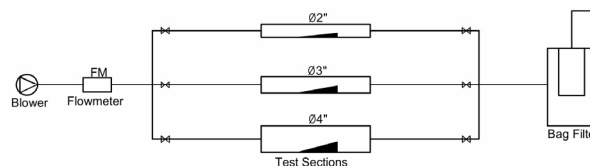

Figure 6: Schematic representation of the experimental setup.

The experimental run starts with a stationary layer of particles placed in the central section of a transparent pipe. Air flow is initiated at a constant volumetric flow rate through the pipe. As the free cross-sectional area of the pipe increases, the air velocity decreases due to the removal of the particles. When the velocity is no longer sufficient to entrain any additional particles, a final state of equilibrium is automatically reached. This procedure is repeated until nearly 95 per cent of the whole material has been captured. Plotting the amount of entrained particles (weight reduction of the layer) as a function of operating gas velocity made it possible to determine the pickup velocity by the intersection of the extrapolated curve passing through the measured points and abscissa (see Figure 7). Obviously, a higher number of measurements will improve the accuracy, especially if determinations with very small weight losses are in progress.

In order to assess the effect of pipe diameter on the pickup velocity, three PVC pipelines were used in an alternate manner. Air flow was initiated at a

constant volumetric flow rate through the pipeline with one of the three butterfly valves opened. The layer started to erode slowly as the gas stream picked up the top particles.
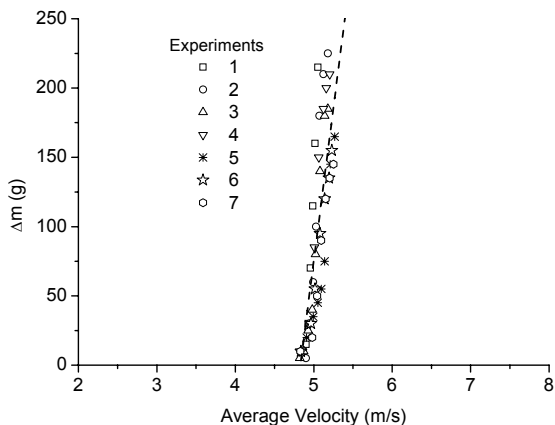

**Figure 7:** Weight loss as a function of the average air velocity. Experimental data. dp = 179.5 μm.

This experiment was performed using sand and alumina particles. The particle diameters used in the tests were obtained by the method of separation by sieves. The mean diameter was calculated as the arithmetic mean of consecutive sieve openings. Figures 8-9 show the sand and alumina particles with non-spherical shape. Table 1 presents the properties (density, size distribution, mean diameter and shape) and Geldart classification of the particles used in the measurements. The density was measured with a pycnometer. All tests were conducted with a narrow range of particle sizes prepared by sieving.

Table 2 shows experimental data used in this paper for the pickup velocity study.

UFPA-FEMAT
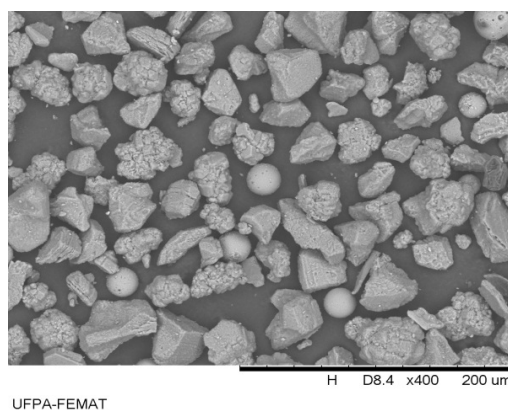
Figure 8: Alumina particles, d_p = 62 μm.

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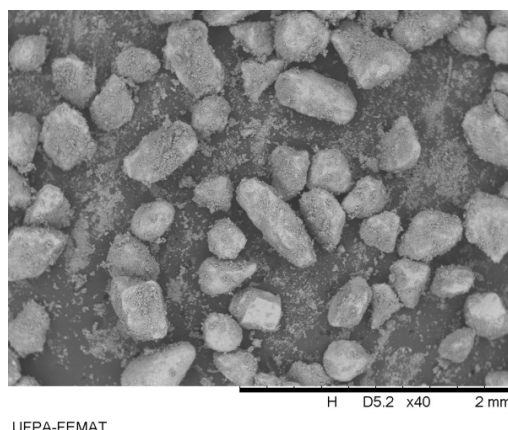
Figure 9: Sand grains, d_p = 340 μm.

Table 1: Properties of the particles tested in this research.

Particle	Density (kg/m³)	Size range (μm)	Mean Diameter (μm)	Sphericity
Sand	2636	50-90	70	ψ = 0.7
		90-150	120	
		150-250	200	
		250-430	340	
		600-430	510	
		600-850	730	
		850-1000	930	
		1000-2360	1680	
		2360-3350	2860	
		3350-4360	3860	
Alumina	3750	53-90	71.5	Ψ = 0.9
		90-125	107.5	
		125-150	137.5	
		150-205	177.5	

Table 2: Experimental data used in this paper for the pickup velocity study and Geldart Classification.

Material	Density (kg/m³)	Sizes (μm)	Geldart Classification
sand	2636	70-3860	A;B;C;D
alumina	3750	71.5-177.5	A;B
glass beads	2834	200-3500	B;D
salt irregular	2234	200-3500	B;D
non-spherical glass	2834	200-3500	B;D
pasta	1200	5400	B;D
spaghetti	1500	4100	D
lentil	1644	3830	D
rice	1590	2940	D
bakelite	930	2700	D

Figure 10 presents the plot of the pickup velocity as a function of average particle diameter. A pipe diameter of 50.4 mm and a particle diameter ranging from 200 to 3500 μm were employed in the simulations. Experimental data are compared for sand particles (ρ_p = 2636 kg/m³), glass beads (ρ_p = 2834 kg/m³) and irregular grains of salt (ρ_p = 2234 kg/m³) with a pickup velocity of sand particles (ρ_p = 2636 kg/m³) obtained from Cabrejos and Klinzing (1992), Cabrejos and Klinzing (1994), Kalman *et al.* (2005) and correlations from Kalman *et al.* (2009).
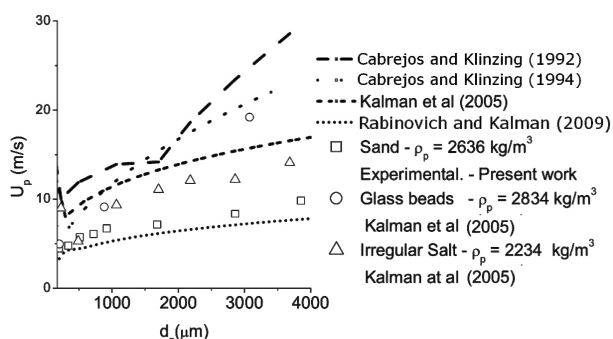


Figure 10: Experimental pickup velocity as a function of the particle diameter and correlation curves. d_p: 200-3500 μm.

From an analysis of the curves obtained with the use of the above mentioned correlations, it was verified that all of them show an increase in the pickup velocity as the average particle diameter is increased. However, for a given average particle size, there is a large divergence between the values of pickup velocities obtained and values predicted by the correlations. This shows that such correlations present limitations in predicting reliable values of pickup velocities. It is noted that three correlations present a fair agreement among themselves for predicting the pickup velocity up to approximately the average particle diameter of 1500 μm. For particle diameters above this limiting value, the results begin to diverge considerably. The values obtained with the correlations of Rabinovich and Kalman (2009) are usually very low and those obtained with the correlation of Cabrejos and Klinzing (1992) for particle average diameter above 1500 μm rise very quickly. It should be noted here that the correlation of Cabrejos and Klinzing (1992) was obtained from a theoretical model and some of the parameters were adjusted empirically. The correlation of Cabrejos and Klinzing (1994) is fully empirical. Note also that the correlations of Cabrejos and Klinzing (1994) and Kalman *et al.* (2005) agree reasonably well with each other. All correlations agree reasonably well with the experimental data, although the correlations by Cabrejos and Klinzing (1994) and Kalman *et al.* (2005) show a better fit when the whole range of particle diameter is considered.

Figure 11 presents the plot of the pickup velocity as a function of average particle diameter for fine particles. The simulations were made with data for sand particles (ρ_p = 2636 kg/m³) and the results compared with experimental data for non-spherical glass (ρ_p = 2834 kg/m³), irregular salt (ρ_p = 2234 kg/m³), sand (ρ_p = 2636 kg/m³) and glass beads (ρ_p = 2834 kg/m³). The pipeline diameter used in the simulations was 50.4 mm. The equation of Rabinovich and Kalman (2009) presents no correlation with the physical phenomenon, since for the smallest particle diameters the pickup velocity should increase with the reduction of the average diameter of the particles, which does not occur. The correlation that provides the best agreement with experimental data (which includes an average particle diameter ranging from 0 to 200 μm) is the correlation of Kalman *et al.* (2005). It is noteworthy to point out that, for the average diameter of 22 μm, the error of this correlation is approximately 100%. The correlation of Cabrejos and Klinzing (1992) overestimates the results, considerably.
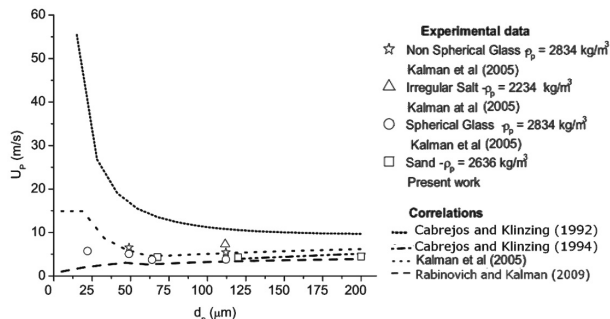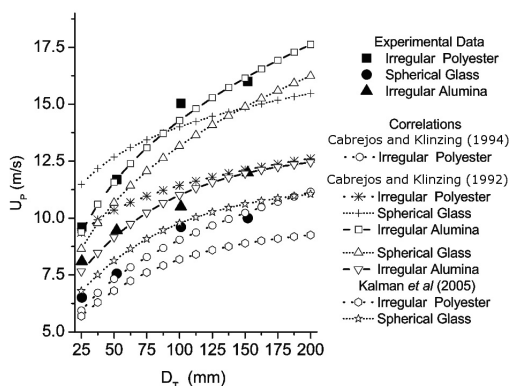
Figure 11: Pickup velocity as function the diameter of the particles. d_p: 0 - 200 μm

Influence of Pipe Diameter

Figure 12 presents the plot of the particle pickup velocities of irregular shaped polyester beads (ρ_p = 1400 kg/m³ and d_p = 3 mm), glass beads (ρ_p = 2480 kg/m³ and d_p = 0.45 mm) and non-spherical alumina (ρ_p = 3750 kg/m³ and d_p = 0.45 mm), as a function of the pipeline diameter obtained with the use of the correlations of Cabrejos and Klinzing (1992), Cabrejos and Klinzing (1994), Kalman *et al.* (2005) and Rabinovich and Kalman (2009). The results obtained are compared with experimental data obtained by Cabrejos and Klinzing (1994). It is found that the correlation of Rabinovich and Kalman (2009) presents a behavior totally different from the other correlations, i.e., the pickup velocity decreases with increasing pipeline diameter. Values obtained with this correlation are also extremely low. The values obtained with the correlation of Cabrejos and Klinzing (1992) for the irregular polyester particles are farther above the experimental results. The results obtained for glass beads and spherical alumina do not agree with the experimental data. The correlations of Cabrejos and Klinzing (1994) and Kalman *et al.* (2005) present a better fit with experimental values.

Figure 12: Pickup velocity as a function of pipeline diameter.
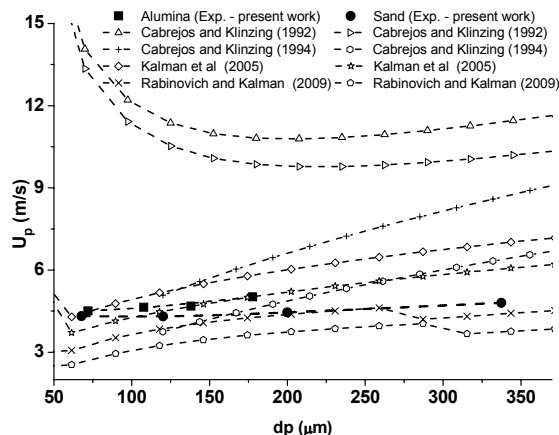
Influence of Particle Density

Figure 13 presents the plot of pickup velocity as a function of the density of sand particles with an average diameter of 1.0 mm. In the simulations the pipeline diameter was equal to 50.4 mm. The correlations of Cabrejos and Klinzing (1992) and Rabinovich and Kalman (2009) show the highest and lowest pickup velocities, respectively. For the density of 5000 kg/m³ the difference between the highest and lowest pickup velocity is approximately 16 m/s.
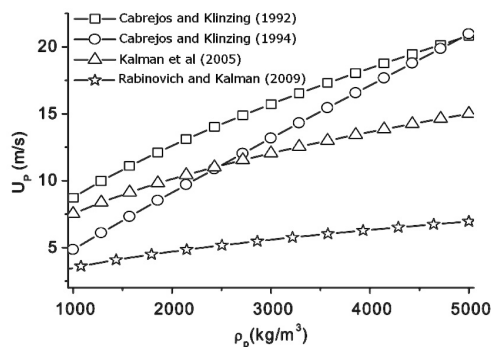
Figure 13: Pickup velocity as a function of particle density.

Figure 14 shows the plot of the pickup velocity as a function of particle diameter for particles of sand and alumina. The experimental data were obtained in this work. Correlations with the best agreement with the experimental data are Cabrejos and Klinzing (1994) and Kalman *et al.* (2005).

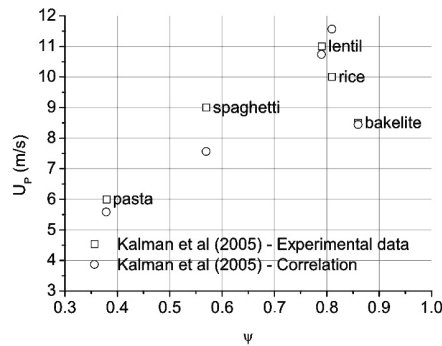**Figure 14:** Pickup velocity as a function of particle density.

Influence of the Particles Sphericity

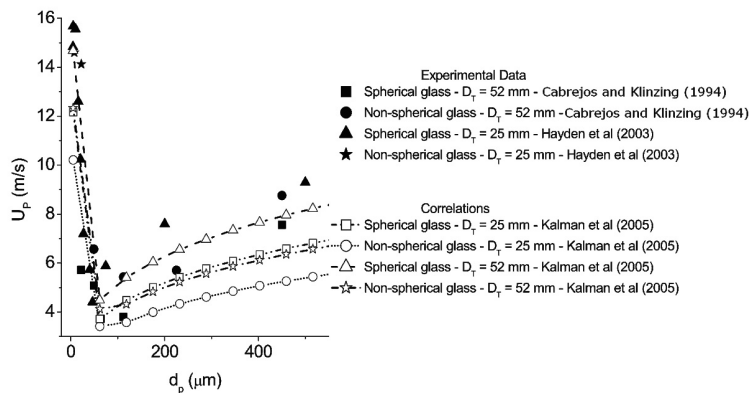Figure 15 shows the pickup velocity as a function of sphericity for pasta (ρ_p = 1200 kg/m³), spaghetti

(ρ_p = 1500 kg/m^3), lentil (ρ_p = 1644 kg/m^3), rice (ρ_p = 1590 kg /m^3) and bakelite (ρ_p = 930 kg/m^3) particulate materials. The analysis was performed only with the Kalman´s correlation (Kalman *et al*., 2005), since it presents a dependence of pickup velocity on sphericity. To obtain the experimental data, a pipe with a 100 mm diameter was used. The correlation shows reasonable agreement with experimental data. However, a careful observation of this correlation demonstrates that the pickup velocity decreases with decreasing sphericity (keeping other parameters constant), which is in contradiction to the physical phenomena involved, since the pickup velocity should increase with the reduction of the sphericity (Cabrejos and Klinzing, 1992; Cabrejos and Klinzing, 1994; Hayden *et al*., 2003) and not the opposite, as is the case of this correlation (see Figure 16).

Figure 16 shows the pickup velocity as a function of particle diameter for pipe diameters of 25 and 52

mm. The materials used were spherical and non-spherical glass. The experimental data are obtained from Cabrejos and Klinzing (1994), Hayden *et al.* (2003) and Kalman *et al.* (2005). The densities are 2480, 2500 and 2834 kg/m^3, respectively. The sphericity of the non-spherical glass is 0.7 (Cabrejos and Klinzing, 1994). Note that the non-spherical glass has greater velocities than the glass spheres in both pipe diameters of 25 and 50 mm. This is due to the fact that, in the case of non-spherical particles, the contact area is larger and therefore there is a greater action of the cohesion forces (Cabrejos and Klinzing, 1994; Hayden *et al.,* 2003; Kalman *et al.*, 2005). In Kalman's correlation (Kalman *et al.*, 2005) the pickup velocities of spherical particles are always larger than those for non-spherical particles, thus showing that the reasonable agreement obtained in the pickup velocity from experimental data was related to its correlation with other parameters and not necessarily with the sphericity.

Figure 15: Pickup velocity as a function of the particles sphericity.

Figure 16: Pickup velocity as a function of particle diameter for pipe diameters of 25 and 52 mm.

CONCLUSION

Due to the different definitions of the minimum conveying velocity used by researchers and the wide scatter of the data and contradictions demonstrated in this paper, it is concluded that the correlations analyzed present great difficulty in predicting the saltation and pickup velocities. The recommendations presented in this work are based on combined quantitative and qualitative analysis, so both the agreement with experimental data (quantitative) as the agreement with the observed physical phenomenon (qualitative) are considered. Based on the analysis of the parameters that influence saltation and pickup velocities, one may conclude that:

▪ In the case of fine particles, the only correlation recommended for saltation velocity is the Rizk correlation (1976), since the others do not agree with the physical phenomenon in question.

▪ It is recommended that the correlations of Rizk (1976), Matsumoto *et al.* (1977) and Cabrejos and Klinzing (1994) be used in determining the saltation velocity of coarse particles (average particle diameter above 200 μm. The use of these correlations should still be considered for pipeline diameters ranging from 25 to 200 mm. It is noteworthy that the use of these correlations must be done with great care, since in some tests even the best correlations (those recommended here) showed low agreement with the experimental results. Nonetheless, these correlations presented the best results, but are recommended here with reservations;

▪ The correlations that presented the best performance for the pickup velocity prediction are those of Cabrejos and Klinzing (1994) and Kalman *et al.* (2005). However, they are limited to a few tests. The Cabrejos correlation (Cabrejos and Klinzing, 1994) has the disadvantage of not providing results for very low average particle diameter (below 120 μm) and also has a tendency to overestimate particle pickup velocity for very large diameters (up to 3 mm). The Cabrejo correlation must be used with caution. Thus, we recommend Kalman´s correlation for predicting pickup velocity, because it showed reasonable success in all tests, except in correlating the influence of sphericity, where it was inefficient.

ACKNOWLEDGEMENTS

NOMECLATURE

A	cross-sectional area of pipe	m^2
A_H	Hamaker constant	N.m
Ar	Archimedes number	-
C_D	drag coefficient	-
C_V	Solids volumetric concentration	-
D_{50}	inside diameter of 2" pipe	m
d_p	particle diameter	m
D_T	pipe diameter	m
Fr_{min}	Froude number at the minimum conveying velocity	-
Fr_S	Froude number at the Saltation velocity	-
f_s	coefficient of sliding friction	-
g	acceleration due to gravity	m/s^2
G_S	solids flux	$kg/m^2.s$
m_p	particle mass	kg
n	Wall effect coefficient	-
Re	Reynolds number related to pipe diameter	-
Re_p	Reynolds number related to particle diameter	-
Re_p^*	Reynolds number modified	-
s	separation length between particle and the wall	m
U_{min}	minimum conveying velocity	m/s
U_{mp}	minimum pressure velocity	m/s
U_p	minimum pickup velocity	m/s
U_{p0}	minimum pickup velocity for single particle	m/s
U_S	Saltation velocity	m/s
U_{s0}	Saltation velocity of an isolated particle	m/s
U_t	terminal velocity	m/s
W_S	solids mass flow rate	kg/s

Greek Letters

ε	porosity	-
ζ	solids loading ratio	-
μ	gas dynamic viscosity	kg/ms
ν	fluid kinematic viscosity	m^2/s
ρ_f	fluid density	kg/m^3
ρ_p	solid particle density	kg/m^3
ψ	Particle sphericity	-

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