# EXPERIMENTAL STUDY OF PARAMETERS INFLUENCING THE PICKUP VELOCITY IN PNEUMATIC CONVEYING SYSTEMS

**Luiz Moreira Gomes**, **luizmg@ufpa.br.**
**André Luiz Amarante Mesquita**, **andream@ufpa.br**
Lab. de Transporte Pneumático - Faculdade de Eng. Mecânica – UFPA - R. Augusto Corrêia, s/n CEP 66075-010.

**Marcelo de Oliveira e Silva, marcelo.silva@solveengenharia.com.br**
**Pedro Henrique da Silva Macias, pedro.macias@solveengenharia.com.br**
Solve Engenharia Ltda. – Rua Curuçá, 260 – s. 206 – 66.050-080 Belém, PA

***Abstract***. *The transport velocity is one of the most important parameters in pneumatic conveying of particles. The success of conveying particulate material depends on the prediction or the determination of the minimum transport velocity. The high conveying velocity will result in greater energy consumption due an increased pressure drop of the system, solids degradation and pipe erosion. On the other hand, conveying velocities that are very low can result in saltation and blockage of the pipeline. In this research work, the particle entrainment is investigated by measuring the velocity required to pick up particles from rest, also known as pickup velocity. An analysis of the influence of several parameters on the pickup velocity, such as particle diameter and density and pipe diameter, is made. A correlation is developed and the numerical results evaluated show good concordance with experimental data.*

***Keywords**:* pickup velocity; minimal velocity; gas-solid flow; pneumatic conveying.

## 1. INTRODUCTION

In the pneumatic transport of solid particles in pipes, it is important to choose an air velocity that is as low as possible in order to reduce power consumption, pipe wear and particle breakage. In accordance to Cabrejos *et al*. (1992), the minimum transport velocity is one of the most important parameters in the pneumatic transport of solids. A velocity greater than the minimum necessary to the steady transport of solid particles leads to a great energy consumption due to the system's pressure drop, solids degradation and pipe erosion. Oppositely, the velocity below this value threshold will certainly result in the deposition of solid particles on the pipe bottom and blockage. If this gas velocity is set at the beginning of a pneumatic transport system (at the feed point), the rest of the pipeline will operate well above this lower velocity threshold, since the gas velocity will increase along the pipeline due to compressibility effects. Keeping gas velocity above minimum conveying velocity in all horizontal sections of a pipeline ensures no deposition of solids in the system and a continuous and steady conveyance of solids.

In literature, several terms are employed to refer to the minimum transport velocity: pickup velocity, saltation velocity, suspension velocity, critical velocity, rolling or sliding velocity, initial mixing velocity, velocity at the pressure minimum point of the general state diagram etc. All these minimum transport velocities have similar numerical values and are based on visual observations and pressure drop measurements. These velocities are characteristic to an alteration in the flow regime, changing from a steady to an unstable phase. It also indicates some transition in the way that the particles are moving or beginning their movements (Herbreteau *et al.*, 2000).

The pickup velocity is relevant in a wide range of applications. For example, some pharmaceutical industries are focused on dry powder inhalers for drug delivery, the movement of sand dunes and soil deposition in river and ocean flows (Kalman *et al.*, 2005) and understanding erosion of silt on riverbeds (Kalman and Rabinovich, 2007). Likewise, pickup velocity is an important parameter in dust control applications. A good estimate of the minimum conveying velocity must be known in order to optimize any solids conveying system. This research work evaluated the influence of diameter and density of the particle and the pipe diameter at the pickup velocity.

## 2. LITERATURE REVIEW

Cabrejos *et al*. (1992) developed a technique to determine the pickup velocity of solid particles in horizontal pneumatic conveying. It was based on visual observations of particles in rest at the bottom of a transparent pipe when the air velocity was gradually increased. Using a structure consisting of a transparent, 7-meter-long, 52-millimeter diameter pipeline with a removable section, a compressed regulated air supply, and a collector of solids, the researchers measured the pickup velocity experimentally.

In order to carry out the measurements, the researchers created, inside a removable and transparent section of the pipe, a 1-meter-long layer of particles with approximately half of the cross-sectional area of the pipe left free. A constant gas flow rate was set through the pipeline and the layer started to erode slowly as the gas stream picks up the top particles. As the free cross-sectional area increased, the gas velocity over the layer decreased and so did the capacity of the stream to pick up more particles. The described phenomenon takes place continuously, and a final equilibrium was automatically reached when no more erosion occurred. By measuring the volumetric flow rate of air ($Q_{air}$) and the free cross-sectional area ($A_{free}$) remaining over the particles, the minimum pickup velocity ($U_{pu}$) could be easily calculated using the equation:

$$U_{pu} = \frac{Q_{air}}{A_{free}} \tag{1}$$

Cabrejos and Klinzing (1994), applying dimensional analysis, found that the following π groups can describe the pickup mechanism of the coarse particles in horizontal tubes

$$f\left(\frac{U}{\sqrt{g\,d_p}}, \frac{\rho_p}{\rho}, \phi, \frac{D}{d_p}, \frac{d_p U \ \ \rho_p}{\mu}\right) = 0 \tag{2}$$

They also analyzed the effect of several parameters that affect the pickup velocity of coarse particles in horizontal pipes. By changing one parameter and keeping the others parameters constant, the following relationships were found:

$$U_{pu} \propto d^{1/2}; U_{pu} \propto \rho_p{}^{3/4}; U_{pu} \propto \rho^{-1/2}; U_{pu} \propto D^{1/4} \tag{3}$$

The authors also verified that the influence of the conveying gas viscosity on the pickup velocity is minimal. Finally, they postulated the following relationship to determine the pickup velocity:

$$\frac{U_{pu}}{\sqrt{g\,d_p}} = 0,0428\,\mathrm{Re}_p{}^{0,175}\left(\frac{D}{d_p}\right)^{0,25}\left(\frac{\rho_p}{\rho}\right)^{0,75} \tag{4}$$

This relationship is valid for $25<R_{ep}<5000$, $8<(D/d_p)<1340$ e $700<(\rho_p/\rho)<4240$.

Kalman *et al.* (2005) used a rectangular wind tunnel (which consisted of 10 square ducts) to measure the pickup velocity of the particles initially in rest. The layer of particles was created by filling a rectangular shallow bath attached to the bottom of the wind tunnel (Fig. 1).The top surface of the particle layer matched the bottom surface of the tunnel. The technique used by them consisted in measuring the pickup velocity by plotting the amount of entrained particles (weight reduction of the layer) as a function of operating gas velocity. The pickup velocity was determined at the intersection of the extrapolated curve passing through the measured points and abscissa.

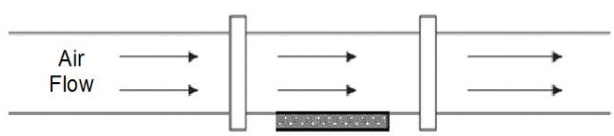


Figure 1. Schema of experimental setup of the Kalman *et al.* (2005)

They also developed a relationship for the pickup velocity in terms of modified Reynolds number as a function of modified Archimedes number. They modified the Reynolds number empirically to take the pipe diameter into account:

$$\mathrm{Re}_p{}^* = \frac{\rho U_{pu} d_p}{\mu\left(1,4 - 0,8.e^{-\frac{D/D_{50}}{1,5}}\right)} \tag{5}$$

Then, they presented the following correlation:

$$\frac{U_{pu}}{U_{pu50}} = 1,4 - 0,8.e^{-\frac{D/D_{50}}{1,5}} \tag{6}$$

By this correlation, all measured pickup velocity found in the literature can be converted to the pickup velocity in a 2-inch pipe for further investigation. In accordance with the authors, this equation agrees well with the measurements conducted with pipe diameters ranging from about 1 up to 6 in.

By using their own experiments and data of others researchers, they developed three relationships, each one applied to a specific flow situation. The three-zone model was reasonable according to the Geldart classification. The first zone applies to large particles and the cohesive forces are negligible.

$$\mathrm{Re}_p{}^* = 5\,Ar^{\frac{3}{7}}, \text{ for Ar} > 16.5 \tag{7}$$

In the second zone, the cohesive forces are considerable, but still the particles are picked up individually.

$$\mathrm{Re}_p{}^* = 16{,}7, \text{ for } 0.45 < \text{Ar} < 16.5 \tag{8}$$

In the third zone, the cohesive forces are very strong, the particles are very small and the capture occurs in agglomerates instead of individual particles.

$$\mathrm{Re}_p{}^* = 21{,}8.Ar^{\frac{1}{3}}, \text{ for Ar} < 0.45 \tag{9}$$

The relationships are valid for $0.5<\mathrm{Re}_p^* <5400$, $2.10^{-5} < \mathrm{Ar} < 8.7.\ 10^7$, $0.53 < d_p < 3675$ μm, $1119 < \rho_p < 8785$ kg/m$^3$ and $1.18 < \rho < 2.04$ kg/m$^3$.

## 3. MODEL FOR INCIPIENT MOTION OF A SINGLE SPHERE

The significant forces acting on a single sphere in rest at the bottom of a horizontal tube are: drag force, friction force, cohesive force, buoyancy force, lift force and gravitational force. Cabrejos and Klinzing (1992) showed that the horizontal movement occurs before the vertical lift-off. According to Hayden e*t al*. (2003), the pickup velocity is considered to be the velocity at which the particle becomes entrained in the moving fluid, which implies vertical movement.

In this paper, the force balance is made for the motion particle in vertical direction. To achieve the vertical pickup, the resulting force in this direction is equal to zero.

$$F_g + F_a = F_l + F_b + F_d \tag{10}$$

The lift, buoyancy and adhesive forces are not appreciated in this demonstration. Thus

$$F_g = F_d = C_D A \rho \frac{v^2}{2} \tag{11}$$

Since $v \sim \mu_\tau$ (friction velocity) and $\mu_\tau{}^2 = \tilde{c}\bar{v}^2 f^2$

$$F_g = C_D A \rho \frac{\mu_\tau{}^2}{2} = C_D A \rho \tilde{c}\bar{v}^2 \frac{f^2}{2} \tag{12}$$

where $\tilde{c}$ is a parameter related the turbulent fluctuations.

Rewriting Eq. (16), in terms of friction factor,

$$f^2 = \frac{2P}{C_D A \rho \tilde{c}\bar{v}^2} \Rightarrow f = \sqrt{\frac{2P}{C_D A \rho \tilde{c}\bar{v}^2}} \tag{13}$$

Using Blasius relation,

$$f = \frac{0.316}{\mathrm{Re}^{1/4}} \tag{14}$$

Making some algebraic manipulations we obtain the relationship,

$$U_{puo} = 5.628289 \frac{g^{2/3} \rho_p{}^{2/3} d_p^{2/3} D^{1/3}}{C_D^{2/3} \rho^{1/3} \tilde{c}^{2/3} \mu^{1/3}} \tag{15}$$

We adjust the parameter $\tilde{c}$ empirically. Then we get

$$U_{puo} = 5.628289 \frac{g^{2/3} \rho_p{}^{2/3} d_p^{2/3} D^{1/3}}{C_D^{2/3} \rho^{1/3} \left(-49.678 \ln(d_p) + 902.5\right)^{2/3} \mu^{1/3}} \tag{16}$$

This relationship shows us the dependency of the pickup velocity of the properties of the particle and conveying gas as well as that of the duct diameter.

## 4. THE GENERAL SEMI-EMPIRICAL CORRELATION

By combining the single particle model with experimental results for pickup velocity of a pile of particles in a pipe on the horizontal direction, it was possible to determine a general semi-empirical correlation which was simple and practical to determinate the pickup velocity of a layer of particles. The semi-empirical correlation developed is valid over the range of particles sizes from 30 to 4000 μm and can be written as follows:

$$U_{pu} = \left(2.7 Ar^{-1/4} + 0.03 Ar^{-1/14} + 0.45\right)\left(1.8 Ar^{-1/4} + 1\right) U_{puo} \tag{17}$$

The Archimedes number was used to correlate the particle-particle interactions and particle shape. It characterizes the particle-gas properties and is related with the Froude number, the Reynolds number and the ratio of gravity to buoyant force.

The next section describes briefly the experimental setup used and the adopted procedures in order to measure the pickup velocity of solid particles in a horizontal pipeline.

## 5. EXPERIMENTAL SETUP

An experimental setup used to determine the pickup velocity of particles was built in the Pneumatic Conveying Laboratory - LTP - UFPA. Experiments were carried out using air at ambient conditions as the conveying gas. The setup consists basically of a 1.5-meter-long, 50mm in diameter. horizontal steel pipeline, three horizontal PVC pipelines (6-meter-long each and 50, 75 and 100mm in diameter) with a butterfly valve on the end of each pipeline, three transparent sections (placed in the middle of the PVC pipelines) where the visual observations were carried out, a roots blower (controlled by a frequency inverter) that provides the gas velocity and pressure necessary to pick up the particles and a solids collector with a paper filter bag placed on top of it. Figure 2 shows schematically the setup designed to carry out pickup velocity experiments.

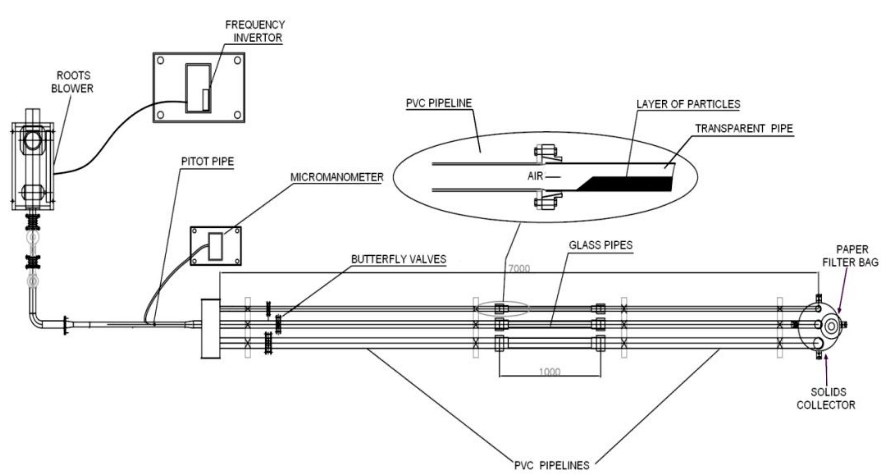


Figure 2.The experimental setup-Schematic representation.

The experimental method used to measure pickup velocity starts with a stationary layer of particles placed in the center 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 due to removal of particles, the air velocity decreases. Eventually, when the velocity is no longer sufficient to entrain any additional particles, a final 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 (Fig. 3). Obviously, a higher quantity of measurements improves the accuracy, especially if measurements with very small weight losses can be achieved.

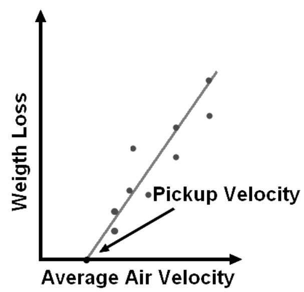


Figure 3. Schematic representation of pickup velocity measurement.

The main difficulty of this method arises when the initial layer consists of very fine powders. This layer induces a compression load in the packed material sample, affecting the measurements.. Therefore, most of the measurements were conducted with coarse particles. This problem was also observed by Cabrejos and Klinzing (1992), Hayden *et al.* (2003) and Kalman *et al.* (2005).

In order to assess the effect of pipe diameter in the pickup velocity, three PVC pipelines were used in an alternate way. 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. The pickup velocity was measured with the use of our technique. This procedure was also carried out with the second and third valves and then we analyzed the effect of the pipe diameter in the pickup velocity.

## 6. RESULTS AND DISCUSSION

In order to assure the accuracy of the methodology developed, the experiments were repeated six times. Figure 4 shows the measures of weight loss as a function of operation gas velocity. In this present research work and in that of Kalman *et al*. (2005), the particles pickup velocity is obtained with the intersection of the extrapolated curve, passing through the measured points, and abscissa. Two indicators used for comparison, the relative deviation and the average absolute deviation, were found to present the highest values equal to 7.1% and 0.268 m/s, respectively, for all measured points.

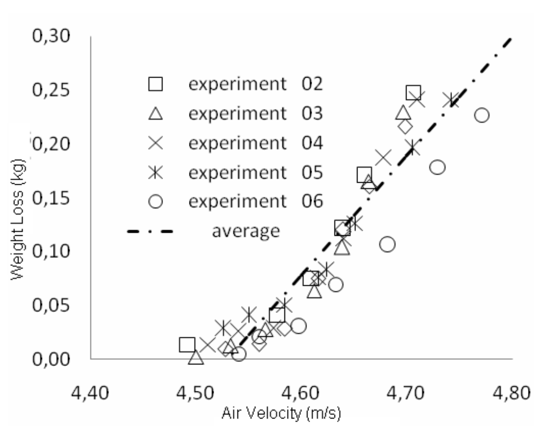


Figure 4. Weight loss as a function of the average air velocity.

In Fig. 5, the effect of particle diameter is illustrated when keeping the others parameters constant, i.e. particle density, conveying gas density and viscosity, and pipe diameter. Several measurements were performed with sand grains in the particle diameters of 22, 48.5, 63.5, 89.5, 179.5 and 253.5 μm. Each experiment was repeated three times and then a curve of average pickup velocity as function of the particle diameter was plotted. An important result obtained is the existence of a minimum point in the curve of minimum pickup velocity as a function of particle diameter, which corroborates Cabrejos and Klinzing (1992), Hayden *et al*. (2003) and Kalman *et al*. (2005). This minimum point appears at particle diameter of 89.5 μm. As expected, bigger particles required higher mean gas velocities to be picked up due the inertial effects to be dominated. For the smaller particles, the pickup velocity is also high due to the particle-particle interactions to be significant in this region.

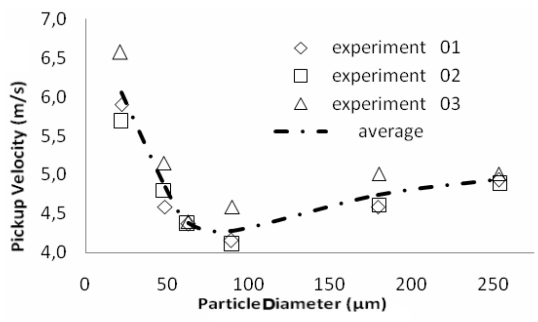


Figure 5. Pickup velocity as a function of the particle diameter

Figure 6 also shows the result of experiments made with sand grains with sizes ranging from 100 to 2800 μm. The experiments were made in 50, 75 and 102 mm pipes. We can see the influence of the duct diameter in the pickup velocity, i.e., higher speeds for larger pipes diameters.

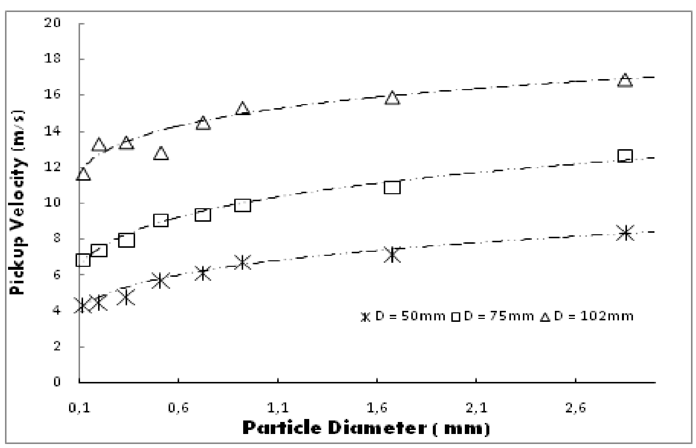


Figure 6. Pickup velocity as a function of the particle diameter.
Pipes Diameters: 50, 75 and 102 mm.

Figure 7 shows in a semilog plot the pickup velocity as a function of the pipe diameter. The particle diameters used were 0.12, 0.34, 0.73 and 1.68 mm. It can be seen that pipe diameter affects the pickup mechanism of solids particles in horizontal pipes, an important fact to be considered in designing scale -up procedures. This results are in good concordance with the Cabrejos and Klinzing (1994). These researchers investigate the influence of the pipe diameter at the pickup velocity, reporting that this velocity varies with the 0.25 power.

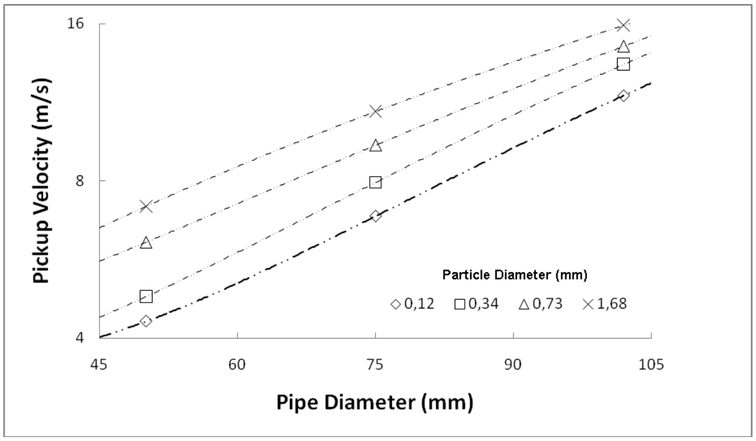


Figure 7. Pickup velocity as a function of pipe diameter.

In order to illustrate the relative significance of particle density, Fig. 8 shows a plot of the pickup velocity as a function of the particle diameter for alumina and sand particles. The densities are 3750 and 2636 kg/m$^3$, respectively. As we have seen, the pickup velocity for alumina is higher, thus corroborating Cabrejos and Klinzing (1994). This is so because the inertial effects dominate and require higher flow rates to entrain particles with higher densities.

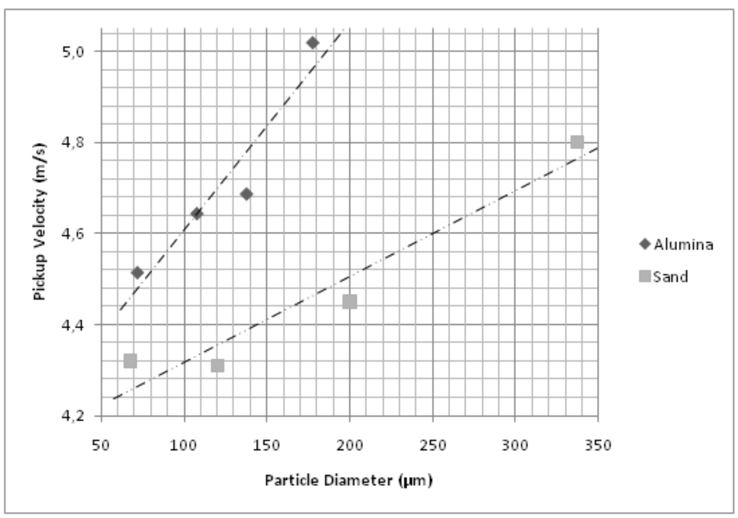


Figure 8. Pickup velocity as a function of the particle diameter. Alumina and sand particles.

The Fig. 9 shows the pickup velocity as a function of the particle diameter of the sand grains obtained experimentally in this present work and the correlations developed by Cabrejos and Klinzing (1994) and Kalman *et al.* (2005). The vertical bars play the experimental error (difference between the higher and the lower measured value) and the black square represents the mean value. The results are good, mainly in the diameter range of 40-80 μm, which is a critical region. The accordance with the correlation of Cabrejos and Klinzing (1994) is reasonable for the measured values, being that with the increased mean diameters of the particles, the values evaluated by Cabrejos and Klinzing (1994) rise up more quickly.

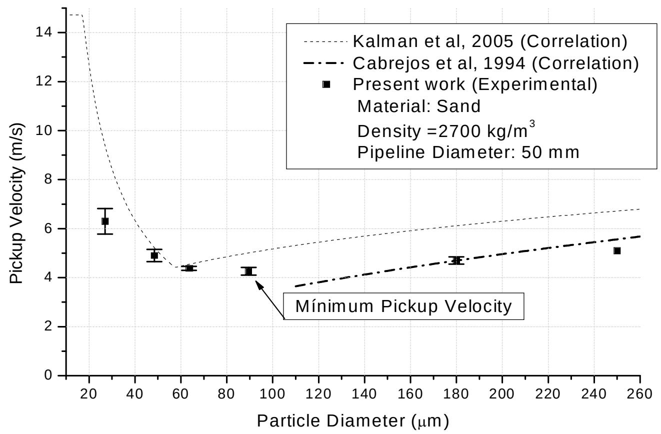


Figure 9 – Pickup velocity as function of the particle diameter

It is important to point out that the proposed technique presents good accordance with the techniques proposed by Cabrejos and Kinzing (1992), Haiden *et al*. (2003) and Kalman *et al*. (2005). Fig. 9 shows that the minimum transport velocity (in this research work) occurs in the mean diameter of 89,5 µm. Therefore, the transport of sand particles to minimum power consumption would have to use this size of particle. In industrial applications, sand grains with a specific diameter are not used; however, this result is very important because it gives one better phenomenological understanding of the physical phenomenon involved. This minimum point corresponds to the transition between the effect of the electrostatic forces and inertial forces. Thus, at the larger particles diameter, 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.

In order to evaluate the accordance of the correlation developed in this work, the pickup velocity was calculated and plotted against the experimental result of Cabrejos and Klinzing (1994), Hayden *et al*. (2003), Kalman *et al*. (2005) and Gomes and Mesquita (2006). The predicted values using the present correlation showed a very good concordance with the experimental data (Figs. 10-11).

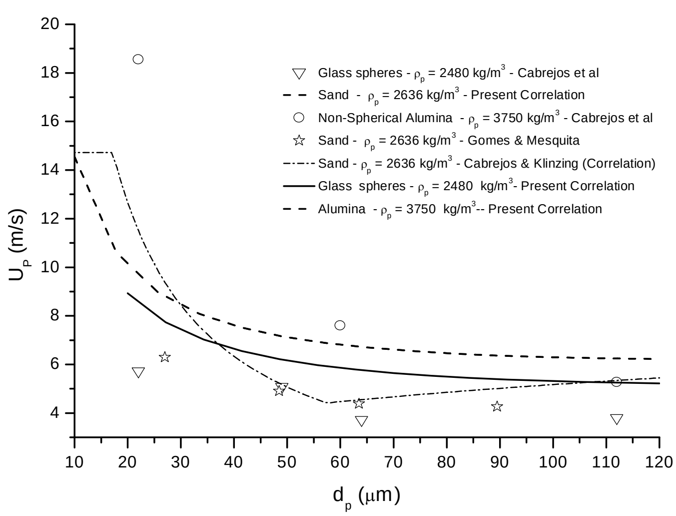


Figure 10. The pickup velocity D = 52 mm.

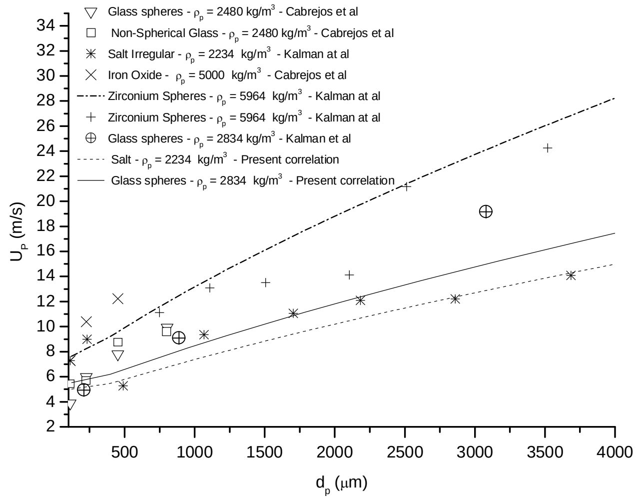


Figure 11. The pickup velocity - D = 52 mm.

Our correlation presents good results for particle densities ranging from 1500 to 6000 kg/m$^{3.}$ Another interesting aspect is the fact that it also shows very good results for particles sizes ranging from 30 to 4000 μm, i.e., a large interval in densities and sizes. Almost all particles handled by industry, in a general way, are within this size range, making evident the great applicability of this correlation.

## 7. CONCLUSIONS

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.

The measured pickup velocity for the different pipe diameters of sand particles indicates a countable effect of the pipe diameter.

The pickup velocity for different solids cannot be easily predicted because this parameter is influenced by many variables. Among these, the characteristics of the material itself, such as particle size, density and shape, the coefficient of sliding friction, and the particle interaction with other particles are the most important variables that affect pickup velocity.

The practical significance of the minimum pickup velocity is that it can be used as the safe gas velocity for the horizontal conveyance of solids. The usefulness of the concept of minimum pickup velocity is that one of the most important parameters for the design of pneumatic conveying systems, i.e., the minimum transport velocity, can be predicted by performing relatively simple and inexpensive experiments with the technique developed, which provides a new alternative for engineers and designers to predict the minimum transport velocity of solids.

## 8. ACKNOWLEDGEMENTS

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