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A METHODOLOGY TO DETERMINE THE PICKUP VELOCITY IN PNEUMATIC CONVEYING SYSTEMS

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Abstract. *The transport velocity is one of the most important parameters in pneumatic conveying of solids. The success of the particulate material conveying 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. A technique to measure the minimum pickup velocity of the solid particles in horizontal pneumatic conveying has been developed. It is based on visual observation of the behavior of particles lying on the bottom of a transparent pipe when the gas stream velocity is gradually increased. Simple and inexpressive experiments were carried out with the objective of the measure the pickup velocity. It is presented a qualitative analysis of the influence of the particle and pipeline diameters in the minimum conveying velocity.*

***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 as low as possible to reduce power consumption, reduce pipe wear and particle breakage. In accordance to Cabrejos *et al.* (1992), the minimum velocity of transport is one of the most important parameters in the pneumatic transport of solids. A velocity greater then minimum necessary to the steady transport of solid particles leads to a great energy consumption due to the system pressure drop, the solids degradation and pipe erosion. Oppositely, the velocity below of this velocity bound certainly will result 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 bound, 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 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 presents similar numerical values and are based on visual observations and pressure drop measurements. These velocities characterize an alteration of the flow regime, changing from a steady to an unstable phase. It also indicates some transition on the way that the particles are moving or beginning their movements (Herbreteau *et al.*, 2000).

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. 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. Likewise, pickup velocity is an important parameter in dust control applications. Other applications of pickup velocity include studying the movement of sand dunes and understanding erosion of silt on riverbeds (Kalman and Rabinovich, 2007).

There are few experimental techniques to measure the pickup velocity. Cabrejos and Klinzing (1992), Hayden *et al.* (2003) and Kalman *et al.* (2005), developed methodologies to determinate de pickup velocity in horizontal pipes. However, these techniques can lead to some slight errors. This work presents an alternative methodology for pickup velocity measurement. We verify its efficiency in measure of the minimal pickup velocity. Obviously, a high quantity of measurements must be carrying out to improve the accuracy.

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 gradually was increased. Using a structure consisting of a transparent, 7 meters long, 52 millimeters in diameter pipeline with a removable section, a compressed regulated air supply, and a solids collector, 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, an 1 m long layer of particles with approximately half of the cross-sectional area of the pipe left free. A constant gas flowrate 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 flowrate 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:

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

Haiden *et al.* (2003) measuring the velocity required to pickup small particles from rest in horizontal ducts verified that the technique to measure the pickup velocity developed by Cabrejos *et al.* (1992) could lead to some slight errors when handled with particles of very small sizes due the effect of compression in the frontal side of the particle pile. The solution was to place the particle pile in slope form (Fig. 1).

Figure 1. Particles pile

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. 2).The top surface of the particle layer matched the bottom surface of the tunnel. The technique used by them consisted in measure the pickup velocity 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.

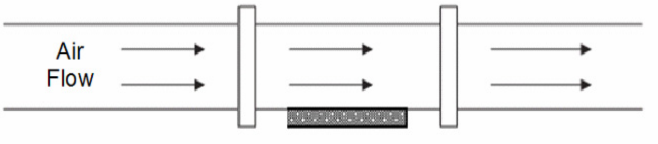

Figure 2. Schema of experimental setup of the Kalman *et al.* (2005)

They also verified the influence of the pipe diameter in the pickup velocity and developed a correlation where the pickup velocity measured in any diameter was divided by the pickup velocity of the same material measured in a pipe of 50 mm in diameter. The correlation developed by them was formulated as,

$$\frac{U_{pu}}{U_{p50}} = 1{,}4 - 0{,}8.e^{-\frac{D/D_{50}}{1{,}5}} \tag{2}$$

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

3. EXPERIMENTAL SETUP

An experimental setup used to determinate the pickup velocity of particles was built in the Pneumatic Transport Laboratory of the Turbomachinary Group - GTDEM - UFPA. Experiments were carried out using air at ambient conditions as the conveying gas. The setup consists basically of a 1.5 m long, 50 mm in diameter. horizontal steel pipeline (where the measurements of the air velocity were carried out), three horizontal PVC pipelines (each having 6m long and 50, 75 and 100 mm in diameter) with a butterfly valve installed on extremity of the each one, three transparent sections (placed in middle of the PVC pipelines) where the visual observations were carried out (Fig. 3), a Roots blower (controlled by a frequency invertor) 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 4 shows schematically the setup designed to carry out pickup velocity experiments.

Figure 3. The experimental setup. Visualization section.

The experimental method used to measure pickup velocity start with a stationary layer of particles placed in the center section of 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 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. 6). Obviously, a higher quantity of measurements improves the accuracy, especially if measurements with very small weight losses can be achieved.

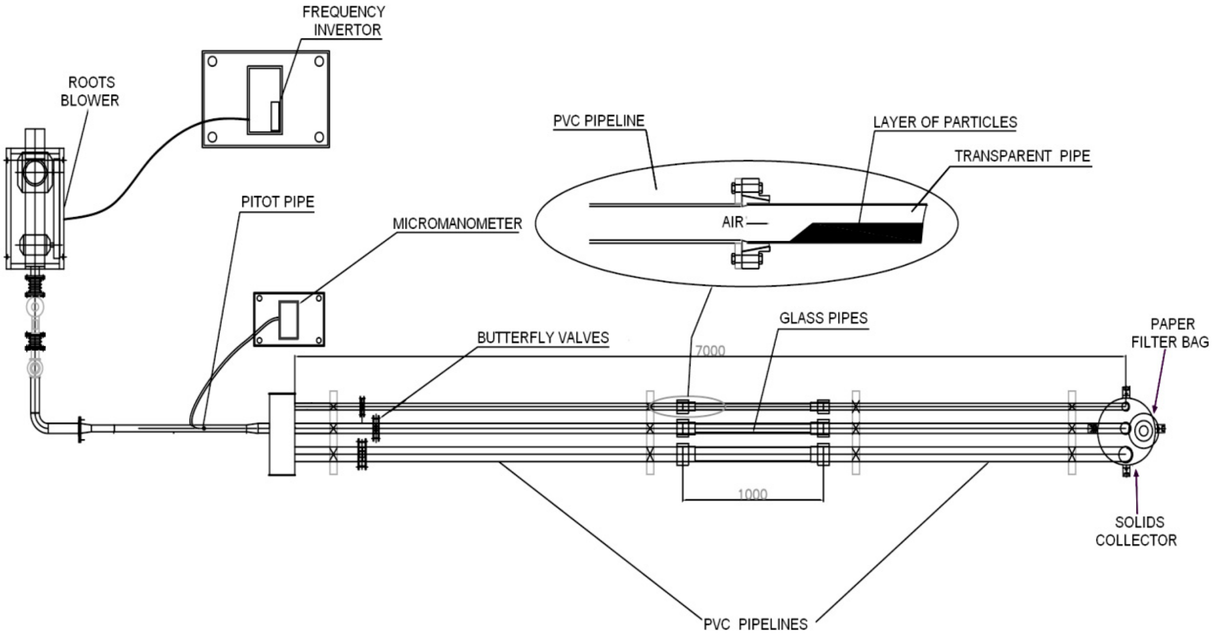

Figure 4.The experimental setup-Schematic representation.

The main drawback of this method arises when the initial layer consists of very fine powders flattening of the surface may impose of compression loads that can affect the measurements. Therefore, most of our measurements were conducted with coarse particles. This drawback also was observed by Cabrejos and Klinzing (1992), Hayden *et al.* (2003) and Kalman *et al.* (2005).

To assess the effect of pipe diameter in the pickup velocity three PVC pipeline were used in 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 carrying out also with the second and third valves and then we analyze the effect of the pipe diameter in the pickup velocity.

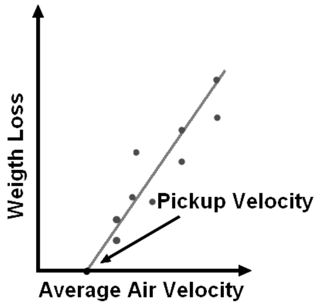

Figure 5. Schematic representation of measuring of the pickup velocity.

4. RESULTS AND DISCUSSION

In order to assess the accuracy of the methodology developed the experiments were repeated six times. Figure 6 show the measures of weight loss as a function of operation gas velocity. In our work and 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.

To assess the reproducibility, the measurements were performed with several particles diameters (Fig. 7). The curve of weight loss as function of the average air velocity is show more clearly in a semi log plot.

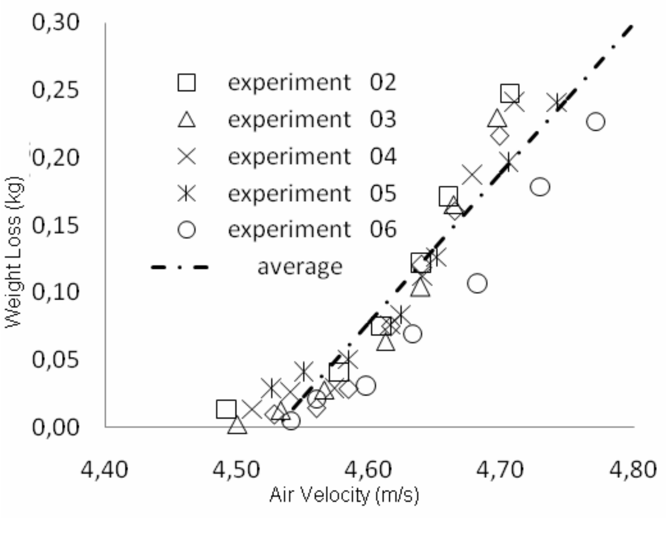

Figure 6. Weight loss as a function of the average air velocity.

In Fig. 8, 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 end then plotted a curve of average pickup velocity as function of the particle diameter. 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 appear 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 dominates. For the smaller particles the pickup velocity also is high due the particle-particle interactions to be significant in this region.

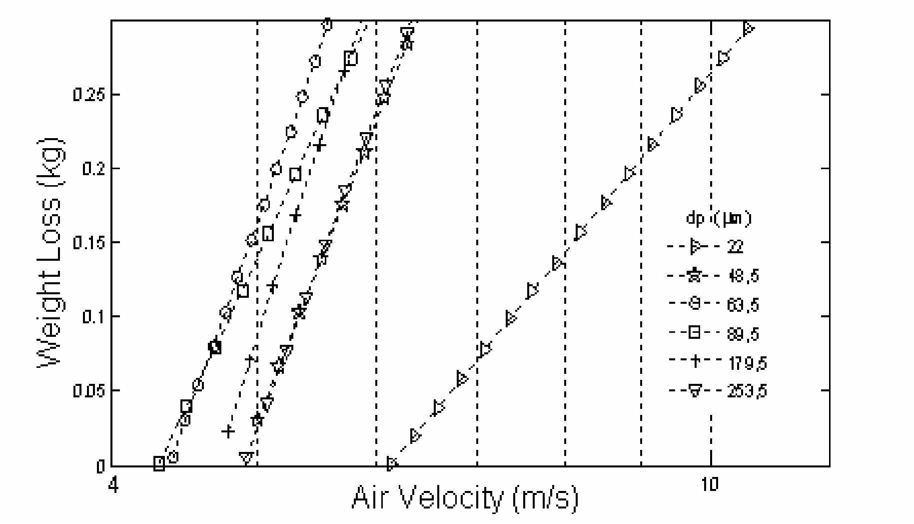

Figure 7. Weight loss as a function of the operation gas velocity

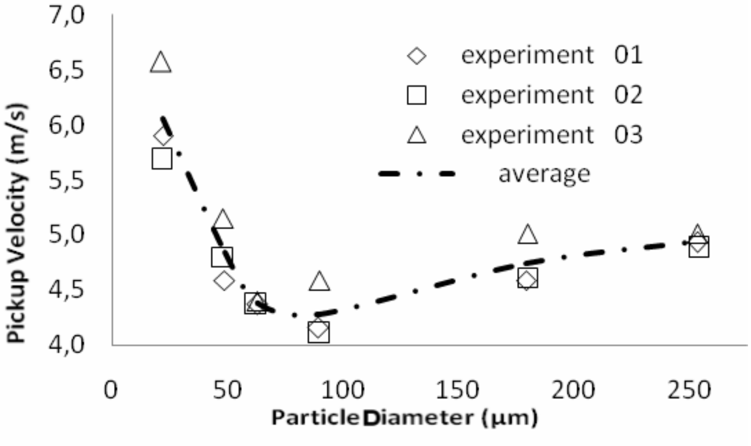

Figure 8. Pickup velocity as function of the particle diameter

We investigate the influence of the pipe diameter on the pickup velocity. The mean particle diameter in these experiments was 179,5 µm. It can be seen that pipe diameter affect the pickup velocity, an important fact to be considered in designed of pneumatic conveying systems. Previous investigators (Cabrejos and Klinzing, 1994 and Kalman *et al.*, 2005) also studied this influence of pipe diameter in the pickup velocity. Cabrejos and Klinzing, for example, verified that the pickup velocity varies with the pipe diameter to the 0.25 power The Tab. 1 shows the measures of the pickup velocity carry out on three experiments and the mean pickup velocity.

Table 1. Pickup velocity as a function of the pipe diameter

pipe diameter (mm)	**U_{pu} (m/s) (Experiment I)**	**U_{pu} (m/s) (Experiment II)**	**U_{pu} (m/s) (Experiment III)**	**mean pickup velocity (m/s)**
50	4,5	4,7	5,0	4,7
75	6,4	5,4	5,5	5,8
100	7,8	6,4	6,9	7,0

In order to evaluate the accuracy of the measured values (Tab.1), we compare the minimum pickup velocity measure by means of experimentation with the predicted values using the Eq. (2).The agreement between measured and calculated values is shown in Tab.2, was found to be generally within the accuracy of the tests, considering the large number of variables involved in the pickup mechanism. It can be seen what the measured values are slightly higher values as compared with the calculated results.

It is seeing that the Eq. (2) was obtained by experiments carried out in a rectangular wind tunnel and also in our work wasn't appreciated the influence of the particles shape.

Table 2. Comparison between the predicted and measured values for minimum pickup velocity.

pipe diameter (m)	**U_{pu} (m/s) – eq. 02**	**U_{pu} (m/s) – measured values**
0,050	4,5	4,7
0,075	5,0	5,8
0,100	5,4	7,3

We do not found in literature any measured data of the pickup velocity of sand grains; therefore, we adopted the following comparatives parameters:

1. Apply our data (particle density, air density, air viscosity etc) to the correlations found in literature and to compare the values measured with the evaluated values;

2. To compare the pickup velocity of the sand grains measured by us with pickup velocity of others materials (measured by others investigators) with similar characteristics (particle density, particle shape, air density, air viscosity, etc).

The Fig. 9 shows the pickup velocity as function of the particle diameter of the sand grains obtained experimentally by us 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 agreement with the correlation of Cabrejos and Klinzing (1994) is reasonable for the measured values, being that with the increases the particles mean diameters, the evaluated values by the investigators Cabrejos and Klinzing (1994) rise up more quickly.

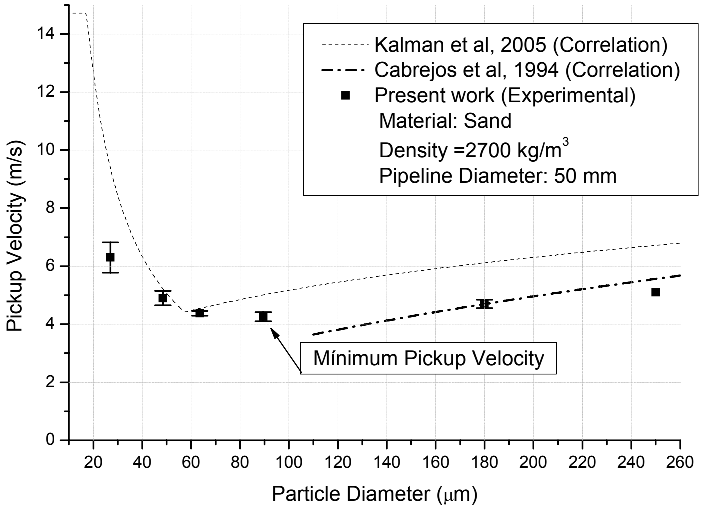

Figure 9 – Pickup velocity as function of the particle diameter

It is important to point out that the proposed technique presents good agreement with the techniques proposed by Cabrejos and Kinzing (1992), Haiden *et al.* (2003) and Kalman *et al.* (2005). The Fig. 9 shows that the minimum transport velocity (in this work) occurs in the mean diameter of 89,5 μm. Therefore, the transport of sand particle 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 flowrates 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.

The second adopted method was to compare the values of the measured pickup velocity with data of other materials with similar characteristics, existing in literature. In this case, one material with characteristics similar to the sand was the glass. Table 3 shows the comparative values. We can verify an agreement of our measured values with the results obtained by others researchers. Evidently, it is too difficult to find particles and their respective experimental setups with similar characteristics with those adopted on ours experiments. This justify the divergence among a few our measures and of the others investigators.

Table 3. Comparison between the properties of materials used by us and others researchers.

material	**shape**	**density (kg/m^3)**	**particle diameter (μm)**	**D (mm)**	**U_p (m/s)**	**Researchers**
glass	spherical	2480	22	52	5,7	Cabrejos *et al.*,1992
sand	nonspherical	2700	22	50	6,08	Present wok
sand	nonspherical	2700	48,5	50	4,88	Present wok
glass	spherical	2480	49	52	5,08	Cabrejos *et al.*,1992
glass	nonspherical	2480	49	52	6,67	Cabrejos *et al.*, 1992
glass	nonspherical	2480	112	52	5,43	Cabrejos *et al.*,1992
sand	nonspherical	2700	179,5	50	4,7	Present work
glass	spherical	2834	200	50	4,12	Kalman *et al.*,2005
salt	nonspherical	2234	215	50	7	Kalman *et al.*,2005
glass	nonspherical	2480	225	52	5,7	Cabrejos *et al.*,1994
glass	spherical	2834	200	100	4,9	Kalman *et al.*,1994

5. 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 new technique proposed for prediction of minimum pickup velocity of solids was successfully tested. It present advantages on techniques of the previous researchers. The techniques developed by Cabrejos and Klinzing (1992) and Hayden *et al.* (2003) present difficults in measuring the cross-sectional area, due the particles layer to erode in a non uniform way. The Kalman technique was developed in rectangular wind tunnel. Pickup Velocities obtained with use this technique must to be used with caution in design of the pneumatic conveying systems once that the geometry of the experimental setup will influence in results.

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 that provides a new alternative for engineers and designers to predict the minimum transport velocity of solids.

Finally, it is suggested that the proposed technique be used to determinate the minimum transport velocity of solid particles in horizontal pneumatic conveying systems.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Cabrejos, Francisco J., Klinzing, G. E., 1992, “Incipient motion of solid particles in horizontal pneumatic conveying”, Powder Technology,Vol. 72, pp. 51-61.

Cabrejos, Francisco J., Klinzing, G. E., 1994, “Pickup and saltation mechanisms of solids particles in horizontal pneumatic transport”, Powder Technology, Vol.79, pp. 173-186.

Hayden, K. S., Park, K, Curtis, J. S. , 2003, “Effect of particle characteristics on particle pickup velocity” , Powder Technology, Vol.131, pp. 7-14.

Herbreteau, C., Bouard, R., 2000, “Experimental study of parameters which influence the energy minimum in horizontal gas–solid conveying”, Powder Technology, Vol. 112, pp. 213-220.

Kalman, H., Satran, A., Meir, D., Rabinovich, E. , 2005, “Pickup (critical) velocity of particles” Powder Technology, Vol. 160, pp. 103-113.

Kalman, H., Rabinovich, E., 2007, “Pickup, critical and wind threshold velocities of particles” Powder Technology, Vol. 176, pp. 9-17.

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