MINIMUM TRANSPORT VELOCITIES OF MINERAL AND METALLIC DUSTS IN EXHAUST SYSTEMS

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ABSTRACT

For exhaust systems that handle dusts, a minimum transport velocity is required to prevent settling and plugging of ductwork. The minimum transport velocity required was studied experimentally for different kinds of dusts.

In the case of horizontal ducts, three different velocities related with the minimum transport velocity were measured: saltation velocity, settling velocity and pick up velocity. The experimental results obtained are shown in different graphs, plotting minimum transport velocities vs. particle size and density. From them, empirical exponential relationships were derived.

INTRODUCTION

The local exhaust ventilation systems used to capture air contaminated with dusts are important in many kinds of industrial plants, such as those of mining industry, extractive metallurgy processes, etc. In these industrial processes dust is produced in many operations related with the handling and processing of dry solid materials, like crushing, grinding, transport and storage of powders, roasting of minerals, etc. These systems are important not only from the health hazard control point of view, but also to increase the recovery of valuable products in the whole process.

As it is well known, for exhaust systems handling dusts, a minimum transport velocity (critical velocity) is required to prevent settling and plugging of ductwork. On the other hand, excessively high velocities are wasteful of power and may cause rapid abrassion of ductwork.

According to this, the design velocity, which is the velocity used to operate the system, has to be higher than the minimum transport velocity, having value enough to protect the system against different practical contingencies such as sticky or wet materials, electrostatics effects, etc. The design velocity is very important because, coupled with the volumetric flow rate will determine the size and type of the exhaust fan. As its requiered motor power varies, approximately, with the cube of the velocity, the economy dictates that the exhaust ventilation systems should operate at the lower possible velocity (Rajhans and Thompkins, 1967). The relation between the two velocities can be written as:

$$v_d = f_s \cdot v_{min} \qquad (1)$$

where f_s is a safety factor higher than one. For example, it could be taken $f_s = 2.0$ to 3.0.

In fact, the definition of minimum transport velocity given before is not precise. This is because the critical velocities required to move particles through horizontal and vertical ducts are different. In the former, the minimum transport velocity is the necessary one to avoid the settling of dust particles at the bottom of the duct. Whereas in the vertical ducts, it is the necessary velocity to avoid the permanent suspension of particles in the upward air flow (forming a disperse phase fluidized bed).

In the case of horizontal ducts, three different velocities related with the minimum transport velocity were measured (Baliff et al, 1948):

1- Saltation velocity: is defined as the average pipeline velocity below which the particles begin to bounce (that is, moving along in a series of short intermittent jumps).
2- Settling velocity: average pipeline velocity below which the particles begin to settle at the bottom of the pipe and the deposit builds up.
3- Pick up velocity: when the particles has been settled and the air flow is increased; it is the velocity above which the settled particles begin to be picked up by the air stream.

As it will be shown later in the experimental results, the pick up velocity v_{pi} , for a given kind of particles, is slightly higher than the settling velocity, v_{se}, but slightly lower than the saltation velocity, v_{sa}. Therefore it is: $v_{se} < v_{pi} < v_{sa}$ (2)

In spite that, theoretically, the exhaust ventilation systems (or the neumatic transport systems), can be operated with transport by saltation, this operating condition is not advisable, because the transport condition may be unstable, with the possibility of a blockage of pipe. According to this, it is convenient to consider that in equation (1) is: $v_{min} = v_{sa}$.

In the case of vertical ducts with upward air flow the condition to get the neumatic transport of the particles is that the air velocity must be slightly higher than the terminal (or free settling) velocity of the particles, v_t (free settling conditions can be assumed, because in ventilation systems there are low particle concentrations in the air phase). Therefore, in this case, in Equation (1) it should be:
$v_{min} = v_t$.

According to these considerations, the equation (1) can be written as:

- Horizontal ducts: $v_d = f_s . v_{sa}$ (3)
- Vertical ducts: $v_d = f_s . v_t$ (4)

EXPERIMENTAL APPARATUS

A diagram of the experimental apparatus used to determine minimum transport velocities in horizontal ducts, is shown in Figure 1. It was an exhaust ventilation system with a duct having an inside diameter of 70 mm and a total length of approximately 5 m. It was constructed of galvanized steel, but with a section of 1 m made of transparent plastic to permit the observation of the behaviour of the flowing mixture of air and dust. The plastic pipe was fitted to the steel one with flanged joints. A cyclone collector was used to remove the dust from the air and an exhaust centrifugal fan was used to produce the required air flow through the system. It was drived with a 15 HP electric motor. The volumetric flow rate measurement was made by the " Throat Suction Method " (A. C. G. I. H. , 1986). This method involves the measurement of the static pressure by means of a U-tube manometer connected to a piezometer ring of four holes (spaced 90° apart), which is situated three duct diameters downstream from the duct inlet. The air flow was controlled using a butterfly valve.The powder material under study was fed with a constant rate by means of a vibrating hopper situated at the inlet of the exhaust duct.

The equipment used to study the dust transport in vertical ducts was similar to the one described for horizontal ducts.

EXPERIMENTAL PROCEDURES

The tests were run with different kinds of solid particles, which are shown in Table 1. The densities of the materials were determined with a picnometer using mineral turpentine. In each case the studied material was grinded (if necessary) and then was separated into narrow size fractions using Tyler Standard sieve series, as it is shown in Table 2.

Table 1. Solids particles used for the experimental tests.

Materials	Composition	Density (g / cm^3)
Lead filings	Pb	11.3
Iron filings	Fe	7.8
Galena	SPb	7.5
Sphalerite (blende)	SZn	4.1
Clinker	Cement compounds	3.0
Limestone	CO_3Ca + gangue	2.7
Sulphur ore	S + gangue	2.6
Pumicite	Volcanic ash	1.9
Ulexite	$NaCa\ B_5O_9.8H_2O$	1.7
Sawdust	Wood	0.9

Table 2. Size fractions studied

Fractions	Meshes (Tyler Series)	Openings (mm)	d_p (mm)
1	14-20	1.17-0.83	1.0
2	20-28	0.83-0.59	0.71
3	28-35	0.59-0.42	0:51
4	35-48	0.42-0.30	0.36
5	48-65	0.30-0.21	0.26
6	65-100	0.21-0.15	0.18
7	100-150	0.15-0.10	0.13
8	150-270	0.10-0.074	0.09
9	270-400	0.074-0.038	0.056

The tests for horizontal ducts were run starting them with high air flow velocities with which the powder material was transported in suspension. The air velocities were gradually decreased until the solid particles began to bounce (v_{sa}), that could be observed in the plastic pipe. With a further slighly decrease in the air velocity the particles began to settle at the bottom of the pipe (v_{se}). When a deposit of particles built up at the bottom, the air velocity was increased slowly until the particles were picked up (v_{pi}).

The tests for vertical ducts were also started with high air flow, which was gradually decreased until in the vertical plastic pipe it could be observed that the particles were suspended in the air flow, forming a disperse phase fluidized bed (v_t).

RESULTS

The test results are presented here by means of different graphs. Figure 2 is included as an example of the results obtained for the different kinds of powders tested. The experimental values of the velocities related to the minimim transport velocity for clinker (v_{sa}, v_{pi} , v_{se} and v_t) as a function of the powder mean diameter are plotted in this figure. As it is shown in the case of horizontal ducts, the values of v_{sa}, v_{pi} and v_{se} are sligtly different, and they agree with the inequalities (2).

In the case of vertical ducts, it can be observed that the plotted results of the tests (v_t vs. d_p) correspond to a straight line which slope is larger than the slopes of the straight lines plotted for the case of horizontal ducts.

The pick up velocities and the saltation velocities for the different kinds of materials studied are plotted in Figures 3 and 4, respectively, as a function of the mean diameter of the samples. As it can be appreciated from these figures, the relationships between velocities and diameters can be represented by equations of the form:

$$v_{pi} = K_1\, d_p^{\,n} \qquad (5)$$

$$v_{sa} = K_2\, d_p^{\,m} \qquad (6)$$

where the constant factors K_1 and K_2, and the constant exponents n and m, are given in Table 3.

Table 3. Constants and exponents of the experimental correlations

Materials	Horizontal transport				Vertical transport	
	v_{pi}		v_{sa}		v_t	
	K_1	n	K_2	m	K_3	p
Lead filings	10.7	0.24	-	-	12.0	0.37
Iron filings	9.6	0.28	10.4	0.19	9.2	0.41
Galena	8.8	0.25	-	-	10.8	0 .41
Blende	7.3	0.27	-	-	8.1	0.41
Clinker	6.7	0.25	7.8	0.20	6.9	0.39
Limestone	6.0	0.29	-	-	-	-
Sulphur ore	6.0	0.29	6.9	0.25	6.0	0.40
Pumicite	5.8	0.29	6.4	0.24	4.3	0.24
Ulexite	5.4	0.28	-	-	4.2	0.35
Sawdust	4.0	0.20	5.4	0.20	-	-

These experimental correlations are limited to applications where the value of the Reynolds number is over 15,000:

$$Re = 10\, D\, v\rho / \mu \quad > 15{,}000 \qquad (7)$$

The limitation established in (7) is due to the fact that when the value of the Reynolds number is less than 15,000, the pick up and the saltation velocities are almost independent of particle sizes.

In the case of the experimental equipment used (D = 70 mm) , operating with air at 20 °C, the limit condition of Re = 15,000 corresponds, approximately, to an air flow velocity of v = 3,3 m/s (650 FPM). This can be observed in Figure 3 for light materials as sawdust and pumicite: for fine particles their straight lines change to horizontal ones. This fact could be explained because the transport of solid particles in horizontal ducts requires a highly turbulent flow to keep particles in suspension.

The constant factors K_1 and K_2 are characteristics of each solid material and they are function of the solid density, as it is shown in Figure 5. The following correlations can be developed from this plot:

$$K_1 = 4.3\ \rho_s^{0.37} \qquad (8)$$
$$K_2 = 5.2\ \rho_s^{0.34} \qquad (9)$$

Substituting the values of K_1 and K_2 from Equations (8) and (9) into Equations (5) and (6) and taking average values for the exponents n and m, the following simplified correlations are obtained:

$$v_{pi} = 4.3\ \rho_s^{0.37}\ d_p^{0.26} \qquad (10)$$
$$v_{sa} = 5.2\ \rho_s^{0.34}\ d_p^{0.22} \qquad (11)$$

These equations are also valid for Re > 15,000 and they give v_{pi} and v_{sa} in terms of particle density and particle diameter.

For the case of vertical transport, the terminal velocities, v_t, are plotted in Figure 6 as a function of the mean diameter. From it, it can be also obtained for vertical transport an equation of the form:

$$v_t = K_3\ d_p^{\,p} \qquad (12)$$

The values of the constants K_3 and p are given in Table 3. Making the same considerations as for horizontal transport, the following simplified correlation can be obtained:

$$v_t = 3.3\ \rho_s^{0.54}\ d_p^{0.39} \qquad (13)$$

It is interesting to point out that, as it can be observed in Figure 6, there is an inversion in the normal position of the straight lines of galena and iron filings (according to their densities). This perhaps could be explained because of the elongated shape of the iron filings particles, which increases the value of the drag coefficient.

The exponents of equation (13) give an indication than the experimental conditions of the tests carried out were into the range of validity of the Newton's law for free settling with turbulent resistance (Wills, 1979):

$$v_t = [\ 3gd_p(\rho_s - \rho)\ /\ \rho\ ]^{1/2} \approx k\ d_p^{1/2}\ \rho_s^{1/2} \qquad (14)$$

because ($\rho_s - \rho$) is approximately equal to ρ_s and $k = (\ 3g/\rho_s)^{1/2}$ is approximately constant.
The deviations of the exponent values of the Equation (13) with respect to Equation (14) are probably due to the non spherical shape of the particles.

CONCLUSIONS

As it is shown in Figure 2, for large particles the values of v_t (vertical transport) are higher than the corresponding values of v_{pi} and v_{sa} (horizontal transport), but for $d_p < 2.0$ mm is $v_t < v_{pi}$, and for $d_p < 0.7$ mm is $v_t < v_{sa}$. This tendency, given in Figure 2 for particles of clinker, is general for all the studied materials. As the local exhaust ventilation systems normally capture small particles, generally of $d_p < 0.2$ mm, such systems can be designed taking the saltation velocity (Equation 11) as the minimum transport velocity, that is to say: $v_{min} = v_{sa}$. According to this, the design velocity for the exhaust systems (Equation 1) can be written as: $v_d = f_s\ v_{sa}$ (15).

As frequently v_{sa} is difficult to measure, specially for small particles, the saltation velocity can be estimated from the pick up velocity experimental determination. Comparing Equations (10) and (11), and rejecting the small differences existing between their exponents, it results:

$$v_{sa} = 1.20\ v_{pi} \qquad (16)$$

Replacing (16) in Equation (15), taking for v_{pi} the value given in (10) and a reasonable safety factor f_s = 2, the following approximated correlation to calculate v_d is obtained:

$$v_d = 10.4\ \rho_s^{0.37} d_p^{0.26} \qquad (17)$$

To apply this Equation to estimate design velocities for dusts of wide size range, as it frecuently occurs in practice, d_p must be taken as the average diameter of the largest narrow size fraction present in the studied sample. It is taken as the average of the mesh openings of the two consecutives standard screems that define the fraction. For example, appling Equation (17) for dust of galena (SPb), having a larger narrow size fraction 100/150 M (0.147/ 0.104 mm), d_p = 0.126 mm is used. In this case it is ρ_s = 7.5, and results a design velocity of : v_d = 12.7 m/s (approx. 2,500 FPM). For this kind of mineral dusts the bibliography (A.C.G.I.H., 1986) recomends a velocity range of 3,500 - 4,000 FPM. It is important to explain that the values given by Equation (17) are the minimum safe design velocities. Actual design velocities should not be less than these minimum design velocities, but may be greater, according to the judgement of the design engineer. The actual design velocities must take into account such factors as the use of blast gates, leakage of ductwork, probable poor maintenance and the possibility of picking up material other than that for which the exhaust systen is designed (A.C.G.I.H , 1986).

NOMENCLATURE

d_p = Mean diameter of solid particles, mm.
D = Inside diameter of the duct, mm.
f_s = Safety factor.
k = Constant factor (Newton's law).
K_1 , K_2 , K_3 = Constant factors in experimental correlations.
m , n, p = Constant exponents in experimental correlations.
Re = Reynolds number (dimensionless number).
v_d = Design velocity, m/s.
v_{min} = Minimum transport velocity, m/s.
v_{st} = Settling velocity (horizontal ducts), m/s.
v_{pu} = Pick up velocity (horizontal ducts), m/s.
v_{sa} = Saltation velocity (horizontal ducts) m/s.
v_t = Terminal velocity (vertical ducts), m/s.
μ = Air viscosity, g / cm s.
ρ = Air density, g / cm^3.
ρ_s = Solid particle density, g/ cm^3.

REFERENCES

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APPENDIX

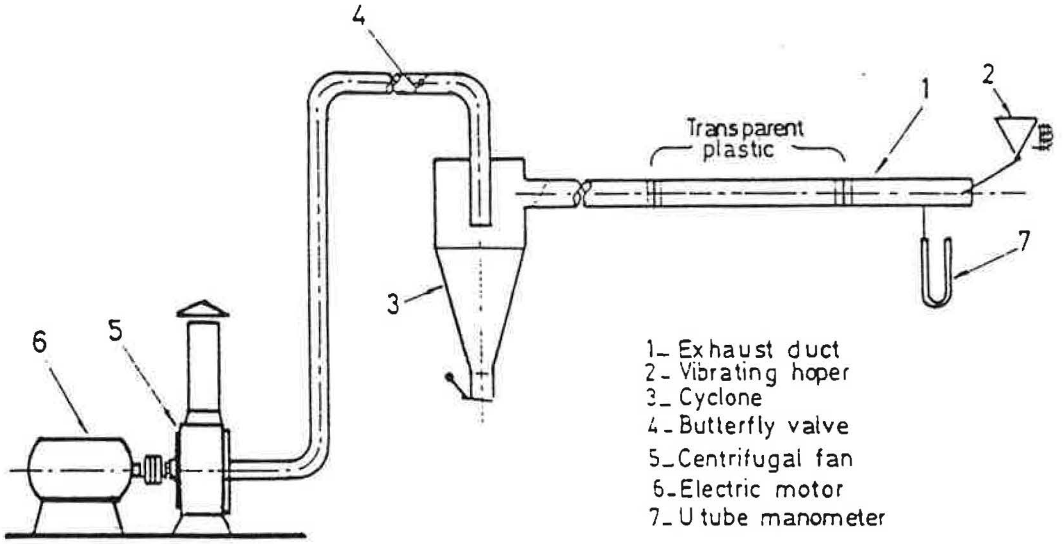

Figure 1. Details of the experimental apparatus to determine critical velocities.

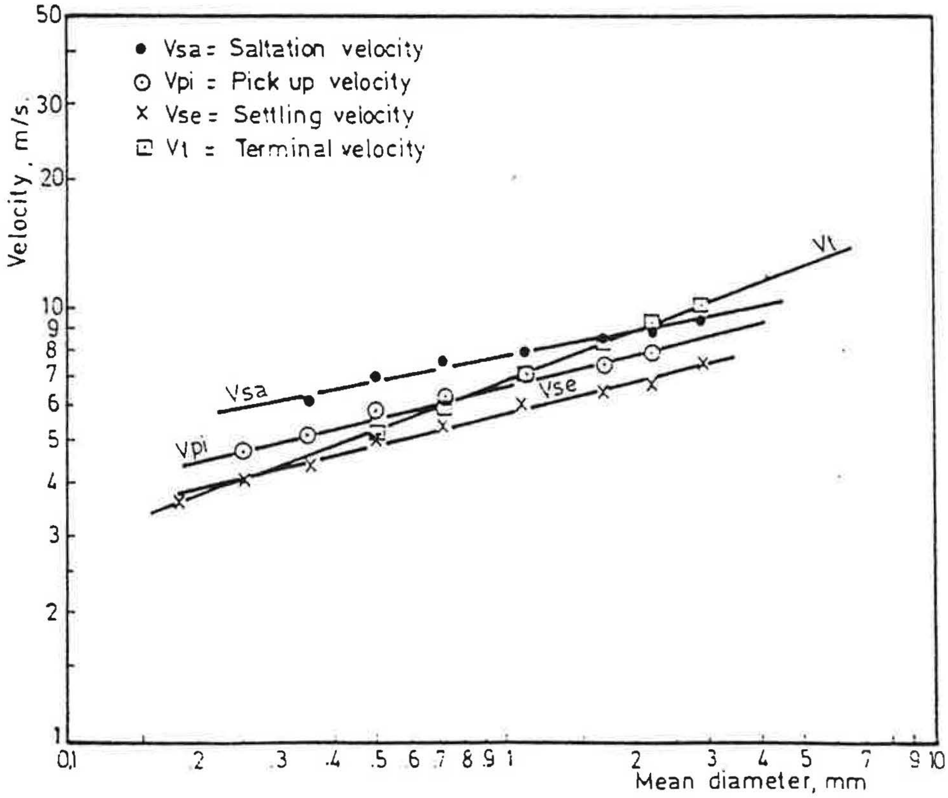

Figure 2. Saltation, settling, pick up and terminal velocities for clinker.

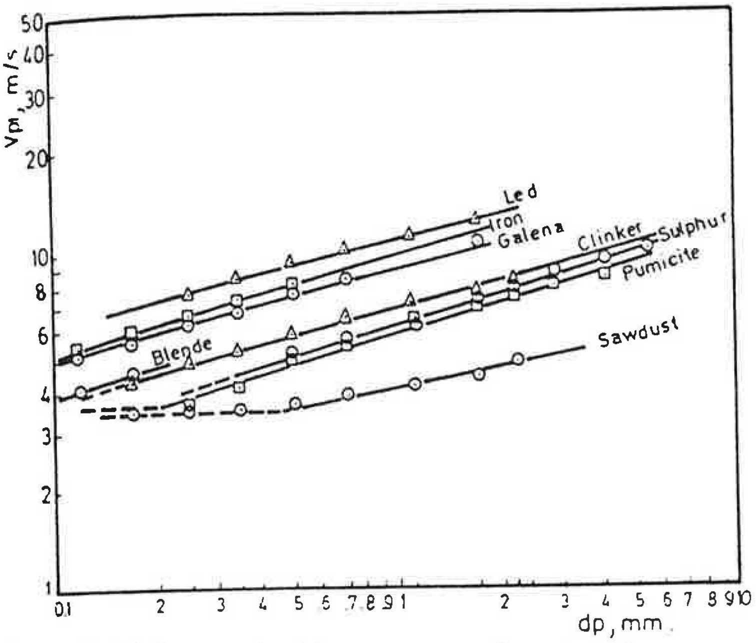

Figure 3. Pick up velocities vs. mean diameters for different powders (Horizontal transport).

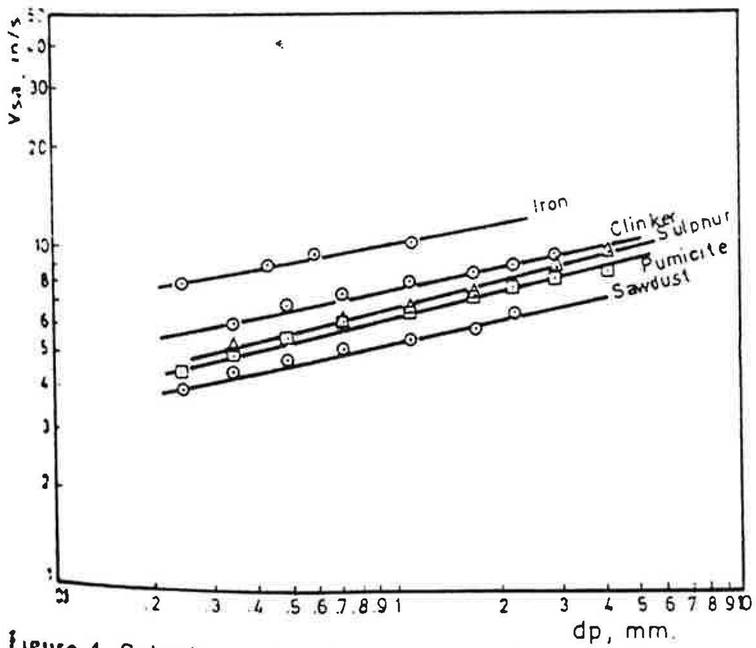

Figure 4 Saltation velocities vs. mean diameters for different powders (Horizontal transport)

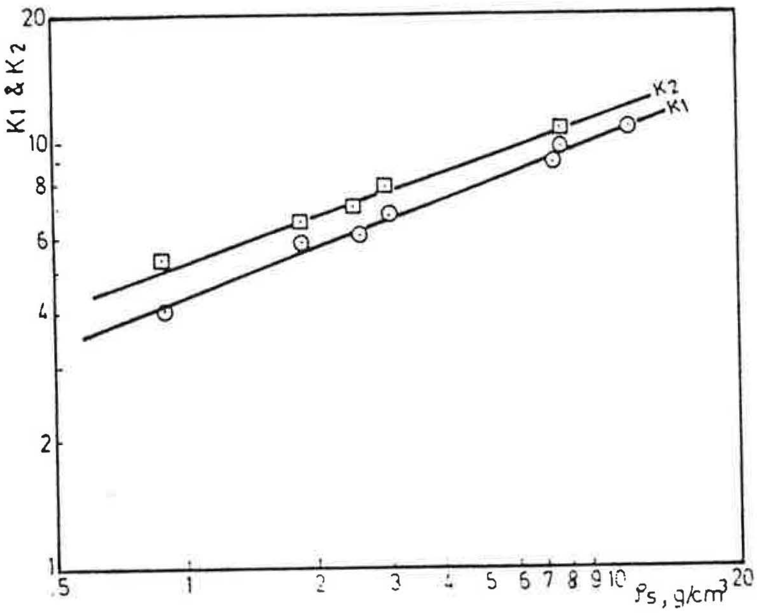

Figure 5. Correlation between constants K_1 and K_2 and particle densities.

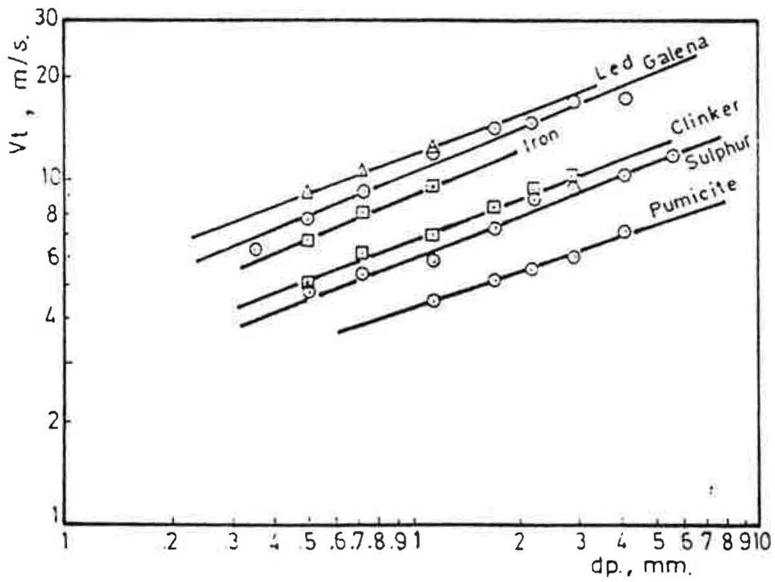

Figure 6. Terminal velocities vs. mean diameters for different powders (Vertical transport)