PARTICLE DEGRADATION

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Abstract

A linear air gun was used to examine the effect of particle velocity, impact angle, particle diameter, the number of impacts, target thickness and target material on the degradation of three types of spherical particles (Aluminum oxide, Polystyrene and Glass).

Introduction

Granular material in pneumatic transportation frequently hits the pipe walls. These collisions will produce a force on the particles that may lead to their degradation.

Although the problem of degradation has a considerable value for industrial use, it is not extensively documented, Mills [1, 2] related that this is because of the large number of variables involved in both the product and the plant.

Among these variables, the six more important ones will be considered. These are: particle velocity, impact angle, particle diameter, number of impacts, target thickness and target material.

We use the word degradation here to mean reduction of any size that can be observed by the eye. Two types of particle degradation were observed, Fig. 1. shows the first, "normal degradation" and the second, "shear degradation".

If degradation is to be examined a means of counting must be devised. This may be done in a simple way by impacting 100 particles under the same velocity. The num-

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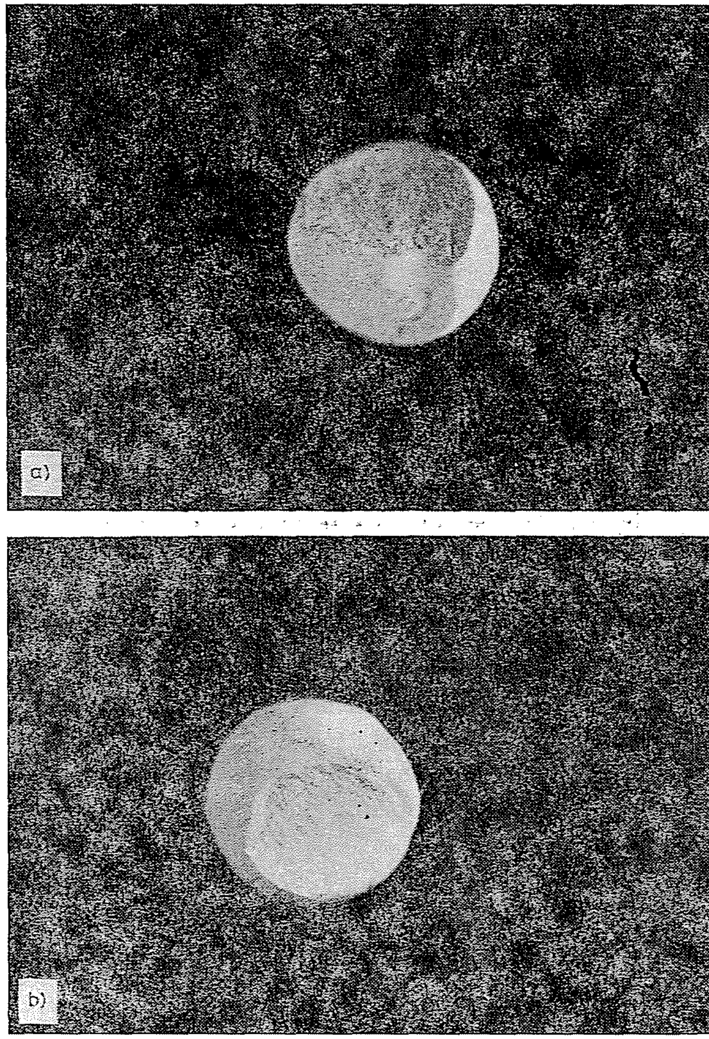

Fig. 1. The two types of particle degradation (AlO: dr=5—5.3 mm): a) Normal degradation in the case of normal impact; b) Shear degradation in the case of glancing impact

ber of degradated particles (*NB*) can be calculated by counting the number of unbroken particles (*NO*) and subtracting that from the number of impacted particles (100):

$$NB = 100 - NO. \tag{1}$$

To simplify the work, the measurement in this paper will be based on the number of unbroken particles (*NO*).

Review of previous work

As mentioned previously, there is remarkably little published work presented up till now on the effect of particle velocity, impact angle, particle diameter, number of impacts, target thickness and target material on particle degradation in pneumatic transport, and the available material is for a range of velocities greater than that used in pneumatic conveying. Goodwin [4] has found that the degradation depends on impact velocity, particle size and target material Fig. 2, he has also found that for the degradation to occur it is necessary to exceed the threshold condition defined by a particular velocity and a particular particle size. By taking photographs of the particle during the impact process, Tilly [5] has found that the particle degrades in a manner superficially similar to a water drop of similar size and that degradation occurs in less than 20μ sec. Uuemois [6] showed that at high impact velocity a substantial part of the particle is reduced to fine dust in the impact zone and that the particle degrades in the way shown in Fig. 3.

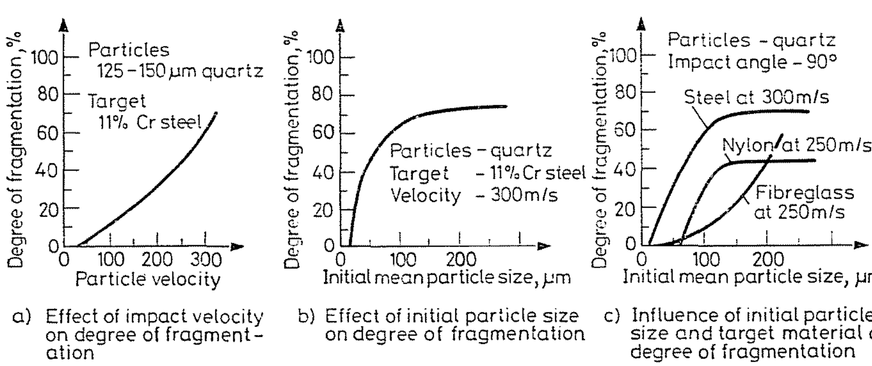

Fig. 2. a) Effect of impact velocity on degree of fragmentation; b) Effect of initial particle size on degree of fragmentation; c) Influence of initial particle size and target material on degree of fragmentation

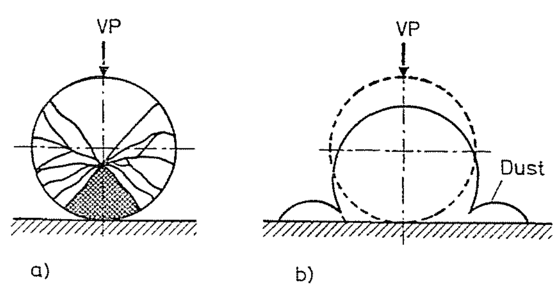

Fig. 3. The degradation of a single particle: a) Zones of degradation at impact; b) a particle in the process of impacting on a hard surface. (From Uuemois, Ref 6.)

Experimental apparatus and measuring technique

The experimetal apparatus used is shown schematically in Fig. 4. A linear air-gun using compressed air is applied to accelerate the particles. The gun is 300 mm in length with a barrel of 8 mm in diameter. A steel target of 5 mm thickness is located at $XL=250$ mm away from the end of the barrel. The firing pressure of the gun is variable to an upper limit of 2 bar in order to get variable velocities. Individual particles are placed into the barrel at point (A) Fig. 4. As a rule, one particle will leave the gun and strike the target surface. The particle impact velocity (V) is determined by measuring the time necessary for the particle to travel from the end of the barrel to the cylindrical target. One photodiode located at the end of the barrel and a loudspeaker behind the cylindrical target, will provide signals to a high-speed electronic timer (HSET) which will measure the time it takes for the particle to travel XL distance. This timer is connected to a personal computer calculating the individual particle velocities (V).

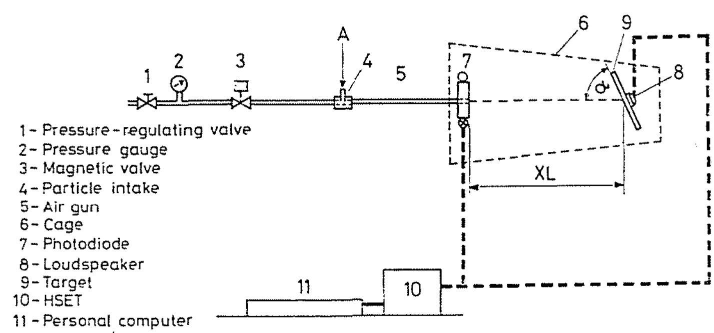

Fig. 4. Schema of impact test apparatus and arrangement of measuring systems

The measurement consists of taking the velocity of 100 individual particle (V) measured under a fixed pressure from which the average velocity (VP) and its standard deviation are calculated, and by counting the number of unbroken particles (NO) out of the 100 impacted particles. The relationship between the number of unbroken particles and the average particle velocity is found by repeating the procedure for different average velocities (VP).

We will use the term "particle velocity" to mean the average velocity of 100 individual particles making flight under a fixed pressure.

At first, we restricted our study to the more important factors which may influence the degradation of the particle, namely:

1. Effect of impact velocity of particle (normal impact)

In order to study the particle degradation process, we used brittle particle material, to ensure that no plastic deformation should take place. If a particle impinges on a surface at a certain velocity, then, according to Mohsenin [7], a maximum stress concentration occurs in the center of the contact area. As long as this stress maximum does not reach the strength of the material, only elastic deformation occurs and the collision is said to be elastic. Increasing the particle velocity further increases the stress, and if this stress is greater than the strength of the material, degradation occurs.

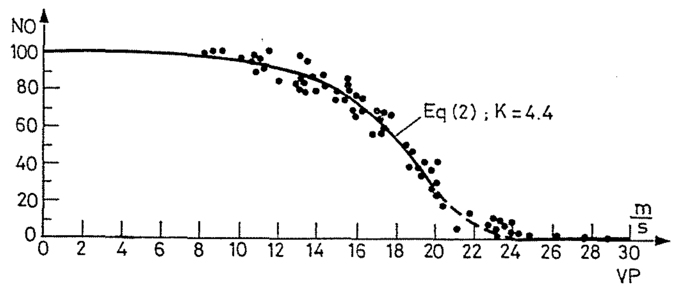

Fig. 5. The relation between the particle velocity and the number of unbroken particles (AlO: dr = 5—5.3 mm; α = 90°)

Fig. 5 shows the relationship between the particle velocity and the number of unbroken particles (NO) for Aluminum oxide particle (ALO) of diameter range ($dr = 5-5.3$ mm). The maximum value of the coefficient of variation of the average velocity was $Z = 3\%$.

Fig. 5 shows that degradation starts at a particle velocity greater than 8.4 m/sec. Increasing the particle velocity will cause a gradual decrease in the number of unbroken particles till a particle velocity of about $VP = 14$ m/sec. Increasing the particle velocity further is followed by a greater decrease in the number of unbroken particles, until an inflection point at $VP = 20.5$ m/sec, followed by a gradual decrease in the number of unbroken particles, till all the particles are broken ($NO = 0$).

Fig. 5 shows that at particle velocity $VP = 24$ m/sec all the particles are broken ($NO = 0$). With increasing the velocity further, the size of the broken particles decreases.

Fig. 6 shows the effect of the particle velocity on the size of the broken particles (in the case $NO = 0$). It is also shows that the size of the broken particles at $VP = 29.4$ m/sec is smaller than that at $VP = 23.1$ m/sec.

Fig. 7 shows the relationship between particle velocity (VP) and the number of unbroken particles (NO) for polystyrene particles (POL), ($dr = 7.4$—7.6 mm) demonstrating that degradation starts at a particle velocity greater than 14 m/sec. For glass

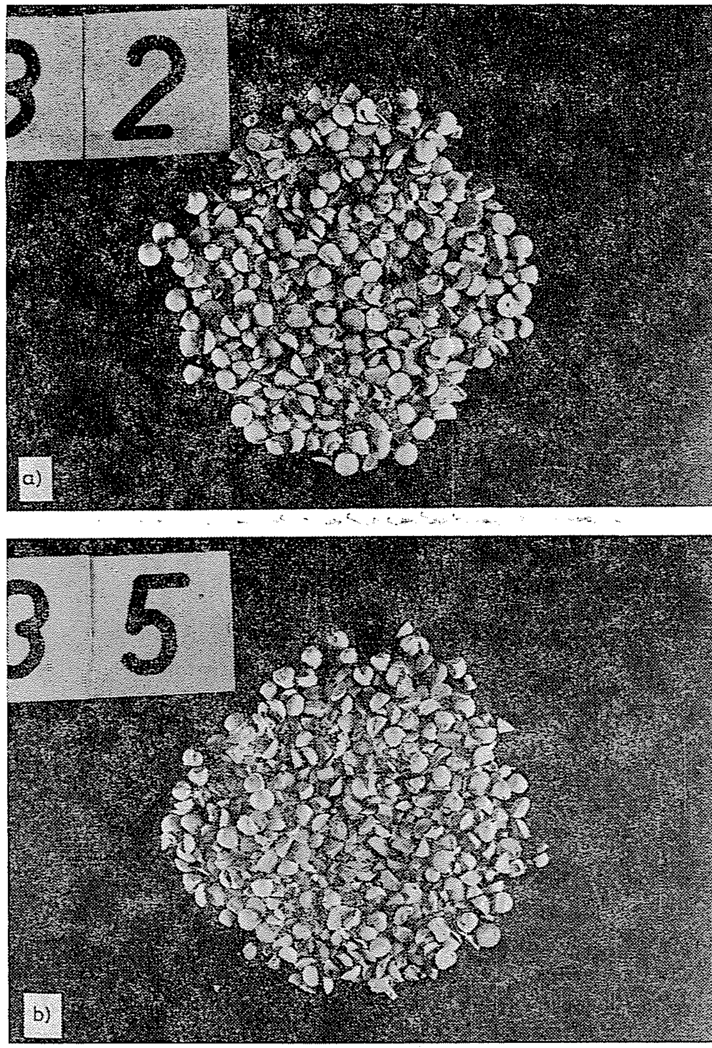

Fig. 6. The effect of increasing the velocity on the size of the broken particles (AlO: $dr=5$—5.3 mm) (in both cases the number of impacted particles$=100$:$NO=0$: $\alpha=90°$)
a) VP$=23.1$m/s,
b) VP$=29.4$m/s

particles (GLS), Fig. 8 shows that no degradation was observed to a velocity of 30 m/sec.

These Figs. 5, 7, 8 show that there is a threshold velocity below which no degradation occurs, and this limit depends on the type of the particle material.

An approximate equation for the relation between the particle velocity (VP)

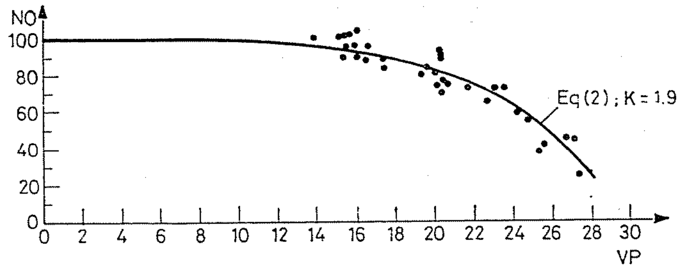

Fig. 7. The relation between the particle velocity and the number of unbroken particles (POL: dr=7.4—7.6 mm: α=90°)

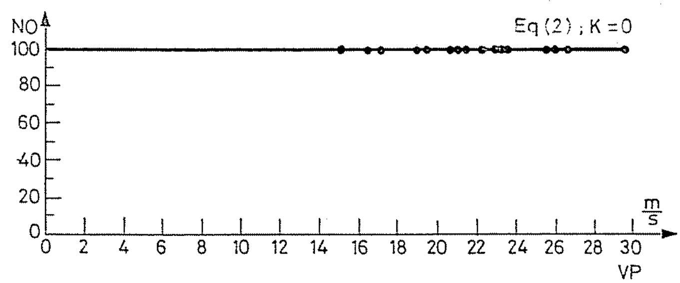

Fig. 8. The relation between the particle velocity and the number of unbroken particles (GLS: dr=5 mm: α=90°)

and number of unbroken particles (*NO*) is proposed in the form of Eq (2).

$$NO = 100 \cdot \arctan\left(\tan(1) - K(VP/30)^3\right). \tag{2}$$

The number of broken particles (*NB*) could be calculated by Eq (1).

The constant of the equation *K* has been determined by the least square method from the experimental value. The constant of this equation and the relative standard deviation for the three types of particles (ALO, GLS, POL) are as follows:
ALO particle (dr=5—5.3 mm) $K=4.4:S=9.12\%$
POL particle (dr=7.4—7.6 mm) $K=1.9:S=9\%$
GLS particle (dr=5 mm) $K=0:S=0\%$.

This equation is valid at particle velocities (VP) between 0 and 30 m/sec and $NO => 20$.

In Figs. 5, 7, 8, the curves represent the calculated approximate relation and the points show the measured values.

2. *Effect of impact angle*

In the preceding section Figs. 5, 7, 8, the angle between the direction of the particle velocity and the target was 90° (normal impact).

In order to examine the angles' effect, we repeated the same measurement for (ALO: dr=5—5.3 mm), but with an angle range: 10°—90°. The results of these tests are shown in Fig. 9.

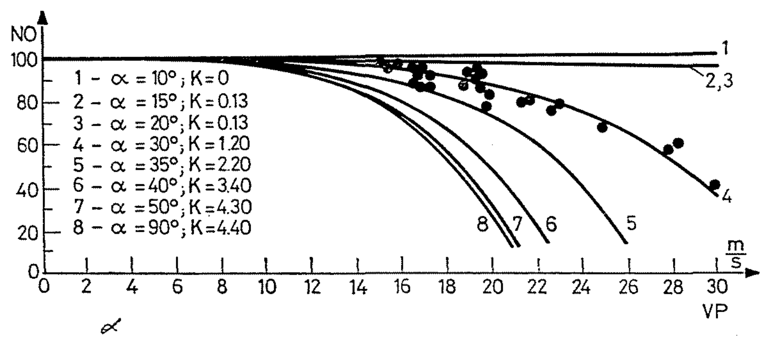

Fig. 9. The relation between the particle velocity and the number of unbroken particles for different impact angles (AlO: dr=5—5.3 mm)

From now on if the figure contains more than one curve, in order to get a clear drawing the experimental points of only one curve will be drawn.

Fig. 9 shows that the effect of the angle on degradation is considerable. For example, for $\alpha=10°$, at a velocity of about 30 m/sec the number of unbroken particles is $NO=100$, while for $\alpha=90°$ at a velocity of 20.5 m/sec, the number of unbroken particles is $NO=20$. It is seen from Fig. 9 that the effect of the angle on degradation increases with increasing the particle velocity. Fig. 9 also shows that in the angle range ($\alpha=90°$ to 50°) a small change in the angle has a small effect on the number of unbroken particles, because the normal component of the velocity decreases gradually in this range. For the angle range ($\alpha=50°$ to 20°), the effect will be greater due to the rapid decrease in the normal component of the velocity. For the angle range ($\alpha=20°$ to 10°) the effect will be small because the normal component is very small in this range.

In order to get more information concerning the influence of the angle, tests similar to the one described above, were made in which the particle velocity (VP) was constant at about (23 m/sec) and the impact angle was varied. The results are shown in Fig. 10a. and indicate that with decreasing the impact angle, the number of unbroken particles increases until a certain angle α_0 after which there is no broken particles (at $\alpha_0=10°$).

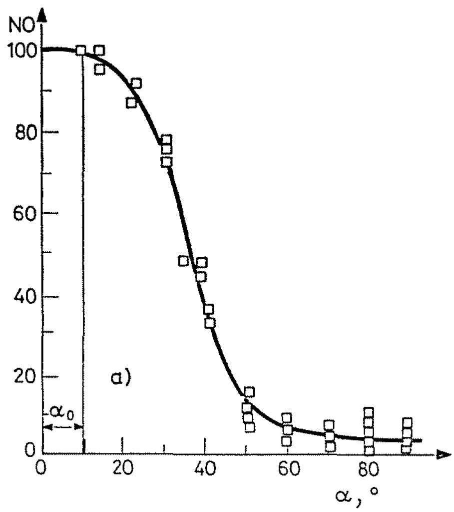

Fig. 10a. The effect of the impact angle on the number of unbroken particles (AlO particles: dr=5—5.3 mm: steel target 5 mm thickness: VP=23 m/sec)

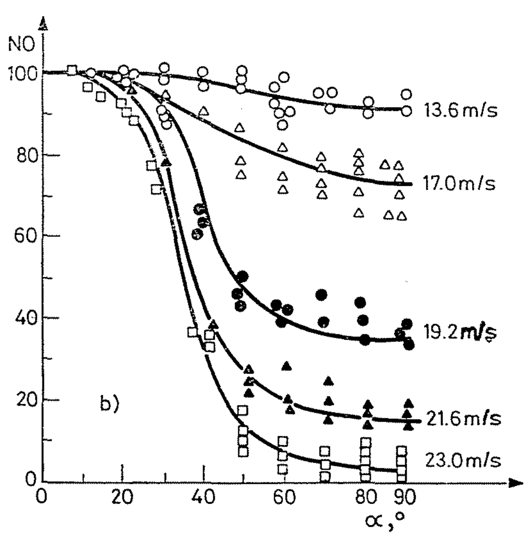

Fig. 10b. The effect of the angle on the number of unbroken particles in the case of constant particle velocity (For AlO particles: dr=5—5.3 mm: steel target of 5 mm thickness)

The same test has also been done under different constant velocities (21.6, 19.2, 17 and 13.6 m/sec), Fig. 10b. From this figure it can also be concluded that the effect of the angle is important and increases with increasing the *VP*, and that at different particle velocities no degradation takes place at an impact angle $\alpha_0=10°$.

As mentioned previously, there are two types of particle degradation, the first the "normal degradation" Fig. 1a. exists in the case of a normal impact when the stress is higher than the particle strength. By decreasing the angle the normal component of velocity decreases, but if this component produces a stress higher than the strength of the particle, normal degradation also exists. In the case of normal degradation the particle is broken down in the way shown in Figs. 1, 10c—I.

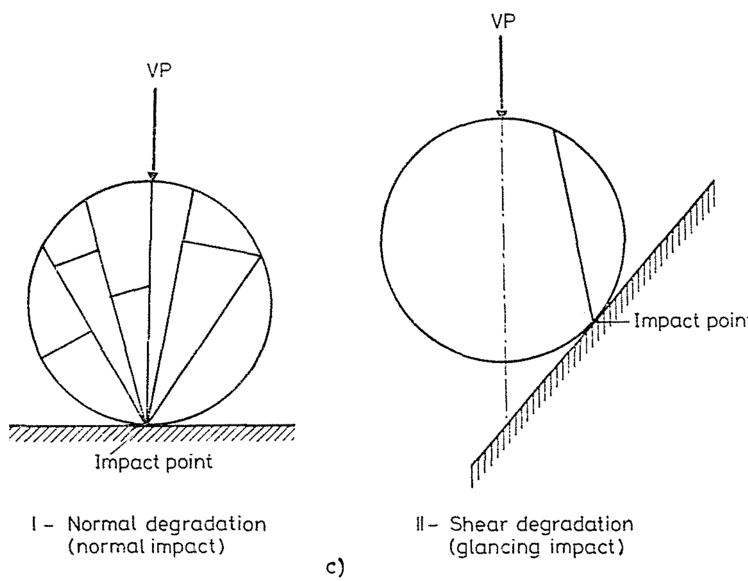

Fig. 10c. The two types of degradation

With decreasing the impact angle, the second type of degradation, "shear degradation", was found, Figs. 1, 10c—II where the broken surface is a plane passing through the impact point. Table 2 shows the number of particles degraded for both types under a fixed particle velocity ($VP=22$ m/sec) and at different impact angles. From Table 2 it can be seen that the decrease of the impact angle (till a certain value $\alpha=20°$), can be associated with:

1 — Increasing the number of the unbroken particles (*NO*).

2 — Decreasing the number of the first type of degradation, "normal degradation".

3 — Increasing the number of the second type of degradation, "shear degradation".

Table 1

Constant (K) of equation (2)

Impact Angle ($\alpha°$)	Aluminum oxide (AlO) dr=7—7.3 mm		dr=5—5.3 mm		dr=3.5—4.2 mm		dr=2.8—3.2 mm		(POL) Polystyrene dr=7.4—7.6 mm		(GLS) Glass dr=5 mm	
	K	S%	K	S%	K	S%	K	S%	K	S%	K	S%
90	21.9	9.19	4.4	9.12	4.27	9.3	2	9.8	1.9	9	0	—
80	—	—	4.26	8.3	—	—	—	—	1.52	6	0	—
70	21.3	5.3	4.31	9.8	4.2	8.4	—	—	1.77	6.99	0	—
60	—	—	4.4	6.68	—	—	—	—	1.3	5.2	0	—
50	15	4.89	4.3	8.4	3.2	9.1	—	—	1.4	8.4	0	—
40	—	—	3.48	7.6	—	—	—	—	1.34	13	0	—
35	—	—	2.22	9.3	—	—	—	—	—	—	0	—
30	1.29	3.67	1.2	2.6	0.22	1.8	—	—	1.25	6.3	—	—
20	0.2	0.35	0.13	2.6	—	—	—	—	—	—	—	—
15	—	—	0.13	1.92	—	—	—	—	—	—	—	—
10	—	—	0	—	—	—	—	—	—	—	—	—

Table 2

The effect of the impact angle on the number of unbroken particles, first type of degradation, "normal degradation" and the number of second type of degradation, "shear degradation" (AlO: steel target of 5 mm thickness: $VP=22.0$ m/sec)

Impact Angle $\alpha°$	Unbroken particle	Normal degradation	Shear degradation
90	3	97	0
70	4	93	3
50	11	65	24
40	30	45	25
35	60	11	29
20	98	0	2
15	100	0	0

Eq (2) was applied here as well to find the relation between the particle velocity (VP) and the number of unbroken particles (NO) for different impact angles (here also $VP=\langle 30$ m/sec and $NO=\rangle 20$), by the least square method the constant (K) for different impact angles was found. The values of this constant and the relative standard deviation for different impact angles are shown in Table 1.

In Fig. 9 too, the curves show the calculated approximation relation and the points show the measured values.

3. *Effect of number of impacts*

In pneumatic conveying, the particle on its way through the pipe hits the pipe wall several times and consequently, the effect of these multiple impacts has to be taken into consideration.

The effect of multiple impact on three types of particle has been examined: *A* — Aluminum oxide (AlO) particles, (dr=4.9—5 mm).

Two groups of particles were used. The first group (A) always consists of 100 particles and it is used for calculations. The second group (B) was only used to replete group (A) by substituting for the broken particles. The first step is impacting the particles of group (A) and counting the number of broken particles, then in the second step the particles of the second group (B) are impacted under the same velocity, the broken particles in group (A) are substituted by unbroken particles from group (B) in order to have always 100 unbroken particles in group (A). By repeating this several times and under the same velocity a relationship between the number of impacts and the number of unbroken particles was found. Fig. 11 shows this relationship

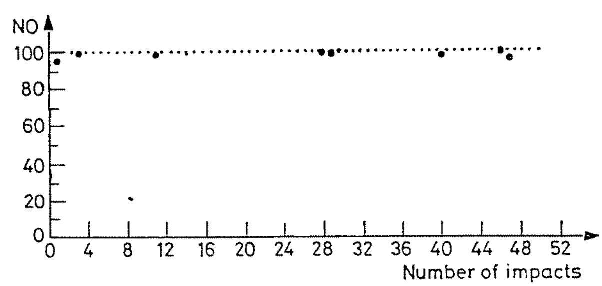

Fig. 11. The relation between the number of impacts and the number of unbroken particles (AlO: dr=4.9—5 mm: VP=9.3 m/sec: α=90°)

for AlO particles (VP=9.3 m/sec: dr=4.9—5 mm). This Figure also shows that we substituted particles from group (B) into group (A) eight times, (at impact numbers 1, 3, 11, 28, 29, 40, 46 and 47). Figure 12 shows another series of measurements where the particle velocities were VP=8.3, 10.2, 12 and 14.3 m/sec, respectively. Both figures show that till the examined impact numbers there is no effect of the number of impacts on the degradation of AlO particles. They also show that the deviation of the number of unbroken particles increases with increasing the particle velocity.

B — Polystyrene (POL) particles:

The same test has been repeated with the Polystyrene particles (dr=7.4—7.6 mm), the particle velocity was VP=16.1 m/sec, Fig. 13, showing that after a certain

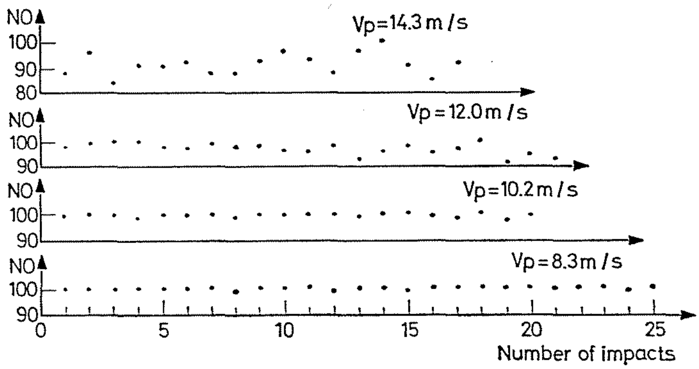

Fig. 12. The effect of the number of impacts on the number of unbroken particles at different particle velocities (AlO: dr = 5—5.3 mm: $\alpha = 90°$)

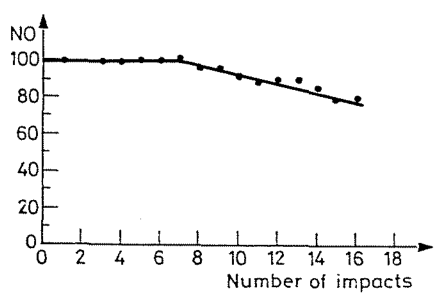

Fig. 13. The relation between the number of impacts and the number of unbroken particles (POL: $dr = 7.4$—7.6 mm)

impact number, the number of unbroken particles starts to decrease linearly.

C — Glass (GLS) particles, ($dr = 5$ mm):

For more than 60 impacts and with different velocities (14.1 to 29.2 m/sec), we have not found any broken particles.

4. *Effect of particle diameter*

For different ranges of AlO particles of diameter ($dr = 2.8$—3.2, 5—5.3 and 7—7.3 mm), an experimental work was carried out to establish the relationship between the particle velocity and the number of unbroken particles (when $\alpha = 90°$). Fig. 14 shows the result of this test. From this Figure it appears that for degradation to occur it is necessary that the particle velocity exceed the threshold limit, and that this limit increases with decreasing the particle diameter. It also shows that the velocity

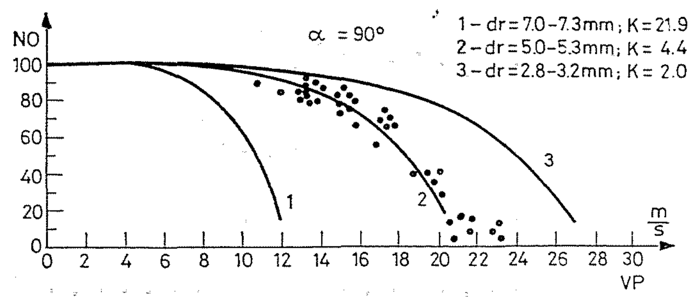

Fig. 14. The relation between the particle velocity and the number of unbroken particles for different particle diameters (AlO)

needed to break 80 particles out of 100 impacted particles, increases with decreasing the particle diameter, for example the velocity needed to break 80 particles for:

dr=(7—7.3 mm)=12.0 m/sec
dr=(5—5.3 mm)=20.4 m/sec
dr=(2.8—3.2 mm)=26.4 m/sec

From this figure it can be concluded that, decreasing the particle diameter increases the velocity needed to break them. This can be well explained by an observation made by Harold [8] that the nature of brittle strength is such that larger volumes of brittle materials can exhibit lower relative strengths than lower volumes.

Finne [9] reported that decreasing the size of particles below a certain size shows an increase in its strength value.

The constant of Eq (2) for AlO particles of different particle diameters and the relative standard deviation are shown in Table 1.

5. *Effect of target thickness*

For the same type of target material, different target thicknesses were used to examine the effect of the target thickness on the relation between particle velocity and the number of unbroken particles. The result is shown in Fig 15 for steel target, for the thicknesses of (5, 2, 1.2 and 1 mm) respectively. This Figure shows that under the same particle velocity, increasing the target thickness decreases the number of unbroken particles until a certain thickness after which there is no effect of increasing the target thickness. The same conclusion can be drawn in the case of plexiglas targets of different thicknesses, Fig. 16.

In both tests, the impact of particles on a thinner target will cause the target to bend, increasing the target thickness will decrease the target stiffness till a certain thickness is reached, after which there is no effect of target thickness.

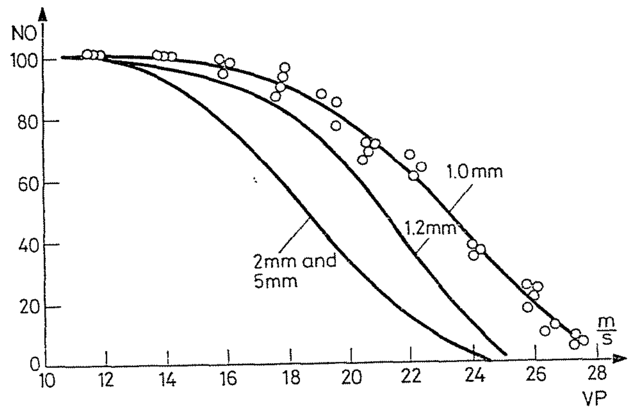

Fig. 15. The effect of the target thickness (steel) on the number of unbroken particles (AlO particles: dr=5—5.3 mm: steel target: impact angle=90°)

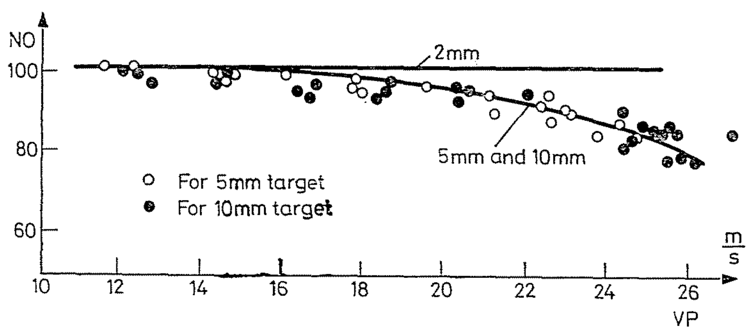

Fig. 16. The effect of the target thickness (plexiglas) on the number of unbroken particles (AlO particles: dr=5—5.3 mm: plexiglas target: impact angle=90°)

6. *Target material*

In order to examine the effect of target material on particle degradation, four types of 5 mm target material were used (Steel, Glass, Plexiglas and Aluminum), and the effect of velocity on the number of unbroken particles for each target was measured. Fig. 17 shows the relation between the number of unbroken particles and the particle velocity (VP) for different target materials, this figure shows that under the same velocity (VP) the number of unbroken particles (NO) for the different surfaces are in the following sequence:

1 — plexiglas surface
2 — aluminum surface
3 — glass surface
4 — steel surface

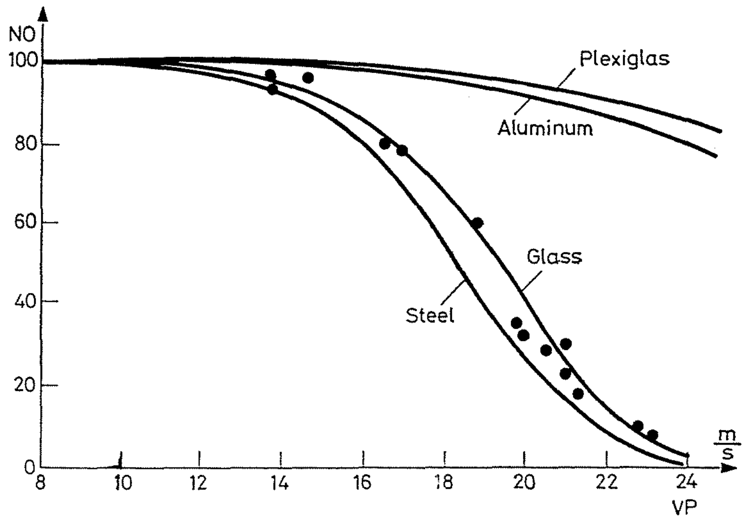

Fig. 17. The effect of the type of the target material on the number of unbroken particles (AlO particle: dr=5—5.3 mm: target thickness=5 mm: impact angle=90°)

We explain the effect of the type of surface on the particle degradation as follows:

During the collision of the particle with the wall the impulse of the force acting on the particle is:

$$P = \int_0^{\Delta t} F\,dt = \bar{F}\Delta t \tag{3}$$

where $\bar{F}$ is the average value of the force F acting on the particle during the time interval Δt, the value of Δt is depending on the deformation which takes place during collision in both the particle and the wall. If large deformation takes place, the contact time Δt is long, and in this case the F value is small, and the force may be insufficient to cause the degradation of the particle. If the deformation is small, the Δt is also small, so the value of F is large, and if this force produces stress greater than the strength of the particle, degradation occurs.

From this we can conclude that the contact time Δt of the AlO particle when colliding with a glass or steel surface is short and the contact time with plexiglas and Aluminum is long, this is the reason why for the same particles under the same velocity, the number of unbroken particles differ from one surface to another.

Ancillary Tests

Some test have been carried out, in order to examine some other factors and the accuracy of the experimental device.

a — The effect of sign of the impact angle:

Fig. 18 shows that under the same particle velocity the sign of impact angle has no effect on the relation between the number of unbroken particles and the impact angle.

b — The effect of the target distance (*XL*):

Fig. 19 shows the relation between the particle velocity and the number of unbroken particles for different *XL* values (100, 150, 200, 250 and 300 mm). From this

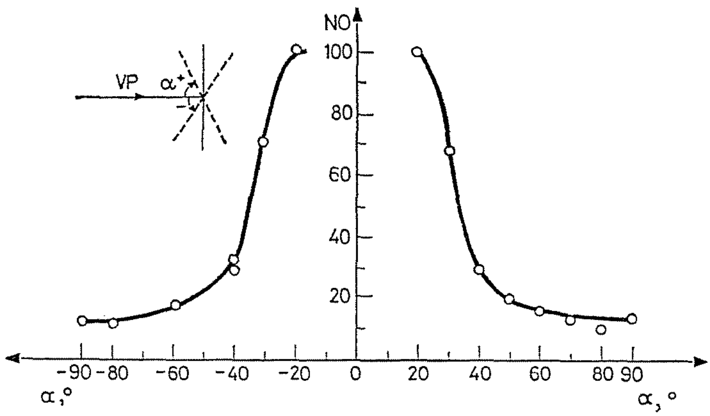

Fig. 18. The effect of the sign of the impact angle on the number of unbroken particles (AlO) *dr* =4.6—5.4 mm: *VP*=22 m/sec)

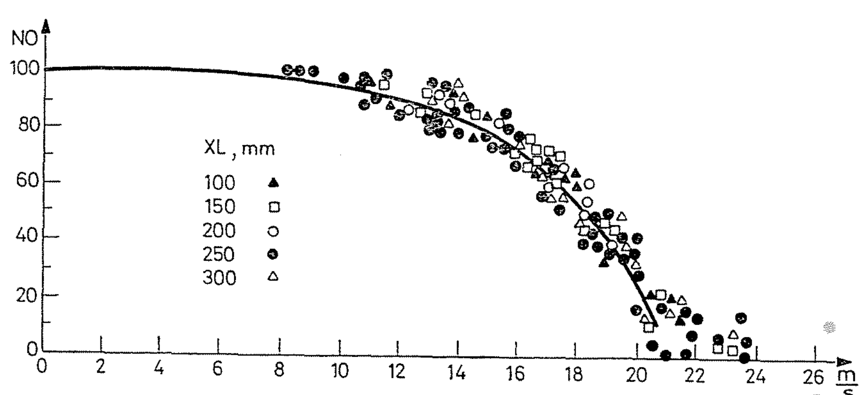

Fig. 19. The relation between the particle velocity and the number of unbroken particles for different *XL* values (AlO: dr=5—5.3 mm: α=90°)

figure it can be seen that the change of the *XL* value (in the above range) has no effect on the relation between *NO* and *VP*.

c — The effect of the barrel on the number of unbroken particles has been examined, by collecting the flying particles (AlO: dr=5—5.3: *VP*=30 m/sec) before reaching the target. The result was that there were no broken particles.

d — Fig 20 shows the impact position of 100 particles on the target surface in the case of normal impact where the particle velocities were 15 m/sec and 22 m/sec. The target diameter is 170 mm, the positions of impact at velocity 15 m/sec were within a circle of 23 mm in diameter and when the velocity was 22 m/sec they were within a circle of 25 mm.

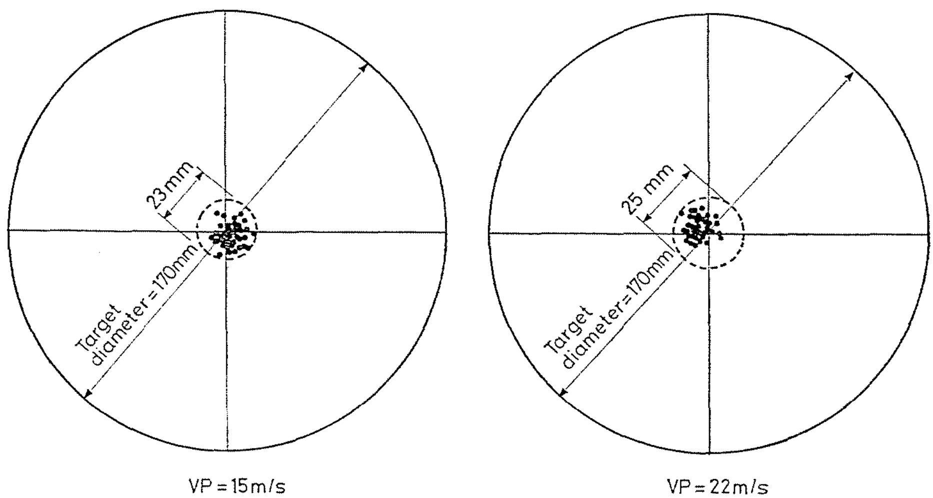

Fig. 20. The position of impact of 100 particles (AlO: dr=5—5.3 mm: $\alpha=90°$) on a steel target (5 mm thickness) in the case of *VP*=15 m/sec and the case of *VP*=22 m/sec

Nomenclature:

dr:	particle diameter
P:	impulse of the force
F:	impulsive force
$\bar{F}$:	the average value of the force *F* during the interval time Δt
K:	constant in Eq (2)
NO:	number of unbroken particles
NB:	number of broken particles (100—*NO*)
S:	relative standard deviation

$$S = 100\left(\sqrt{(\Sigma(1-NO_{mes}/NO_{cal})^2/98)}\right)$$

Sl:	standard deviation
	$Sl = \sqrt{(\Sigma(V-VP)^2/98)}$
Δt:	time of collision
V:	individual particle velocity
VP:	average velocities of 100 particles
Z:	coefficient of variation ($Z=Sl/VP$)
XL:	the distance between the end of the barrel and the target surface
α:	impact angle
α_0:	impact angle equal to or lower than this value the number of unbroken particles equals the number of impacted particles
AlO:	Aluminum Oxide
POL:	Polystyrene
GLS:	Glass

Subscripts:

mes:	measured
cal:	calculated

Literature

1. Mills, D. and Mason, J. S.: "The Effect of Pipe Bends and Conveying Length Upon Particle Degradation in Pneumatic Conveying Systems". Proc. of the Inter, Powder & Bulk Solids Handling and Processing Conference. Illinois. May 16—18, (1978).
2. Mills, D. and Mason, J. S.: "Problems of Particle Degradation in Pneumatic Conveying Systems", Pneumotransport 4, BHRA., California, paper F3. (1978).
3. Mills, D. and Mason, J. S.: "Learning to Live with Erosion of Bends", Proc. 1st. Int. Conf. on Protection of Pipes. BHRA Conf., Durham, Paper G1. (1975).
4. Goodwin, J. E., Sage, W. and Tilly, G. P.: "Study of Erosion by Solid Particles." Proc. Instn. Mech. Engrs., *184*, Ptl, 279 (1960—70).
5. Tilly, G. P. and Wendy, S.: "The Interaction of Particle and Material Behaviour in Erosion Processes", Wear, *16*, 447 (1970).
6. Uuemois, H. and Kleis, I.: "A Critical Analysis of Erosin Problems which have been Little Studied". Wear, *31*, 359 (1975).
7. Mohsenin, N. N.: "Physical Properties of Plant and Animal Materials", VOL *1*, Gordon and Breach Science Publishers Ltd., (1970).
8. Harold, E. G.: "The Size Reduction Paradox", Ind & ENG Chem, *55*, 46 (1963).
9. Finnie, I.: "Some Observations on the Erosion of Ductile Metals"; Wear, *19*, 81 (1972).

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