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VARIATION IN ENTRANCE EFFICIENCY WITH CROSS WIND SPEED WHEN SAMPLING AIR-BORNE PARTICULATE MATTER WITH A CYLINDRICAL ELUTRIATOR.

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SUMMARY

The effect of cross wind velocity and particle size on the entrance efficiency of particles for a cylindrical elutriator was studied in an open wind tunnel. Isokinetic samples were used as references for determining the efficiency. The particles were collected on membrane filters, and their total mass was determined by x-ray fluorescence analysis. Cross wind velocities from 0.5 to 9 m/s, and ground talc with mean values of 4 and 9 µm Stokes diameter were studied. The entrance efficiency decreased with increasing cross wind velocity, reached a minimum, and then increased. The coarse talc showed a stronger dependence on wind speed than the fine talc. The observed trend is probably due to turbulent flow and the formation of vortices. Because of this, the quantitative results cannot directly be used with other flow conditions, e.g. open air, or with other types of elutriators.

INTRODUCTION

When sampling air-borne particulate matter to determine the concentration of respirable dust or the abundance of certain elements or compounds carried by particles, samples are normally taken as recommended in the OECD report: Methods of Measuring Air Pollution (1). When analyzing the results little consideration is given to the fact that the entrance efficiency of particles may differ considerably from 100 per cent. The most important parameters affecting the entrance of particles into the sampling funnel and thereby the entrance efficiency are: cross wind velocity, angle between cross wind and funnel, flow rate into the funnel, turbulent flow of the atmosphere and particle size. The effects of variations of these parameters are little known.

This study deals with the effects on entrance efficiency of cross wind speed and particle size when sampling air-borne particulate matter with a cylindrical elutriator. The cylinder is placed with the axis vertically and the opening downwards. The cross wind is perpendicular to the axis of the cylinder.

A large number of articles on isokinetic or nearly isokinetic sampling have been published. There are, however, few articles dealing with sampling by elutriation in a cross wind.

Walton (2) has theoretically studied sampling with a vertical cylinder probe with the opening downwards and in no cross wind.

Davies (3) has theoretically studied sampling with a horizontal cylinder with an orifice in the underside. He treats the special case when the cross wind speed is the same as the sedimentation velocity of the particles.

Davies (4) theoretically deals with sampling by means of a cylindrical probe in a cross wind. He deduces conditions for particle inertia effects in the entrance flow to be neglible, and conditions required for the probe to be taken as a point sink.

Lundgren and Calvert (5) have experimentally studied the entrance efficiency for two types of side port probes in cross winds. They found the ratio between the cross wind velocity and the entrance flow velocity together with the inertial impaction parameter to be important parameters. They did not arrive at any mathematical expression describing the entrance efficiency.

Raynor (6) has experimentally studied sampling with a cylinder probe in a cross wind. He has varied cross wind velocity, flow rate into probe, direction of probe and particle size. He has set up an empirical expression that qualitatively agrees with his experimental results.

NOMENCLATURE

U_o	cross wind velocity
U_i	entrance flow velocity into cylinder probe
v_o	sedimentation velocity of a particle
$P = v_o U_o / gD$	inertial impaction parameter of a particle (v_o) with a velocity U_o
E	entrance efficiency

EQUIPMENT

Probes

A commercial filter holder of the type used in field work was lengthened to form a cylinder probe with an internal diameter D of 32 mm and an internal height of 36 mm. The wall thickness was 4 mm. A filter was mounted at the top of the cylinder. The cylinder probe is shown in figure 1.

The isokinetic probe was made out of a glass tube of an internal diameter of 6.1 mm. The tube was bent and sharpened at one end to form a probe tip with a wall thickness of 0.5 mm. The other end was connected to a filter holder with a filter. The isokinetic probe is shown in figure 2.

Membrane filters, Millipore AA WP 037 00, with a pore diameter of 0.8 µm, were used in all tests.

The probes were connected to a rotameter, a pump, and a gas meter. A reciprotor pump was used for the isokinetic probe, and a membrane pump for the cylinder probe.

Wind tunnel

The tests were run in an open wind tunnel, constructed at the laboratory. The tunnel was built in accordance with conventional commercial ventilation technique.

It consists of an entrance chamber, a contraction (area ratio 4:1), a test chamber, a damper, and a fan. The main part of the tunnel has a square cross section. A longitudinal cross section of the tunnel is shown in figure 3.

The cross wind velocity, that is the velocity in the tunnel, was regulated with the damper. With a Pitot-static tube and a micromanometer the cross wind velocity was determined as a function of the pressure loss over the contraction of the tunnel.

Test dust

The ideal test dust should be monodisperse and available in Stokes' diameters from 1 to 10 µm. It should also be easily dispersed, hydrofobic and cheap. Ground talc was found to satisfy these requirements except with respect to dispersion: The commercially available talc is polydisperse with quite wide distributions. The two particle size distributions chosen for this investigation have the following properties.

Per cent of weight with a Stokes diameter less than:

	fine talc	coarse talc
2 µm	40 %	20 %
5 "	85 "	48 "
10 "	99 "	81 "
20 "	100 "	98 "
30 "		99 "
45 "		100 "

Dispersion of test dust

A vibration unit, built at the laboratory, was used to feed the test dust into an air jet for dispersion. Th air jet was obtained from compressed air (pressure $60 \cdot 10^4 N/m^2$) let through a 0.5 mm capillary. According to Fuchs (7) dust with a diameter larger than 20 µm can efficiently be dispersed by an air jet.

The dispersion was tested. The air stream in the tunnel was sampled isokinetically and was drawn through a cascade impactor. The measured size distribution agreed, within estimated accuracy, with the data given for the fine and coarse talc.

To eliminate the air jet disturbing the entering of particles into the probes the jet was aimed at a circular (radius 50 mm) disc, mounted at the mouth of the entrance chamber.

BASIC THEORY

Similarity of systems with air-borne particles

In order that the motion of two systems with air-borne particles is to be similar, it is necessary to have

(1) geometrical similarity of the flow boundaries,
(2) similarity of fluid flow in each system,
(3) similarity of particle trajectories

As is well known from hydrodynamics, the dynamical condition for similarity of the motion of the fluids in two geometrically similar systems is that Reynold's number is constant. Reynold's number is proportional to some characteristic velocity times some geometrical dimension.

Fuchs (8) assumes that the resistance of a medium on a particle is proportional to the velocity difference (Stokes' law). For the particle trajectories to be similar he derives the condition that the dimensionless ratio between the stop distance of a particle and a characteristic dimension of the system, the inertial impaction parameter, is to be constant. When taking also gravity into consideration, he finds that the ratio between the sedimentation velocity of a particle and the entrance flow velocity is to be constant.

Another dimensionless parameter that can be formed is the ratio between cross wind velocity and entrance flow velocity. This parameter is important according to Lundgren and Calvert (4).

Dimensionless parameters

Dimensionless parameters which then might characterize the elutriation of particles are the inertial impaction parameter $p = v_o U_o / gD$, and the velocity ratios v_o/U_i and the velocity ratios v_o/U_i and U_o/U_i.

Entrance efficiency

The entrance efficiency of a probe is defined as the ratio between the concentration measured by the probe and the true concentration.

PROCEDURE

Particle sampling

The probes were mounted in the wind tunnel test chamber, so that the probe openings were side by side with a transverse separation of 90 mm. Two samples were taken for a given wind speed after which the positions of the probes were exchanged and another two samples were taken. This procedure was designed to eliminate any possible bias due to location within the test chamber. Tests were conducted at wind tunnel speeds, i.e. cross wind velocities, from 0.5 to 9 m/s with the fine and coarse talc respectively. Wind tunnel speeds were set by using a micro-manometer recording the pressure loss over the contraction of the tunnel. The lowest speeds were set by using a hot wire anemometer.

Flow through the isokinetic probe was set by means of a rotameter and varied from 0.9 to 16 l/min. Flow through the cylinder probe varied from 2.9 to 3.1 l/min. This flow corresponds to an entrance flow velocity of 9.9 to 10.3 cm/s. In order to reach this magnitude of particle sedimentation velocity, a Stokes' diamter of 60 μm is required.

Test dust handling

The talc was well dried at 110°C and was kept in air-tight glass jars until the tests were carried out. It was dispersed for 1.5-5 minutes and during this time the sampling was performed. The variation in time was due to deficiencies of the feeder function of the vibrating unit. However, the sampling time did not seem to bias the results.

X-ray fluorescence analysis

The filters were studied by means of X-ray fluorescence spectrometry with respect to silica. It was assumed that the mass of the filter-collected talc was proportional to the number of impulses obtained during 20 seconds. The maximum amount giving linearity for K_2SiF_6 is a layer thickness of 300 $\mu g/cm^2$, according to Grennfelt et al. (9). A maximum amount of talc of 300 $\mu g/cm^2$ was selected, since the coefficients of mass absorption of the test dusts are 5-10 % lower than for K_2SiF_6.

EXPERIMENTAL RESULTS

Isokinetic sampling was assumed to give the true concentration. From primary data (table 1 and 2) the entrance efficiency E and its standard deviation s were calculated as a function of cross wind velocity U_o or as a function of the inertial impaction parameter p, $p = v_o U_o / gD$. The linear mean sedimentation velocity with respect to weight v_o was determined from given test dust data and was found to be 0.048 cm/s for the fine talc and 0.24 cm/s for the coarse talc. Since these means are linear, they are meaningful mainly if the entrance efficiency is linear with respect to sedimentation velocity.

fine talc, $p = 1,53 \cdot 10^{-3}\ U_o$

U_o m/s	0,5	1.5	3.0	5.0	7.0	9.0
$p \cdot 10^{-3}$	0.8	2.3	4.6	7.6	10.7	13.8
E %	88	68	58	55	51	65
s %	7	4	8	7	16	42
s/E	0,08	0.06	0.14	0.13	0.31	0.65

coarse talc, $P = 7.75 \cdot 10^{-3}\, U_o$

U_o	m/s	0.5	1.5	3.0	5.0	7.0	8.8
P	10^{-3}	3.9	11.6	23.3	38.8	54.3	69.8
E	%	98	78	53	61	85	121
s	%	15	23	19	11	38	46
s/E		0.15	0.29	0.36	0.18	0.45	0.38

Entrance efficiency as a function of cross wind velocity is shown in figure 4, and as a function of inertial impaction parameter in figure 5. The entrance efficiency decreases with increasing cross wind velocity, reaches a minimum, and increases. The coarse talc shows a stronger dependence on cross wind velocity than the fine talc. Figures 4 and 5 also show that the cross wind velocity is a more important parameter than the inertial impaction parameter.

A few tests were run with no flow through the cylinder probe. Talc was dispersed and the tunnel was run at cross wind speeds of 1.5, 5 and 9 m/s. It was found that the amount of talc deposited on a filter might form a considerable part of the amount found in ordinary tests. For the fine talc the effect was in the order of the magnitude of a few per cent of the normal amount at a cross wind speed of 1.5 m/s, increasing to 15 per cent at 9 m/s. The effect was greater for the coarse talc, ranging from 10 to 35 per cent. If this dust deposition effect is taken into account, the general trend of the entrance efficiency still persists, although the increase after the minimum is slower.

Sampling of the laboratory air was done in order to estimate its amount of particulate matter. It was found that the relative background effect was greatest at wind tunnel speeds of 9 m/s, sometimes contribution up to 2-4 per cent of the normal amount of talc, and that it decreased to one per cent or less at speeds lower than 3 m/s.

DISCUSSION

Turbulent flow and vortices inside and around the cylinder probe might affect the entrance efficiency. Indications of this could be the increase in the standard deviation and dust deposition with increasing cross wind velocity and increasing particle size.

Higher cross wind velocities give a higher Reynold's number and therefore an increasing probability of turbulence and the formation of vortices. This should cause increased standard deviation and increased dust deposition. Furthermore, larger particles follow turbulent flow to a lesser extent than do finer particles and this should cause greater standard deviation and increased dust deposition for the coarse dust .

The dependence on cross wind velocity might also indicate that the velocity ratio between the cross wind velocity and the entrance flow velocity is an important parameter. According to Lundgren and Calvert this ratio is essential.

Neither Lundgren and Calvert nor Raynor have found any increase in entrance efficiency for higher cross wind velocities. They have performed studies with cross wind velocities, probe sizes and particle sizes of the same magnitude as in this study, but their entrance flow velocities, especially when compared to their cross wind velocities, have been considerably higher.

The observed trends are probably a result of turbulent flow and the formation of vortices. Consequently the quantitative results will not necessarily be the same at other flow conditions, e.g. open air, or with other types of elutriators. The results point out the need for further research on entrance efficiency when sampling by an elutriator.

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Table 1.

Sampling of fine talc for cross wind speeds ranging from 0.5 to 9 m/s.

Sampling time, sampled volume and number of impulses obtained by x-ray fluorescence analysis of filters and entrance efficiency. The number of impulses is proportional to the amount of talc on a filter. The entrance efficiency E is calculated from x-ray fluorescence results and sampled volume. "iso" denotes isokinetic sampling and "cyl" denotes sampling by the cylinder probe.

sampling time (min)	sampled volume (l)		impulses per 20 sec (10^3)		E
	iso	cyl	iso	cyl	%
U_o = 0,5 m/s					
3,75	3,33	11,3	12,0	35,3	86,7
5,75	5,07	17,7	12,3	38,8	90,4
3,50	3,06	10,7	12,4	34,4	79,3
3,75	3,16	11,2	10,3	35,1	96,1
U_o = 1,5 m/s					
4,50	12,2	13,2	43,7	29,8	63,0
3,25	8,5	9,5	39,2	31,9	72,8
4,25	11,3	12,5	44,5	33,5	68,1
2,50	6,6	7,4	44,0	32,8	66,5
U_o = 3,0 m/s					
5,00	26,6	14,8	64,3	23,0	64,2
3,00	16.0	9,0	58,6	22,7	68,9
3,00	15,8	9,3	64,5	22,9	60,3
U_o = 3,0 m/s					
2,25	11,7	6,5	69,1	21,0	54,7
3,50	18,5	10,4	69,5	20,4	52,2
2,75	14,4	10,6	71,1	23,5	44,9
3,75	19,4	10,8	64,5	22,0	61,2
4,00	21,1	11,5	64,7	20,6	58,4

Table 1 (cont)

sampling time (min)	sampled volume (l)		Impulses per 20 sec (10^3)		E
	iso	cyl	iso	cyl	%
U_o = 5,0 m/s					
6,25	54,4	18,7	50,5	10,7	61,6
3,75	32,8	10,8	59,8	10,3	52,3
4,00	34,8	10,6	60,1	11,7	63,9
4,75	41,7	13,9	67,5	10,5	46,7
4,25	37,0	12,7	64,2	11,1	50,4
U_o = 7,0 m/s					
4,00	49,6	11,1	48,5	5,08	46,8
3,00	37,1	9,0	50,1	9,17	75,5
4,50	55,1	13,0	63,1	5,99	40,2
3,75	46,4	11,0	69,0	6,92	42,3
U_o = 9,0 m/s					
3,50	55,0	10,5	46,1	6,51	74,0
2,50	39,8	7,5	30,6	7,09	123,0
3,50	55,1	10,2	64,5	3,46	29,0
2,50	39,2	7,4	60,2	3,81	33,3

Table 2

Sampling of coarse talc for cross wind speeds ranging from 0.5 to 8.8 m/s.

Sampling time, sampled volume and number of impulses obtained by x-ray fluorescence analysis of filters and entrance efficiency. The number of impulses is proportional to the amount of talc on a filter. The entrance efficiency E is calculated from x-ray fluorescence results and sampled volume. "iso" denotes isokinetic sampling an "cyl" denotes sampling by the cylinder probe.

sampling time (min)	sampled volume (1)		impulses per 20 sec (10^3)		E
	iso	cyl	iso	cyl	%
U_o = 0,5 m/s					
2,25	1,94	6,65	5,95	17,8	87,2
2,90	2,56	8,63	4,92	18,9	114,0
3,30	2,91	9,84	5,18	18,6	106,2
3,20	2,75	9,31	5,85	16,7	84,3
U_o = 1,5 m/s					
4,75	12,6	14,1	20,1	13,7	60,9
1,75	4,54	5,28	17,6	12,7	62,0
1,50	3,88	4,50	10,1	12,7	109,3
2,00	5,30	5,80	14,7	13.1	81,4
U_o = 3,0 m/s					
2,65	13,9	7,8	22,7	5,79	45,5
2,50	13.0	7,4	24,2	4,88	35,4
4,35	22,8	12,7	23,3	6,46	49,8
3.25	16,9	9,3	15,4	6,82	80,5
U_o = 5,0 m/s					
(2,75	23,5	8,2	7,2	4,55	181,1)
3.00	26,4	9,0	17,6	4,39	73,2
1,75	15,3	5,3	22,3	4,06	52,6
2,50	21,8	7,5	20,9	4,07	56,6

Table 2 (cont)

sampling time (min)		sampled volume (l)		impulses per 20 sec (10^3)		E
		iso	cyl	iso	cyl	%
U_o = 7,0 m/s						
3,50	a	43,2	10,2	9,87	2,99	128,3
2.50	a	30,4	7,1	10,9	2,55	100,5
1,75	b	21,8	5,1	16,6	2,90	72,1
5,10	b	62,7	15,1	15,9	1,52	39,8
U_o = 8,8 m/s						
1,60	a	24,6	4,73	7,01	2,28	169,1
3,35	a	51,8	9,8	7,89	2,07	138,7
4,00	b	61,8	11,9	15.5	3,44	115,3
2.50	b	38,7	7,3	12.7	1,47	60,5

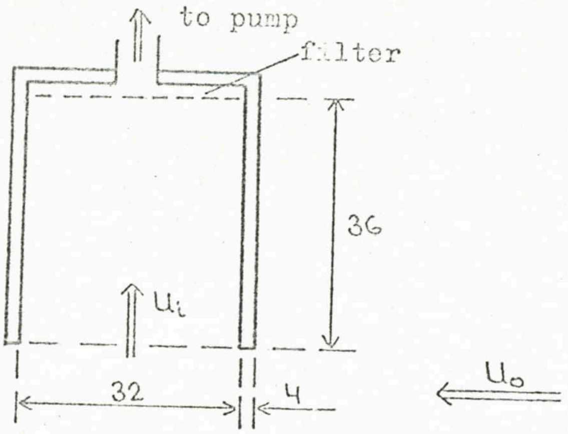
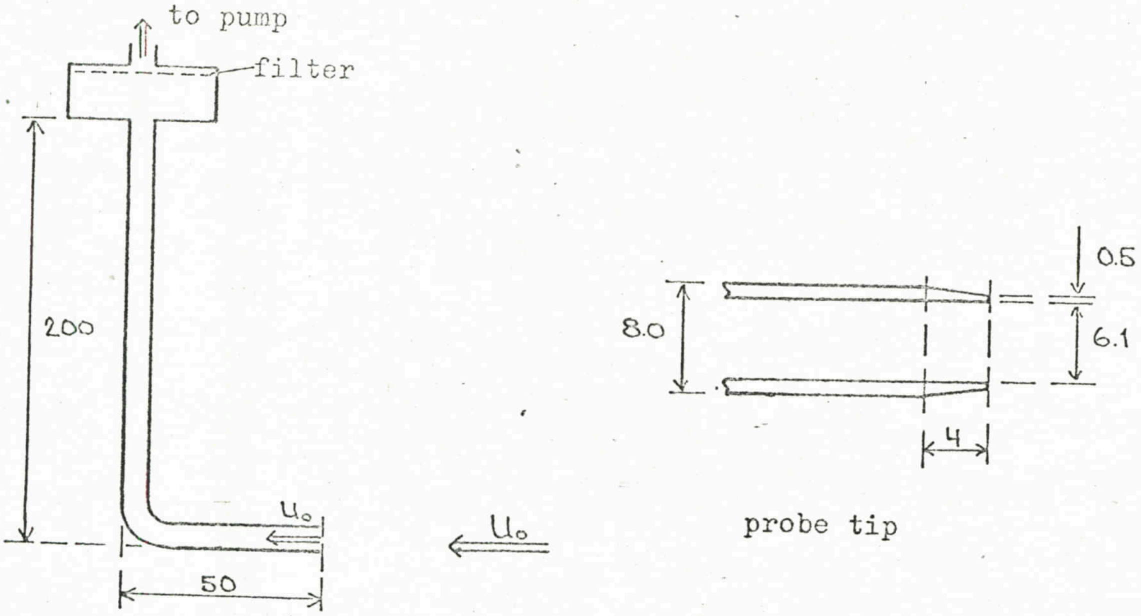


Fig. 1. Cylinder probe.



probe tip

Fig. 2. Isokinetic probe and probe tip.

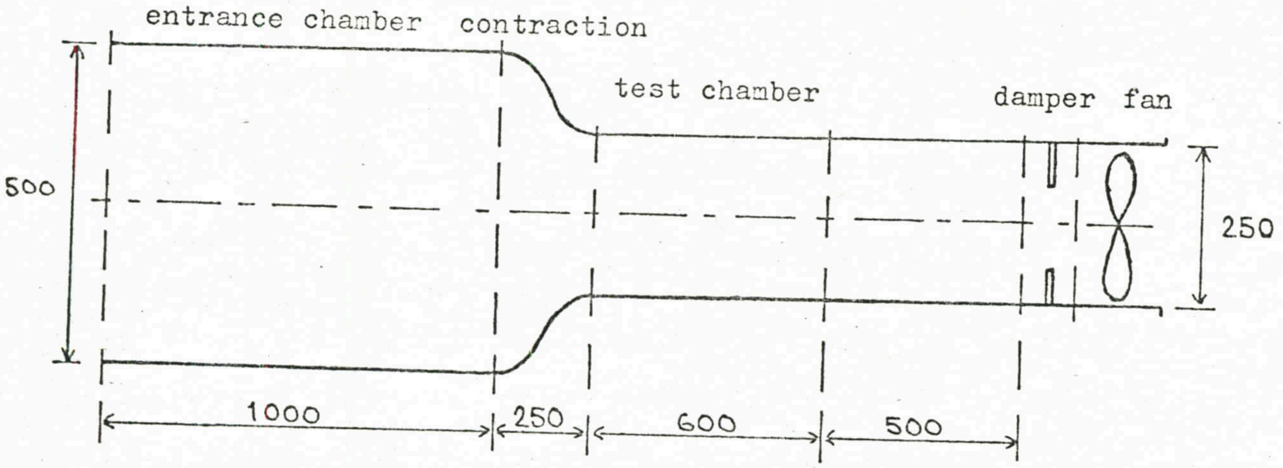


Fig. 3. Longitudinal cross section of wind tunnel.

Distances are given in mm.

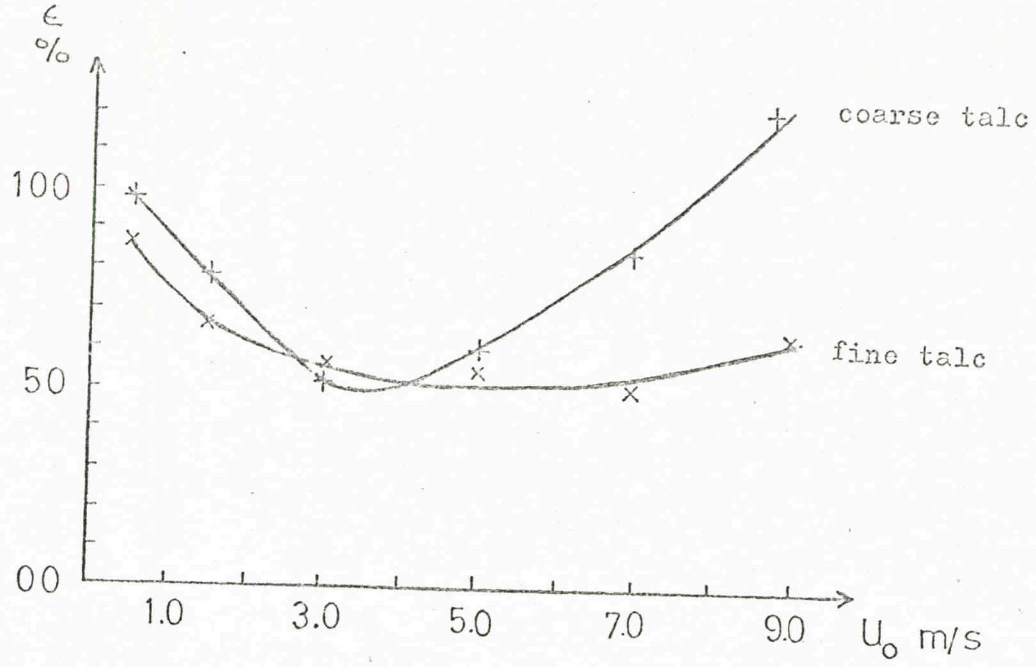


Fig. 4. Entrance efficiency ε as a function of cross wind velocity U_o .

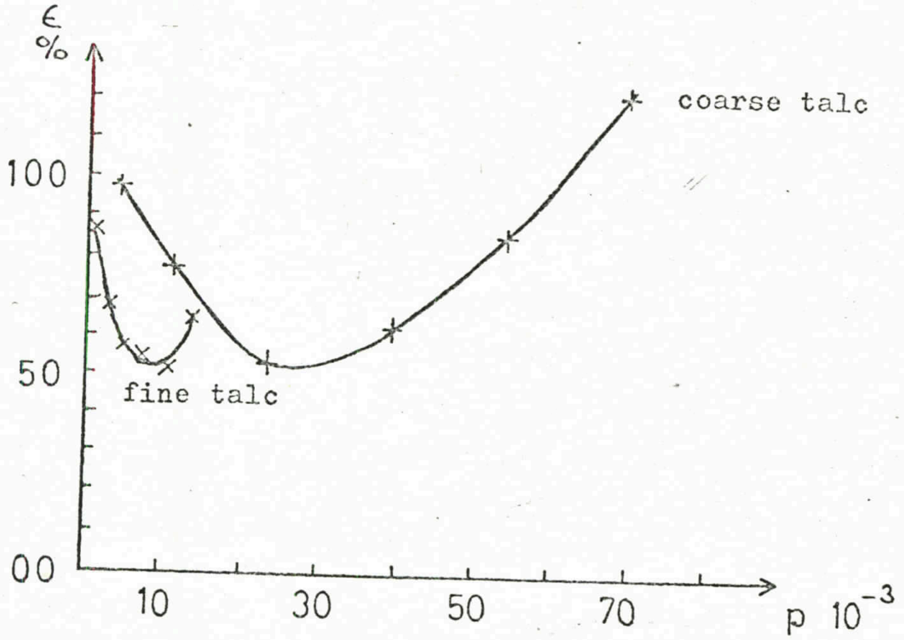


Fig. 5. Entrance efficiency ε as a function of inertial impaction parameter p .