IVL
SWEDISH WATER AND AIR POLLUTION RESEARCH LABORATORY
INSTITUTET FÖR VATTEN- OCH LUFTVÅRDSFORSKNING

DROTTNING KRISTINAS VÄG 47 D · BOX 5607 · S-114 86 STOCKHOLM 5 · SWEDEN · TEL. 08-22 25 40
DJURGÅRDSGATAN 26 · BOX 4052 · S-400 40 GOTHENBURG 4 · SWEDEN · TEL. 031-42 01 60

DEPOSITION OF AMBIENT AIR PARTICLES IN TUBES OF 4.5 - 6.5 MM DIAMETER AT FLOW RATES OF 1.4 AND 3 l/MIN.

Kenth Andreasson

Bengt Steen

B 129
Gothenburg
September
1973

Abstract

The deposition of ambient air particles in tubes was investigated. Tests were made in order to study the influence of different tube parameters on the particle deposition. The results show that in tubes of 4.5 - 6.5 mm diameter at flow rates of 1.4 and 3 l/min the deposition is strongly influenced by tube length and material, and to some extent by previously deposited particles. No effects on deposition from tube bending radius, orientation of tube or from tube diameter were found. Influence from different tube parameters on the rate of deposition was greater for large particles than for small ones.

1. INTRODUCTION

When collecting small samples of particulates on small filters for subsequent physical analysis, a sampling train of the type shown in fig. 1 is commonly used. This arrangement requires long tubing between sampling probe and filter. It is well known that long tubing can cause losses of particles due to deposition on the tube walls. This deposition is a function of many variables, the influence on the total effect of which is, as pointed out by many authors, not yet fully understood and thus not fully predictable. The objective of this investigation has therefore been to ascertain which of these variables were of the greatest importance under normal ambient air conditions, so that at least the order of magnitude of the particle losses can be predicted in some practical cases. Tests have been performed with tubes of diameters between 4.5 and 6.5 mm and flow rates of 1.4 and 3 l air/min in such a way that influence of length, diameter, material, previously deposited particles and orientation of tube could be determined for different particles size ranges. Whereas losses of particles and consequently, too small samples on the filter is the expected result of using long tubings, the effect may, in a certain case, be the opposite: If old tubes with walls covered by large amounts of particles are exposed to a mechanical shock, some of these particles will collect on the filter and result in an erroneously large sample.

Agents that could influence the deposition are:

1. diffusional processes
2. gravitational forces
3. inertial "
4. electrostatic "

These will be dealt with separately in the following.

1.1 Diffusional processes

These can be of two kinds: Brownian and turbulent.
Losses due to Brownian diffusion can be calculated by the formulas given by Gormeley and Kennedy (1949), which show that in this case - assuming that particles larger than 0,3 µm constitute the main part of the total mass - losses are negligible.

Losses from turbulent diffusion do not seem likely when considering that turbulence normally does not occur at the Reynold numbers (Re) relevant here, i.e. 300 - 1,000. It is not unlikely however that there are deviations from a strict laminar flow. Some kind of turbulence could arise from an uneven surface inside the tube from effects due to tube bends, or from uneven pumping. Unfortunately, today there is no way by which the losses due to turbulent diffusion can be predicted through theoretical calculation.

1.2 Gravitational forces

The effects of gravitational forces can be calculated at laminar flow according to Fuchs (1964). The length of a circular, horisontally oriented tube required for complete precipitation is:

$$L_{cr} = \frac{8 R \bar{U}}{3 V_s}$$

Where Vs = terminal rate of the settling of a particle, R = tube radius and $\bar{U}$ = mean gas velocity.

In fig. 2 is shown L_{cr} as a function of particle diameter for spheres of the density 2 g/cm^3.

1.3 Inertial forces

Inertial forces can cause deposition of particles in tube bends. A particle passing thorugh a tube bend in a laminair flow will move a distance d_a, relative to the gas flow lines. After passing the bend it will continue moving perpendicularly to the gas flow lines a distance d_s, after which due to drag forces it ceases to move in this direction.

Under certain conditions the total displacement $\Delta = d_a + d_s$ is relatively easy to calculate.

These conditions are:

a. Stokes law is obeyed.

b. The particle studied moves on a line of approximately constant bending radius.

c. The velocity of the gas can be regarded as equal to the mean gas velocity in all parts of the tube.

According to Fuchs (1964) the movement of a spherical particle travelling in a straight line through a gas at low Reynold numbers can be described by:

$$m \cdot \frac{dV}{dt} = F(t) - 3\pi\eta \cdot Dp \cdot V$$

where m = particle mass
V = particle velocity perpendicularly to the flow lines
t = time
F = external force put upon particle (varies in general with time)
Dp = particel diameter
η = gas viscosity

In a tube bend with a bending radius of R and a mean gas velocity of u we get

$$m \cdot \frac{dV}{dt} = \frac{m \cdot u^2}{r} - 3\pi\eta \cdot Dp \cdot V \quad \text{or} \quad \frac{dV}{dt} + \frac{V}{\tau} - \frac{u^2}{r} = 0$$

where the relaxtion time $\tau = \dfrac{m}{3\ \pi\eta \cdot Dp}$

The solution of this equation is:

$$V = \tau \frac{u^2}{r} (1 - e^{-\frac{t}{\tau}}) \qquad \text{if } V = 0 \qquad \text{for } t = 0$$

The distance d_a travelled by the particle in the direction of V is then:

$$d_a = \tau \frac{u^2}{r} \cdot t - \frac{2}{\tau} \cdot \frac{u^2}{r} (1 - e^{-\frac{t}{\tau}}) \text{ as } d_a = 0 \text{ for } t = 0$$

According to Davies (1968), the distance travelled by a particle introduced into still air at a velocity of V_1 until it has reached the velocity zero is:

$$d_s = V_1 \cdot \tau$$

If a particle leaves the tube bend at $t = t_1$ and $V = V_1$ the total displacement can be written as follows (for a 90° tube bend):

$$\Delta = d_a + d_s = \tau \cdot \frac{u^2}{r} \cdot t_1 = \tau \frac{\pi}{2} u = \frac{\pi\, Dp^2 \cdot \rho s \cdot u}{36\, \eta}$$

which is independent of the bending radius. ρ_s is the density of the particle, and η the viscosity of the gas.

Δ as a function of D_p for spherical particles of density 2 g/cm^3 at a velocity of u = 3.25 m/s in air of 20°C is shown in fig. 3. This calculation was, however, based on three assumptions. The first was that Stoke's law is obeyed. This is normally the case for Re numbers lower than 2. (The lower limit of Re for which Stoke's law is obeyed is of little interest here, as the displacement of such a small particle in this centrifugal field due to inertial forces would be negligible).

When calculating the Re number we have to take into account not only the movement caused by inertial forces, but also the movement caused by gravitational forces. In the most unfavourable orientation of the tube bend the terminal setting velocity due to gravitation and V_1 would add up to give V_r. In the critical case (that is Re = 2) we get six equations:

$$2 = \frac{V_r \cdot D_p \cdot \rho}{\eta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$V_1 + V_g = V_r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$V_1 = \tau \, \frac{u^2}{r} \left(1 - e^{-\frac{t}{\tau}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$\tau = \frac{m}{3\pi\eta \;\; Dp} = \frac{\rho \; s \cdot Dp^2}{18\rho} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

$$V_g = \frac{Dp^2 \cdot \rho \; s \cdot g}{18 \; \eta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$t_1 = \frac{\pi \; r}{2 \; U} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Where ρ is the density of the gas.
This system of equations have the solution

$D_p = 28.2$ µm, when

$\eta = 18.20 \cdot 10 - 6$ Ns/m^2, $\rho = 1.2045$ kg/m^3, $s = 2000$ kg/m^3

$r = 0.05$ m and $U = 3.25$ m/s

Thus, the result from the calculation of the displacement as a function of particle size in a tube bend with these conditions can not be used for particles larger than 28 µm diameter. (As Re then is > 2).

If $r = 0.01$ m, the maximum diameter will be 17 µm.

The second condition for the calculation of the displacement is that the particle is to move in a line of approximately constant bending radius. In all cases of practical interest here this condition is fulfilled, as the bending radius of the tube is large compared to the tube diameter and thus also to the possible displacement. When the displacement is larger than the tube diameter its exact value is of minor interest.

The third condition is that the velocity of the gas can be regarded as equal to the mean gas velocity in all parts of the tube.

This is probably not true in the practical case, since normally there is a parabolic velocity distribution in a long tube with laminar flow. In the straight part of the tube the maximum gas velocity is equal to twice the mean velocity. In a tube bend this velocity distribution is likely to be somewhat disformed as the gas in "the inner **curve**" has a shorter run than the gas travelling along the opposite wall. This will in some cases bring turbulence into the flow in the tube bend and in the nearest straight part of the tube (Davies, 1973). However, as the difference in "displacement properties" are so clear between different particle sizes the result is still useful in this context to determine the particle size ranges in which deposition in tube bends due to inertial forces can be expected to occur if laminar or close to laminar flow exists.

1.4 Electrostatic forces

The effects of electrostatic forces are difficult to predict by theoretical calculations. However, it should be possible to detect such effects by practical tests with different materials and resistivity.

Since, as mentioned above, the total particle loss is a function of a large number of variables, it was of interest to carry out measurements that could add to clarification of how these variables influenced the total effect of deposition. These measurements are described in the following sections.

2. EXPERIMENTAL

The tests have been performed in two different ways: Measurement by particle-counting and measurement by **analysis of elements in total particle mass.**

2.1 Measurement by particle-counting

These measurements were carried out at Råö, an experimental station, located at the sea-side 46 km south of Gothenburg on the west coast of Sweden. Under normal conditions Råö is regarded as a clean-air station and is used for back-ground measurements of air pollutants.

Samples were taken by drawing approx. 40 m^3 air/hour through a large sampling probe (fig. 4). From this air flow and under close-to-isokinetic conditions, a smaller sample of 3 l/min. was drawn through a glass probe connected to a particle counter by means of the tube to be studied. The number of particles per 3 litres of air was determined within the size ranges 0.3 - 0.4, 0.4 - 0.6, 0.6 - 1.0, 1.0 - 1.8, 1.8 - 3.4, 3.4 - 6.6, 6.6 - 13.0 and 13.0 µm projected diameters.

Each counting period being 1 minute, it was possible to make several measurements under several different conditions within a relatively short period of time. The aerosol composition was therefore regarded as constant during each of these comparative measurements.

When the influence of a certain tube parameter was studied with respect to the degree of particle deposition in the tube, a number of tubes which were identical except for this parameter were used to transport air from the glass probe to the particle counter.

The particle counter operated on a scheme of one minute counting period followed by one minute rest, then repeated the operation. The comparative measurements were made permutatively. Thus, using four tubes (a, b, c, d), the measurements were carried out as follows: One-minute count using tube a, one minute rest during which was exchanged for tube b, one minute count with tube b, and so on with c, d, a, b, etc. One such counting period in this sequence (a - d) is here called a "permutative counting period".

The reproducibility of the measurements and the influence from tube length, diameter, material, previously deposited particles and orientation of tube were studied. The results of the measurements are presented in Table 1, together with details about test conditions and tube parameters studied.

2.2 Measurements by analysis of elements in total particle mass

Samples were taken with two sampling units of the same type as illustrated in fig. 1. In the first unit, the air passed through the sampling probe, of 6 m length, a filter, a gas meter and a pump. The second unit was identical to the first one, except for the position of the filter, which was placed directly behind the sampling probe. Millipore membrane filters (mixed esters of cellulose) were used and the particles collected were analysed by x-ray fluorescence (1971). Sampling was done both at Råö and in Gothenburg for the purpose of obtaining samples with different size distributions. The mass mean particle diameter is normally larger in Gothenburg than at Råö. The two sampling units were used in parallel. One pair of units operated at Råö for the time 21 January - 17 April 1972 and another pair in Gothenburg from 20 March to 26 April 1972. Sampling was continuous and sampling time was 24 - 72 h. New tubes were installed before the measurements were started and used throughout the entire measurement period.

The amount of S, Cl and Si in particles sampled on the membrane filters was determined. These elements were chosen because of their abundance and also because they represent different size fractions: Sulphur has been found mainly in particles smaller than 1 μ m (A & S 1973) and silicon in larger particles (B + M 1972). Chlorine is represented mostly by a size fraction between those of S and Si.

3. RESULTS

3.1 Measurement by particle counting

The results of these measurements are summarized in Table 1.

3.1.1 Reproducibility

In measurements using four separate tubes with as similar characteristics as possible, the reproducibility with respect to tube specimen was better for small particles (<0.6 μm) than for large ones. The reproducibility of mean values from ten permutative counts for each tube, expressed as percentage standard deviation, is shown in Table 2.

3.1.2 Tube length

Fig. 5 illustrates the influence of tube length (L) on the particle loss. The measured particle concentration is plotted against the tube length.

If the curve is extrapolated to $L = 0$, it will be seen that the loss of particles smaller than 13 m, is less than 20 percent at a tube length of 1 m. A more accurate relationship between tube length and loss could not be measured because other interfering parameters such as equivalent particle settling velocity, diameter, particle charge, tube surface roughness, etc. could not be measured or controlled. As in the case of reproducibility, it seems that the losses of large particles are influenced somewhat more by variation in tube length than losses of smaller particles. (table 1)

3.1.3 Tube diameters

The result indicates no difference in deposition rate between tubes with diameters ranging from 4.5 to 6.5 mm. It is however, not possible to entirely isolate the effect of a change in tube diameter as this also influences the residence time for a particle in the tube.

3.1.4 Tube material

Tube material has a marked effect on particle loss. The "affinity" to the particles was least for glass, but increased with copper, Dekoron P, PVC and Teflon, in that order. (Dekoron P is a polyetylen tube).

3.1.5 Previously deposited particles

Particle losses in a tube increased with the length of time it had been in use. When the tube was exposed to a mechanical shock, a very high particle concentration was observed on the particle counter.

3.1.6 Orientation

When a cut was made perpendicular to the tube axis in the Dekoron P tube which had been used in sampling for some time and a piece of the tube was held against the light, one could easily see that particles were deposited in the lower part of the inside of the tube. This implied that gravitational forces had caused some of the particle loss. To assess the magnitude of this loss, measurements were made with alternatively vertical and horizontal orientation of the tube in which the aerosol was transported to the particle counter. No difference could, however, be detected.

3.2 Measurements by analysis of elements in total particle mass

The results of the measurements at Råö are shown in Table 3.

The mean values of losses of particle-borne Si was 52 percent. 22 percent of particle-borne Cl was lost. As for S, an excess of 7 percent was measured on the filter placed behind a 6 m tube. This result confirms the indications of the measurements by particle counting that losses of large particles are greater than losses of small particles. Large particles are here represented by Si and small particles by S. The same tendency is found when examining the results of the measurements in Gothenburg (Table 4) where the average particle diameter is expected to be larger than at Råö. The mean value of the losses of particle-borne Si was 85 percent, of Cl 28 percent and of S it was 24 percent.

From Table 3 it can be seen that in some cases, contrary to expectation, much higher values were obtained on the filter placed behind a 6 m tube than on the filter in front of the tube.

4. DISCUSSION OF RESULTS

As mentioned in the Introduction, the causes of particle deposition in tubes can be referred to

1) diffusional processes
2) gravitational forces
3) inertial forces
4) electrostatic forces

It is of interest here to see what theoretical models for the deposition that would best agree with the findings of this study:

4.1 Diffusional processes

4.1.1 Brownian diffusion

According to this theory, the diffusion velocity is higher for small particles than for large particles and will not cause any deposition of importance in this case of particles larger than 0.3 µm.

The results of the tests described above (including those which show that losses of large particles are greater than of small ones) confirm that mere Brownian diffusion cannot affect the deposition to any larger extent.

4.1.2 Turbulent diffusion

According to common theories about turbulent flow in tubes, turbulence occurs in the middle of the tube, and laminar flow occurs close to the walls. A particle in the turbulent part would then have to pass both through turbulent and through laminar flow before deposition on the wall. The slowest step would determine the total deposition velocity. The turbulent diffusion velocity is difficult to predict but it is generally known to be faster than the Brownian diffusion. Thus for the submicron particles studied here the total deposition velocity would be relatively slow, (determined by the Brownian diffusion) which in fact it was. The transport of the larger particles through the laminar part of the flow could be relatively fast, as the inertial forces, (introduced by turbulence) then could make these particles go straight through it.

The result of the tests reported above does qualitatively agree with this model. The differences in the amount of deposited particles due to variations in tube length and tube material are greater when the particles are large than when they are small. It is also in agreement with the model that the surface properties of the tube wall influence the deposition.

4.2 Gravitational forces

In accordance with the theory (1.2), particle losses in a 4 m tube should be observed only for particles with a Stoke's diameter > 6,6 µm Since the density of the particles was not known during the comparative measurements performed by particle counting, this theory could not be used to explain why no effect of gravitational forces could be observed in the size range 6.6 - 13 µm particle diameter. A turbulent flow in the tube, would counteract sedimentation of particles.

4.3 Inertial forces

The theory described earlier (1.3) purports that an effect of inertial forces when having pure laminar flow would be observed in comparative measurements by particle counting involving a horizontal, straight tube and horizontal tubes with loops of different diameters. The results of the comparative test did not show any difference between the tubes. This could only be explained, provided the density of all particles larger then 5 µm was much less than 1 g/cm^3. If there was a turbulent flow in the tubes, inertial forces could be regarded as responsible for the particle losses according to the theory mentioned in the discussion on the turbulent diffusion (4.1.2).

4.4 Electrostatic forces

Although the surface of the copper tube seemed relatively rough compared to the plastic materials, the particle deposition in a copper tube was less than in a Dekoron-P tube. This indicates that electrostatic forces influence the deposition rate. To further support this is the fact that among the plastic materials the greatest loss of particles occurred in a Teflon tube. As Teflon has the highest resistivity of all these materials it can also easily keep high charges unevenly distributed over its surface.

References

1. Andreasson, K. and Steen, B., "A study of air-borne particulate matter on the Swedish west-coast. Correlation between particle concentration with different size ranges and total particulate sulfate and sulfur concentration". IVL-report B 146. (1973).

2. Blanco, A.J. and McIntyre, R.G. Atmospheric Environment, 6 (1972) pp 537-562.

3. Davies, C.N., Staub, 28, No. 6 (1968) pp 219-262.

4. Fuchs. "The mechanics of aerosols". Oxford 1964 (Pergamon Press).

5. Gormley, P., Kennedy, M., Proc. Roy. Irish Acad., 52 A, 163 (1949).

6. Grennfelt, P., Åkerström, Å., and Brosset, C., Atmospheric Environment, 5 (1971) 1-6.

7. Davies, C.N. Aerosol Science, 1973, Vol 4 pp 317-328.

Table 1

Results of particle counts in comparative measurements on aerosols transported through different tubes at a flow rate of 3 l/min

Influence from tube	General test conditions				Tube parameters				Mean values of number of counted particles in 3 l of air with a projected diameter of (um)							
	test run No.	wind speed (m/s)	wind direction	number of permutative counts	length (m)	diameter (mm)	orientation	material	0.3-0.4	0.4-0.6	0.6-1.0	1.0-1.8	1.8-3.4	3.4-6.6	6.6-13	> 13
REPRODU-CIBILITY	1a	5	S	10	4	4.5	horizontal,	Dekoron P	38770	43642	24581	6519	519	61	6	0
	"b	"	"	"	4	"	straight	"	40114	46412	29623	6660	578	67	6	0
"	"c	"	"	"	4	"	"	"	40357	39755	29450	6752	584	63	6	1
"	"d	"	"	"	4	"	"	"	38054	42080	23316	5763	497	54	5	0
LENGTH	2a	0-3	W	11	1	4.5	horizontal,	"	9187	9501	7883	4781	1247	214	31	3
"	"b	"	"	"	2	"	straight	"	8201	8558	6699	4405	1038	205	31	3
"	"c	"	"	"	4	"	"	"	7930	8128	6383	4170	1046	170	24	2
"	"d	"	"	"	8	"	"	"	6576	6726	5617	3433	799	99	17	0
"	3a	8-16	N	10	4	"	"	"	5364	6429	6749	5051	1878	336	40	5
"	"b	"	"	"	8	"	"	"	4577	5512	5711	4145	1434	224	22	1
"	4a	5	S	10	1	"	"	"	49356	67406	39866	8463	984	153	32	4
"	"b	"	"	"	2	"	"	"	49866	67711	40052	8490	980	153	27	2
"	"c	"	"	"	4	"	"	"	51011	68456	37353	7885	911	125	20	3
"	"d	"	"	"	8	"	"	"	52079	63575	34027	7176	815	108	14	4
DIAMETER	5a	0-5	WNW	19	2.2	4.5	"	"	863	845	649	452	188	65	14	1
"	"b	"	"	"	"	6.5	"	"	966	804	670	486	204	67	16	1
ORIENTA-TION	6a	5	S	10	4	4.5	Horizontal, straight	"	41070	54472	42304	13694	1550	184	25	2
	"b	"	"	"	"	"	1)	"	42178	61013	46597	15200	1627	196	24	2
"	"c	"	"	"	"	"	2)	"	42008	60792	46610	15238	1714	195	25	1
"	"d	"	"	"	"	"	3)	"	40955	57446	42562	13789	1562	180	22	3
"	7a	10	SW	10	4	4.5	vertical, U-formed	"	13518	21602	26588	24308	9808	228	8	0
"	"b	"	"	"	"	"	horizontal, U-formed	"	13409	21504	26380	23878	8803	205	8	0
MATERIAL	8a	8-16	N	15	3	"	horizontal, straight	"	3452	3790	3660	2710	1132	215	34	4
"	"b	"	"	"	"	5.0	"	Copper	4104	4542	4467	3366	1506	326	57	7
"	"c	"	"	"	"	"	"	Glass	4837	5469	5975	4192	1826	392	69	8
"	9a	10	SW	13	3	"	"	Teflon	16910	20143	20492	15755	3046	156	13	0
"	"b	"	"	"	"	4.5	"	Dekoron P	19037	23747	24172	19673	4131	220	19	1
"	"c	"	"	"	"	6.5	"	"	19268	23268	23483	18732	3604	184	15	1
"	"d	"	"	"	"	6.0	"	PVC	19630	23832	24261	19305	3946	225	17	1
PREVIOUSLY DEPOSITED PARTICLES	10a	4	NW	5		4.5	"	Dekoron P (new tube)	12105	10020	7984	5202	1391	154	18	1
	"b	"	"	"	"	"	"	Dekoron P (old tube)	10167	8691	7018	4631	1208	126	17	0

1) horizontal + one loop with a diameter of 65 mm
2) " " " " " " " 130 mm
3) " " " " " " " 170 mm

Table 2.

Reproducibility with respect to tube specimen expressed as percentage standard deviation of mean values from 10 permutative particle counts after 4 tubes of equal size

	Particle size range (μm)							
	0.3-0.4	0.4-0.6	0.6-1.0	1.0-1.8	1.8-3.4	3.4-6.6	6.6-14	13
Standard deviation (%)	2.8	6.5	12	7.0	7.9	8.9	8.7	-

Table 3

Results from comparative sampling on membrane filters at Råö and subsequent x-ray fluorescence analysis

Date for sampling	concentration, measured with filter placed directly behind sampling probe ($\mu g/m^3$)			concentration, measured with filter placed behind probe and a 6m tube ($\mu g/m^3$)		
	SO_3	Cl	SiO_2	SO_3	Cl	SiO_2
21 - 23.1	1,8	0,0	0,2	5,0	0,0	0,2
24 - 25.1	3,7	0,0	11,0	16,0	0,1	3,7
26 - 27.1	12,5	0,0	2,4	11,5	0,0	1,9
28 - 30.1	6,3	0,0	1,9	5,0	0,0	1,1
2 - 3.2	10,6	0,1	3,5	10,5	0,0	2,5
9 - 10.2	1,8	0,0	0,3	5,1	0,0	0,2
18 - 20.2	10,2	0,0	3,3	10,1	0,0	2,0
21 - 22.2	3,2	0,0	11,0	13,4	0,0	3,5
23 - 24.2	7,1	0,0	3,4	6,4	0,0	1,7
25 - 27.2	6,3	0,0	1,9	6,0	0,0	0,8
28 - 29.2	4,9	0,1	4,6	2,4	0,1	1,2
1 - 2.3	6,0	0,1	2,1	1,6	0,1	0,3
3 - 5.3	5,6	0,0	1,3	11,0	0,0	2,0
6 - 9.3	6,1	0,2	3,8	6,0	0,1	2,7
10 - 12.3	3,8	0,7	2,2	3,7	0,3	1,3
13 - 15.3	12,7	0,1	12,4	11,7	0,0	4,5
15 - 17.3	15,5	0,0	5,0	16,6	0,0	2,6
17 - 20.3	6,0	0,1	3,3	6,5	0,0	1,6
20 - 21.3	8,5	1,8	3,8	7,4	1,0	1,3
22 - 24.3	1,9	5,4	0,6	1,9	6,4	0,4
24 - 27.3	5,1	2,2	2,1	4,6	1,9	1,2
27 - 29.3	2,8	4,8	0,8	2,1	3,5	0,6
29.3- 5.4	3,0	4,7	1,1	2,5	3,2	0,8
5 - 7.4	3,5	2,5	1,1	4,9	1,7	1,0
7 - 10.4	6,3	0,1	0,6	5,4	0,3	0,5
10 - 12.4	7,0	0,2	2,7	6,6	0,3	1,5
12 - 14.4	15,2		0,8	10,5		0,4
14 - 17.4	6,4		4,4	6,9		2,6

Table 4

Results from comparative sampling on membrane filters in Gothenburg and subsequent x-ray fluorescence analysis

Date for sampling	concentration, measured with filter placed directly behind sampling probe ($\mu g/m^3$)			concentration, measured with filter placed behind probe and a 6m tube ($\mu g/m^3$)		
	SO_3	Cl	SiO_2	SO_3	Cl	SiO_2
20 - 22.3	9,1	1,7	43,5	6,3	0,8	3,2
22 - 24.3	3,8	5,3	36,5	2,0	2,3	2,7
24 - 27.3	6,2	1,2	18,0	4,4	1,4	1,9
27 - 29.3	4,6	3,3	9,3	2,3	1,4	1,3
29.3-5.4	3,3	2,0	14,2	2,6	1,9	2,0
5 - 7.4	7,9	1,9	12,7	5,8	1,6	1,5
7 - 10.4	6,7	0,4	6,9	5,2	0,5	0,9
10 - 14.4	10,0		15,4	8,2		2,0
14 - 17.4	11,4		16,1	10,3		7,3
19 - 21.4	3,5		10,3	2,7		1,8
21 - 24.4	3,7		8,1	2,5		2,8
24 - 26.4	4,7		25,4	3,6		3,2

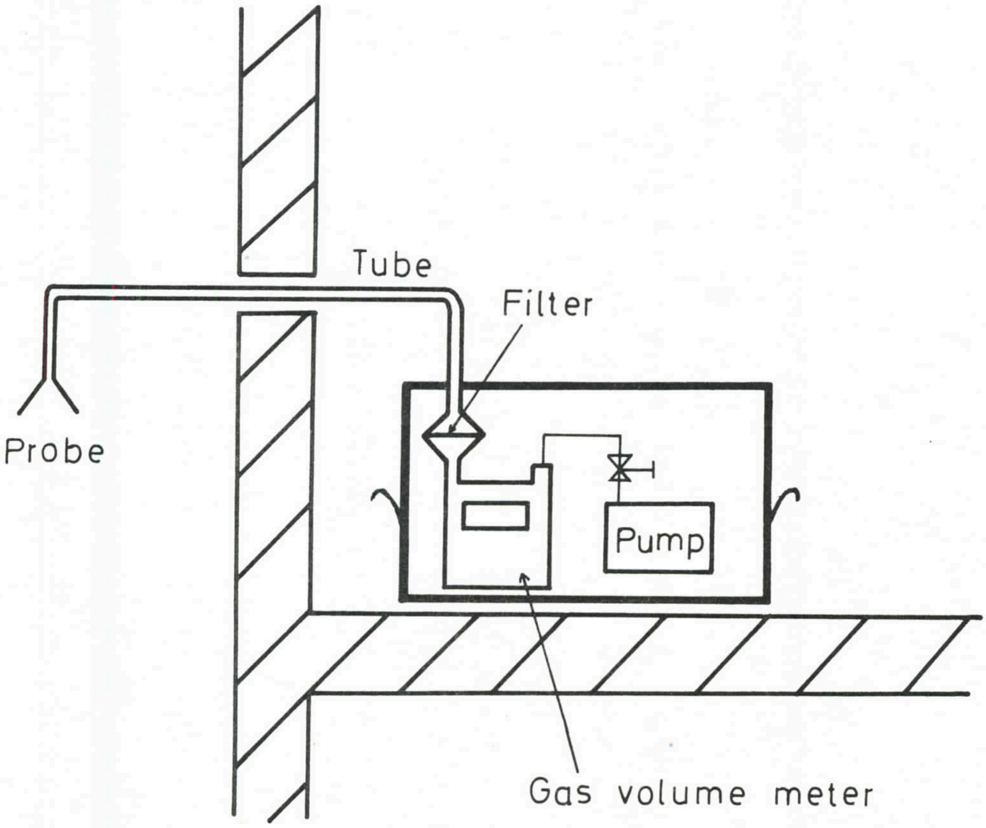


Fig 1

Sampling train for particles in ambient air.

Fig. 2.

Length (Lcr) of a circular horisontally oriented tube, with inner diameter = 4.5 mm and a flow of 3 l/min, required for complete gravitational precipitation of spheres, as a function of particle size, at 20°C.

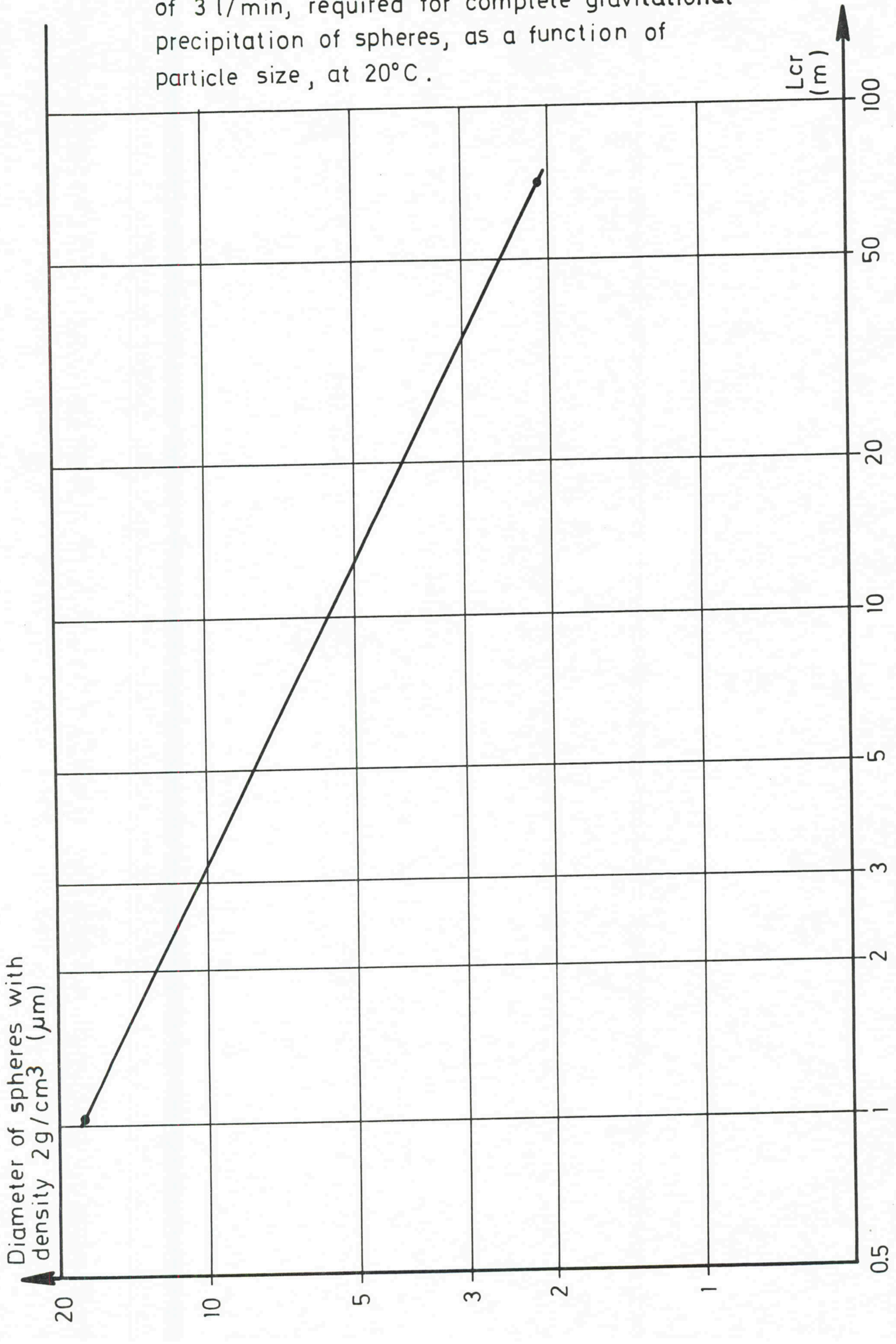
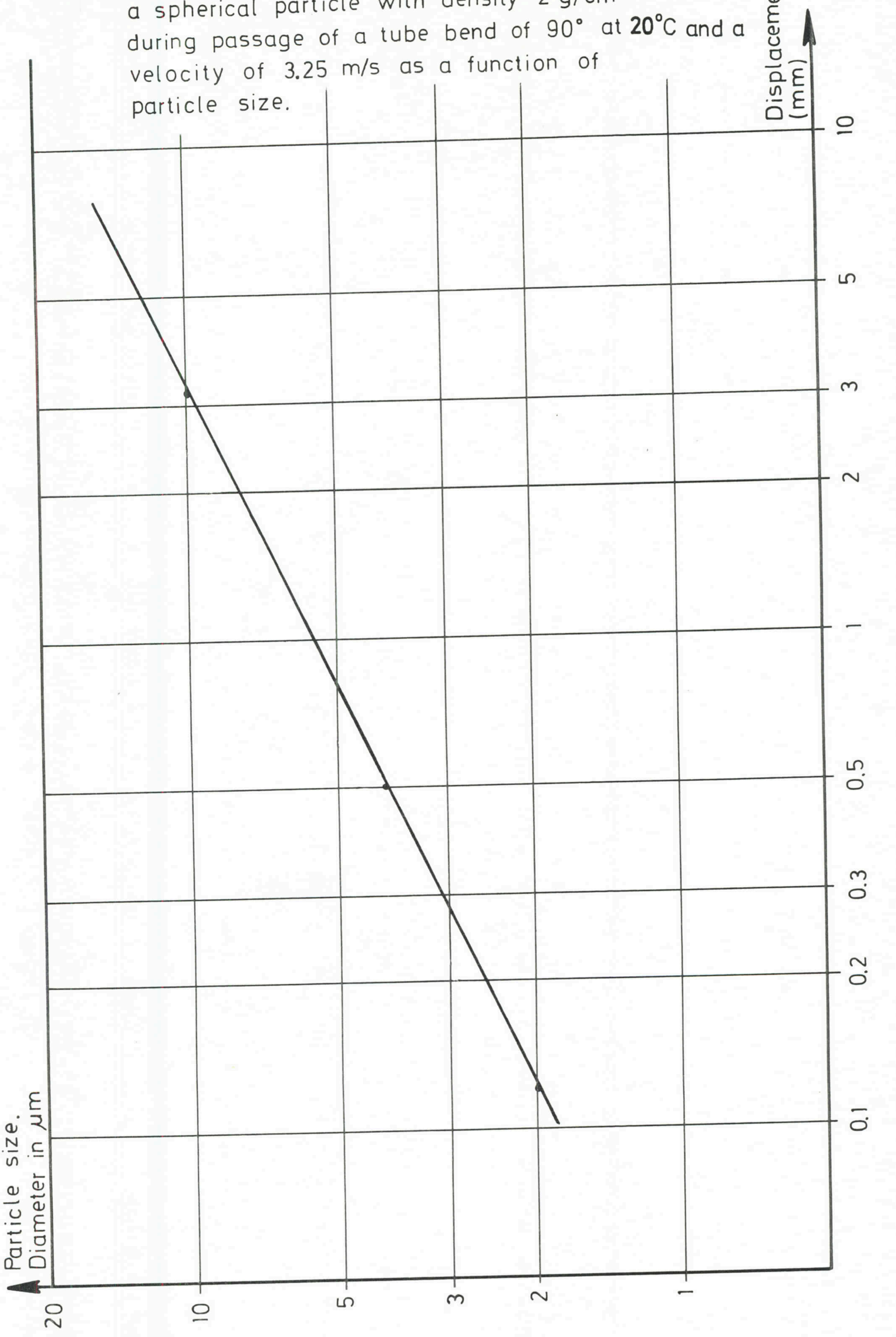


Fig. 3.

The displacement relative to the flow lines of a spherical particle with density 2 g/cm^3 during passage of a tube bend of 90° at **20°C** and a velocity of 3.25 m/s as a function of particle size.



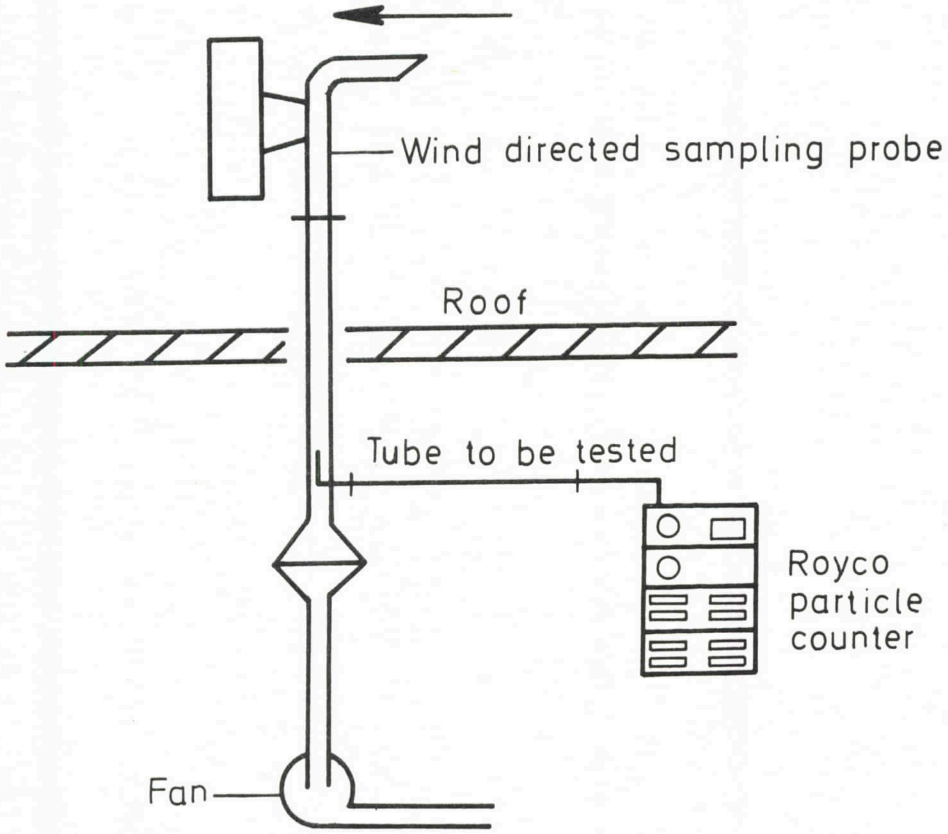


Fig 4

Comparative tests of particle losses in tubes by particle counting.

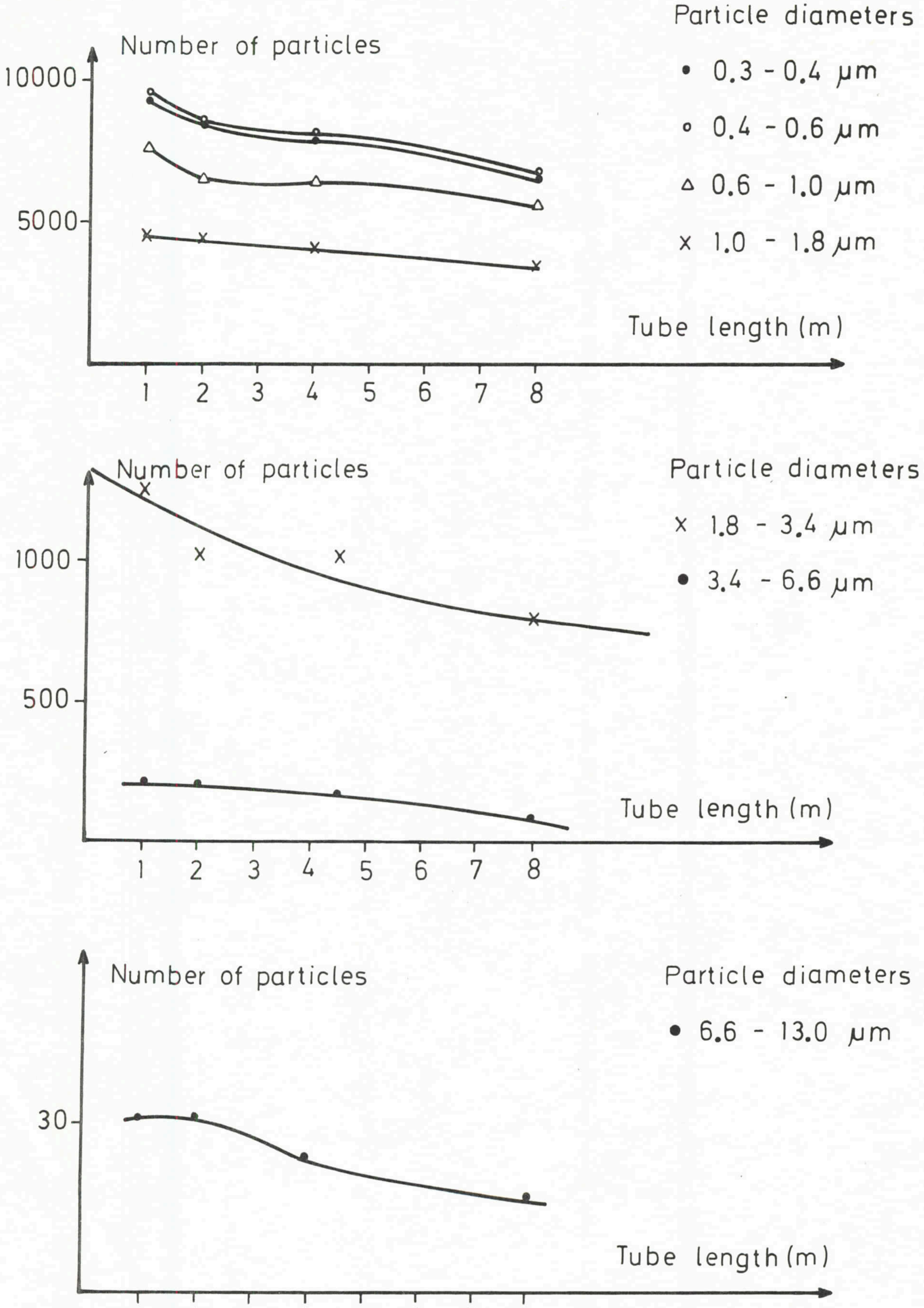


Fig. 5
Influence of tube length on particle loss.