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ON THE TECHNIQUES OF AEROSOL ELECTRICAL GRANULOMETRY

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Symbols and units

All equations in the paper are in SI. Alongside with the units of SI, also practical measurement units, which are multiples of SI units, are used. Below, the symbols of physical quantities are followed by a practical measurement unit or a SI unit.

d - particle diameter, $1 \text{ nm} = 10^{-9} \text{ m}$, (d_c - critical diameter, d_D - characteristic diffusion diameter, d_m - characteristic field diameter),
 e - $1.602 \cdot 10^{-19} \text{ C}$ - elementary charge,
 h - thickness of the charging layer, $1 \text{ cm} = 10^{-2} \text{ m}$,
 k - air ion mobility, $1 \text{ cm}^2/(\text{V}\cdot\text{s}) = 10^{-4} \text{ m}^2/(\text{V}\cdot\text{s})$,
 k_{st} = $1.5 \text{ cm}^2/(\text{V}\cdot\text{s})$ - conventional standard mobility of small air ions,
 n - concentration of small air ions, $1 \text{ cm}^{-3} = 10^6 \text{ m}^{-3}$,
 r - particle radius, $1 \text{ nm} = 10^{-9} \text{ m}$,
 t - time, s, (t_c - particle charging time),
 q - particle charge, C,
 A - dimensionless coefficient of relaxation of diffusion charging,
 C - electric capacitance, F,
 E - electric field, $1 \text{ V/cm} = 100 \text{ V/m}$ (E_0 characteristic field of particle charging),
 F - air flow rate $1 \text{ cm}^3/\text{s} = 10^{-6} \text{ m}^3/\text{s}$,
 K = $1.38 \cdot 10^{-23} \text{ J/K}$ - Boltzmann's constant,
 R - electric resistance, Ω ,
 T - temperature, K,
 U - electric voltage, V,
 α - dimensionless coefficient of charging intensity,
 β - coefficient of nonuniformity of charging conditions, $1 \text{ cm/s} = 10^{-2} \text{ m/s}$,
 γ = q/e - dimensionless particle charge,
 ν - dimensionless coefficient of nonuniformity of charging level,
 ε - dimensionless relative permittivity of aerosol particles,
 ε_0 - $8.86 \text{ pF/m} = 8.86 \cdot 10^{-12} \text{ F/m}$ - absolute permittivity of the air,

τ - RC - time constant, s,
 ω - dimensionless electrostatic coefficient,
 θ - dimensionless coefficient of nonuniformity of the charging process,

Introduction

Electrical aerosol granulometry is proved to be a promising technique of aerosol analysis in practice. The most important contributions to the field have been made by the laboratory of aerosol technology of the University of Minnesota [1]. Despite the practical success it should be said that the technique of electrical granulometry is but at the start of its development and far from perfect.

The process of electrical granulometry can be divided into three stages :

- charging of aerosol particles,
- separation and registration of the particles,
- calculation of size spectrum of the particles.

All three stages are equally responsible for the correctness of the results and the efficiency of the measurement method. Different methods can be used at every stage. Therefore the technology of the process as a whole makes possible numerous modifications.

The present paper will deal only with two first stages of the process of electrical granulometry. Some considerations of the author concerning the third stage can be found in [2]. Of the numerous possible methods, the paper will consider only the unipolar charging of particles in a flow of small air ions, and particle registration by the electric current in the same measurement capacitor where particles are separated. The paper does not attempt to develop the charging theory of aerosol particles, it concentrates on the technique of granulometry, whereas the mathematical model of particle charging is considered only with the narrow aim of establishing the dependence of granulometer properties on the charger. The treatment is limited to a fairly rough mathematical model proposed by Mirzabekyan [3]; new improvements in the theory of particle charging have not been taken into account. It is assumed that the particles are spherical. Only the average charge of a particle is estimated and the statistical dispersion of the charges is ignored. This does not mean that the mathematical model simplified to such an

extent is taken to be sufficient at the stage of calculation of particle size spectra. Here, evidently, none of the known theories of particle charging can be viewed as totally reliable. It is better to describe particle charging with a semi-empirical formula which would take into account the statistical dispersion and loss of charged particles in the charger. Semi-empirical formulas contain theoretically indeterminate constants which should be determined by calibration of the granulometer by test aerosols having known particle size distributions.

Mathematical models of particle charging

The charging parameter α

The traditional parameter of diffusion charging of aerosol particles is the product of small air ion concentration and the time of charging. It arises from the assumption that small air ions have fixed mobilities. In the opposite case the intensity of charging is proportional also to the average mobility of the air ions. Sometimes also the change of small air ion concentration over time is to be taken into account. In view of the above, instead of the traditional product nt_q , the charging parameter

$$\alpha = \frac{1}{\epsilon_0} \int_{t_0}^{\infty} \lambda dt \quad (1)$$

is introduced, where $\lambda = ekn$ - conductivity caused by small air ions. Permittivity of the air is included in order to obtain a dimensionless quantity.

For air ions with a conventional standard mobility of $1.5 \text{ cm}^2/(\text{V}\cdot\text{s})$ and a steady concentration over time, we have

$$\alpha = 2.71 \frac{nt_q}{10^8 \text{ cm}^{-3}\text{s}} \quad (2)$$

Electrostatic dispersion of air ions

Let us consider air containing monomobile small air ions of only one polarity, and follow a point moving along the trajectory of an air ion. In such a point the space charge density decreases according to the law of electrostatic dispersion

$$\frac{dq}{dt} = - \frac{kq^2}{\epsilon_0}, \quad (3)$$

which is valid also in external electrostatic field and in moving air [4]. A general solution of the equation can be written as

$$\lambda = \frac{\epsilon_0}{t - t_0}, \quad (4)$$

where the moment t_0 is determined by the initial conditions.

Let us henceforth agree to take into account time in accordance to concrete conditions starting from the moment t_0 . Then $t_0 = 0$ and

$$\lambda = \frac{\epsilon_0}{t}. \quad (5)$$

For $t \rightarrow 0$, we have $\lambda \rightarrow \infty$. $t = 0$ can be assumed at the beginning of an air ion trajectory on the point of the corona discharger. The time counted from the moment t_0 is henceforth called the conventional age of small air ions.

For small air ions with standard mobility $t = 1 \text{ s}$ gives us $n = 369000 \text{ cm}^{-3}$.

An ideal transversal charger

The design of the charger is schematically depicted in Fig. 1.

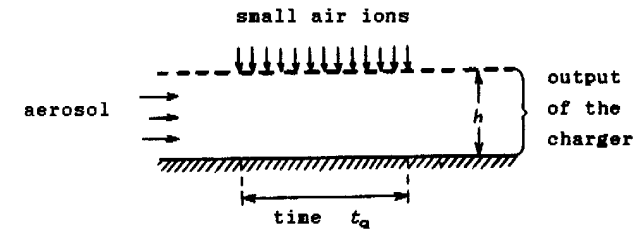


Fig. 1. Longitudinal section of an ideal transversal charger.

A uniform flow of air passes through the charger from left to right. An air layer of a certain limited thickness h is used as the output of the charger. Influenced by the external electric field, the small air ions move approximately cross-wise to the air flow. Compared to h , the charging zone is

relatively long, the time of air flow through this zone is t_q . Due to electrostatic dispersion, the conductivity is better in the layers which are nearer to the air ion source and worse at the bottom side of the charger. Let us denote the values of the parameter α on the upper and lower limit of the charging zone with α_{max} and α_{min} . Non-uniformity of the charging process can be described with the parameter

$$\theta = \frac{\alpha_{max} - \alpha_{min}}{\bar{\alpha}}, \quad (6)$$

where

$$\bar{\alpha} = \sqrt{\alpha_{max}\alpha_{min}} \quad (7)$$

is the average value of the charging parameter α .

The electric field in an transversal charger

A certain aerosol particle passes through the charger at a certain height where the conductivity has a certain value. Then $\alpha = \lambda t_q / \epsilon_0$ and according to (5) we have

$$\alpha = t_q / t, \quad (8)$$

where t - the conventional age of air ions at the considered height. Using (8), it is easy to find that

$$\theta = \delta t / t, \quad (9)$$

where $\delta t = t_{max} - t_{min}$ - the time of the flow of small air ions through the charging zone, and $\bar{t} = \sqrt{t_{max}t_{min}}$ - the average age of small air ions in the charging zone. Let us now determine the average intensity of the electric field in the charging zone so that

$$\frac{h}{\delta t} = \bar{E}k. \quad (10)$$

Now it is possible to write the basic relation

$$\bar{E} = \frac{h}{\theta t_q} \frac{\bar{\alpha}}{k}. \quad (11)$$

From this result it follows that the average intensity of the electric field in a transversal charger is limited from below by the permitted non-uniformity of the charging process.

The parameter of charger β

If to fix the parameter α and the mobility k , then, according to formula (11), the field intensity in the charger depends on the design of the charger only through the factor $h/\theta t_q$. This factor is denoted by β :

$$\beta = \frac{h}{\theta t_q} \quad (12)$$

and viewed as the second basic parameter of the charger. The parameter β has a dimension of velocity. It is proportional to the average velocity of small air ions in the charger.

$$\beta = \frac{1}{\bar{\alpha}} \bar{E}k. \quad (13)$$

The larger the parameter β , the stronger is the influence of the mechanism of field charging of aerosol particles in the electric field.

Example

Let an ideal transversal charger have the following characteristics:

$$n = 3 \cdot 10^8 \text{ cm}^{-3}, \quad k = k_{at}, \quad t_q \approx 1 \text{ s}, \quad h = 1 \text{ cm}, \quad \theta \approx 20\%.$$

These data unambiguously determine the intensity of the electric field in the charger. Using the above formulas, we obtain

$$\alpha = 8.14, \quad \beta = 5 \text{ cm/s}, \quad E = 27 \text{ V/cm}.$$

If to decrease the electric field, then the parameter of non-uniformity β will correspondingly grow.

Non-uniformity of the charging in a real transversal charger

As a rule, the parameters of a real device are worse than those of an ideal device. In the case of transversal charger there are exceptions to the above regularity. An ideal transversal charger presupposes a uniform profile of the air flow. If the air enters a real charger through a long channel, then the profile will be close to parabolic. Then the time t_q is longer in lower and shorter in higher layers of the air in the charger. This compensates for the non-uniformity of conductivity and lessens the value of the parameter θ in comparison with an ideal charger. This effect can be fairly

significant. In devices with relatively short inlet channels the profile of air flow velocities is close to uniform and the above effect is weak.

In relatively short chargers a phenomenon of longitudinal widening of the air ion flow from the top to the bottom is observed. This also compensates for the non-uniformity of conductivity.

There can also be some deviations from the ideal conditions which cause the deterioration of the parameters of the charger. The biggest danger is spatial non-uniformity of the source of small air ions. However, a good design makes it possible to reduce the non-uniformity of charging when compared with the theory of ideal transversal charger.

Mirzabekyan's model

Mirzabekyan [3] demonstrated that the charge of the particle q_D , acquired on the account of the diffusion mechanism, and the charge of the particle q_E , acquired on the account of the field mechanism, are simply added in the first approximation and the particle charge is

$$q = q_D + q_E \quad (14)$$

To calculate the charge q_D , Mirzabekyan proposes the equation

$$\frac{\epsilon_0}{ek} \left[\text{Ei} \left(\frac{q_D e}{4\pi\epsilon_0 rKT} \right) - \ln \left(\frac{q_D e}{4\pi\epsilon_0 rKT} \right) - 0,5772 \right] = nt_a \quad (15)$$

and for the charge q_E , he proposes the Pauthenier equation

$$q_E = 4\pi\epsilon_0 \left(1 + 2 \frac{\epsilon - 1}{\epsilon + 2} \right) E r^2 \frac{\pi k e n t_a}{4\pi\epsilon_0 + \pi k e n t_a} \quad (16)$$

Below Mirzabekyan's model will be presented in a shape which is easier to interpret. For this purpose it is necessary to determine certain supplementary quantities.

The relaxation coefficient and electrostatic coefficient

Equation (15) can be written as:

$$\sum_{n=1}^{\infty} \frac{A^n}{n \cdot n!} = a \quad (17)$$

The quantity

$$A = \frac{q_D e}{4\pi\epsilon_0 rKT} \quad (18)$$

is considered as a dimensionless coefficient of the relaxation of diffusion charging.

In the interval $a = 3 \dots 300$ with an error less than 0.1, the approximate equation is valid

$$A \approx \ln(1 + a^{4/3}) \quad (19)$$

To keep the Pauthenier formula short we will use a special denotation for the electrostatic coefficient

$$\omega = \frac{1}{2} + \frac{\epsilon - 1}{\epsilon - 2} \quad (20)$$

The values of this coefficient are in the interval 1 ± 0.5 . In the examples $\omega = 1$ will be considered as the standard value, the corresponding permittivity $\epsilon = 4$.

Characteristic sizes and electric field

Let us determine the characteristic size of diffusion charging

$$d_D = \frac{e^2}{2\pi\epsilon_0 kT} \quad (21)$$

the characteristic size of field charging

$$d_E = \sqrt{\frac{k}{\omega\beta} \frac{e}{2\pi\epsilon_0}} = \sqrt{\frac{\bar{a}}{\omega\beta} \frac{e}{2\pi\epsilon_0}} \quad (22)$$

and the characteristic intensity of the electric field

$$E_0 = kT/d_D e \quad (23)$$

At a temperature of 18°C we have:

$$d_D = 115 \text{ nm}, \quad E_0 = 2185 \text{ V/cm.}$$

If to assume $k = k_{m\epsilon}$ and $\omega = 1$, then

$$d_E = \frac{8570 \text{ nm}}{\sqrt{\beta} : (\text{cm/s})}$$

The equation of particle charging

The above characteristic quantities allow us to describe Mirzabekyan's model using the expressive equation

$$\bar{\gamma} = \frac{\bar{q}}{e} = A \frac{d}{d_p} + \frac{\alpha}{1 + 4/\alpha} \left(\frac{d}{d_p} \right)^2 \quad (24)$$

or an equivalent equation

$$\bar{\gamma} = A \frac{d}{d_p} + \frac{\omega}{1 + 4/\alpha} \frac{E}{E_0} \left(\frac{d}{d_p} \right)^2 \quad (25)$$

In the case of small particles $\bar{\gamma} < 1$, this indicates that many particles are uncharged. The electric mobility of the particles is dependent not on the average charge of all particles $\bar{\gamma}$, but on the average charge of charged particles γ . Evidently γ is never less than a unit. For obtaining the first approximation the following equation can be proposed

$$\gamma \approx \sqrt{1 + \bar{\gamma}^2} \quad (26)$$

The electric mobility of particles

At the description of the movement of spherical particles the well-known Millikan equation is acknowledged to be sufficiently precise over the size range we are concerned with. Let us express the numeric value of the diameter in nm through d' , then the Millikan equation will acquire the shape

$$k = (9.44/d') \cdot 1 + (165/d')(1 + 0.336 \exp(-d'/153)) \cdot 10^{-8} \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \quad (27)$$

Here it has been assumed that the temperature is 18°C and the atmospheric pressure is 1000 mb.

The dependence of particle mobility on the size is illustrated in Fig. 2. The four upper curves correspond to four typical combination of charger parameters α and β . The fifth curve will be explained in the second part of the paper.

Critical particle diameter

We will call the diameter at which particle mobility is minimal the critical diameter. Usually the critical diameter is of an order of μm . In the case of micrometric particles the exponential member of the Millikan formula may be ignored and $\gamma = \bar{\gamma}$ can be assumed. Let us assume that the mobility of small air ions is k_{air} and $\omega = 1$. Then

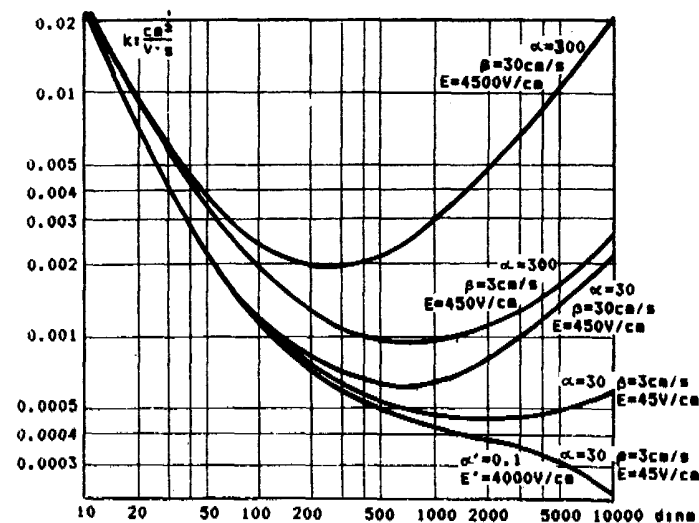


Fig. 2. The dependence of the mobility on particle diameter and charger parameters.

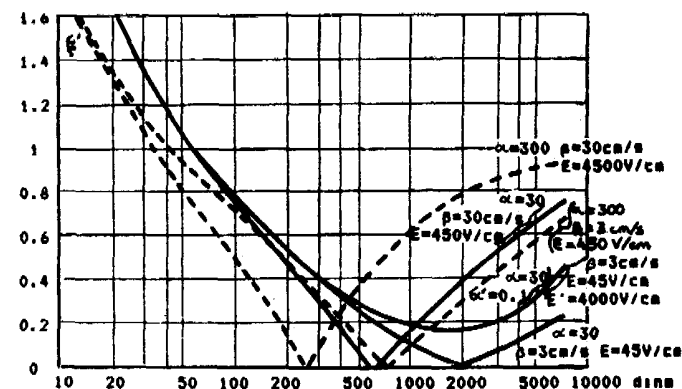


Fig. 3. The dependence of the criterion of quality of the charging law on particle diameter and charger parameters.

$$k \sim \left(\frac{A}{115} + \frac{\alpha\beta:(\text{cm/s})}{(1+4/\alpha)6570^2} d' \right) \left(1 + \frac{165}{d'} \right). \quad (28)$$

This expression achieves a minimum at the diameter

$$d_0 = \sqrt{\frac{(1+4/\alpha) \ln(1+\alpha^{4/3})}{\alpha\beta:(\text{cm/s})}} \cdot 7870 \text{ nm}. \quad (29)$$

Some values of the critical diameter are presented in Table 1.

Table 1

Critical diameter in nm for different values of the parameters α and $\beta:(\text{cm/s})$, according to formula (29)

$\alpha \setminus \beta$	1	3	10	30
10	5200	3000	1640	850
30	3260	1880	1030	800
100	1980	1150	630	360
300	1260	730	400	230

Near the critical diameter granulometers lose the ability to discriminate particles by size. In the case of large values of d_0 we will speak of a regime of dominant diffusion charging; in the case of small values, of a regime of dominant field charging.

Criterion of the quality of the charging law

Tamm [5] has proposed the following criterion of the quality of analytic particle charging

$$\xi = \frac{r}{\sigma_x}, \quad (30)$$

where σ_x - the standard deviation of radii at the mobility considered. The criterion ξ depends on the coefficient of variation of the mobility of particles of one and the same size and on the law of average charging. These factors can be taken into account separately

$$\xi = \varkappa \xi'. \quad (31)$$

Here $\varkappa = k/\sigma_k$ - the criterion of the quality of mono-disperse particle charging and

$$\xi' = \frac{r}{k} \left| \frac{dk}{dr} \right| \quad (32)$$

is the criterion of the quality of the charging law.

The paper [5] contains also a graphic analysis of the dependence of the criterion of the quality of the charging law on particle size and charging regime. In Fig.3 this analysis is repeated for our system of charger parameters. The curves in Fig.3 exactly correspond to the curves in Fig.2. Similarly to Fig.2, the fifth curve will be explained below.

Spatial non-uniformity of the aerosol charge

The criterion θ describes the non-uniformity of the charging process. In practice, the most interesting is the regime of dominant diffusion charging where the non-uniformity is levelled out due to the effect of saturation. Therefore other criteria should be determined for the description of the non-uniformity of the result of diffusion charging

$$j = \frac{\delta A}{A}. \quad (33)$$

In the first approximation

$$\frac{j}{\theta} = \frac{\alpha}{A} \frac{dA}{d\alpha}. \quad (34)$$

Using the approximation (19), we get

$$j \approx \frac{4}{3(1+\alpha^{-4/3}) \ln(1+\alpha^{4/3})} \theta. \quad (35)$$

In the regime of practically interesting values of the parameter α , the criterion j is 25...50% of the criterion θ .

Devices for particle charging

The Whitby charger

Let us evaluate the features of the most well-known granulometric aerosol charger described in [6]. It is a typical transversal charger where the air ions are let in through a grid maintained at a certain potential. The authors of the charger present the following data:

height h	1.43 cm
length	0.95 cm
time t_q	0.21 s
voltage	100 V
nt_q	$10^7 \text{ cm}^{-2}\text{s}$

On the basis of these data it is easy to calculate :

$$\begin{aligned} \alpha &= 27 \\ \beta &= 4 \text{ cm/s} \\ \theta &= 1.75 \\ \delta &= 50\% \\ d_c &= 1.8 \mu\text{m} \end{aligned}$$

These values enable us to doubt the ability of the device to discriminate fractions in the size range in the neighbourhood of $1 \mu\text{m}$. Our calculation points out the simplest way to improve the parameters of the charger - the length of the charger and charging time should be increased. Then θ and δ are proportionally decreased. After the achievement of a sufficiently low value of the criterion θ , voltage can be decreased on the account of further increase of the time t_q ; this makes it possible to increase the critical particle size.

We do not have sufficient data to evaluate modifications of the Whitby charger built after the device [6].

The ways of widening the size range

The range of particle size for a granulometer using a regime of dominant diffusion charging is limited from above. The only effective way to expand the measurement range towards large sizes is the use of the regime of dominant field charging. Two chargers are necessary : one with a high value of critical size, and the other with a low critical size. Three basic technical solutions can be pointed out :

1. Design a "double" device with parallel measuring capacitors, whereas one capacitor is used in the regime of dominant diffusion charging and the other in the regime of dominant field charging.
2. Make the granulometer to alternate the regimes of dominant diffusion and dominant field charging.
3. Provide the granulometer with a double charger so that the main charger would work in the dominant diffusion regime and the subsidiary charger in the dominant field regime with polarity opposite to the one of the main charger.

The method of compensation charging

The third technical solution could be called the method of compensation charging. There is no correct and rigorous theory of charging compensation. Rough estimates can be obtained by adding the charges taken into account separately for main and subsidiary chargers. In such an approximation the lowest curve in Fig. 2 is taken into account; this curve provides a good illustration of the practical effect achieved by the method of compensation. The symbols with apostrophes at the curves indicate the parameters of the subsidiary charger. Fig. 3 also includes the curve of the quality of average charging for the compensation method. As can be seen, the criterion of the quality of average charging still has a rather deep minimum in the neighbourhood of one-micrometer sizes.

If the electric field strength in the subsidiary charger exceeds the critical value

$$E'_c = \frac{1 + 4/\alpha'}{1 + 4/\alpha} \frac{\alpha\beta}{k}, \quad (36)$$

then large particles are recharged to the other polarity. In the formula the symbols without apostrophes refer to the main charger and the symbols with apostrophes to the subsidiary charger.

In practice slight exceeding of the critical field strength is permissible, as the recharging of particles whose sizes are beyond the measurement range does not have negative consequences. The curves illustrating the compensation charging in Fig. 2 and 3 are drawn for a charger with parameters $E'_c = 2200 \text{ V/cm}$ and $E = 4000 \text{ V/cm}$.

A shortcoming of the compensation method is the low mobility of large particles which significantly complicates their registration. Technical difficulties may also be caused by the necessity to ensure extremely high stability of the chargers.

Deactivation of the air by opposite charging

As a rule, the differential method of mobility spectrum measurement is used in granulometers. Then the air flow entering the measuring capacitor is divided into two parts. One part with the air flow δF contains the investigated aerosol. The other part with the air flow $F - \delta F$ should be

inactive. This inactivity means that the air does not contain particles which would cause signal at the outlet of the granulometer. Usually, the air is deactivated by conducting it through a mechanical or electric filter. A significant technical difficulty at this point is sufficient filtering of the air. Instead of filtering, deactivation could be carried out by unipolar charging to the polarity opposite of the polarities of the measured particles. This simplifies the design of the granulometer. During deactivation with opposite charging, it should be carefully checked, if the space charge of the oppositely charged aerosol does not cause interference in the measuring capacitor. If necessary, the space charge could be suppressed using an electric filter.

The effect of focussing

In the granulometers of the University of Minnesota the geometrical position of the layers of the air is not retained during the passage from the charger to the measuring capacitor. In this case the non-uniformity of charge indubitably causes deterioration of the discrimination power of the granulometer.

However, the geometrical position of the air layers can be retained during the passage from the charger to the measuring capacitor. In this case the mutual relations of the processes in the charger and the measuring capacitor become essential. If charging is absolutely uniform ($\delta F/F = 0$), then the places of precipitation of the particles of the same size are scattered to the extent determined by the relation of air flows $\delta F/F$. If $\delta F/F \neq 0$ and the position of layers is retained, then the effects of the scattering caused by non-uniformity of charging and the final relation of the air flows interfere with each other. If the particles, entering nearer to the collector electrode of the measuring capacitor are charged more strongly, then the interference increases the scattering. If the particles, entering nearer to the collector electrode are charged more weakly, then the interference weakens the scattering. In the latter case charging non-uniformity is useful. This effect, though described already in [7], has been somewhat forgotten.

We can imagine a charging non-uniformity where the distance of the spot of precipitation from the inlet of the measuring capacitor is absolutely independent of the point of

entrance of the particle into the granulometer. Then we can speak of perfect focussing of particles.

The use of the effect of focussing makes it possible to select the ratio $\delta F/F$ in the measuring capacitor to be 50%, and simultaneously to guarantee an apparatus function of the granulometer which would be characteristic of a good differential spectrometer. This means a combination of the high sensitivity on integral measuring capacitor and the high discrimination of a differential measuring capacitor.

An inner charger for a measurement capacitor with an inner collector electrode

Fig. 4 presents a diagram of one of the possible designs of an axial charger

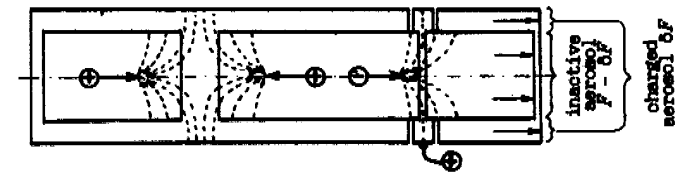


Fig. 4. Diagram of an axial inner charger for a measuring capacitor with an inner collector electrode.

A corona discharge is used for generation of small air ions. Special design makes it possible not to use a partition grid. The field strength and air ion flow are controlled by the depth of insertion of the positive corona points into the inner tube. A subsidiary charger of negative polarity makes it possible to carry out compensation charging. The intensity of compensation charging is adjusted by the width of the slit. Opposite the slit is an electrode which gets voltage to achieve sufficient field strength. At the same time the negative charger has the function of the deactivation of the air passing through the inner tube with the rate $F - \delta F$.

In a device of this type the non-uniformity of the charge increases the scattering of the particles on the collector electrode in the measuring capacitor.

An outer charger for a measuring capacitor with an inner collector electrode.

To achieve the effect of focussing in the case of an inner collector electrode it is necessary to direct the movement of small air ions towards the axis of the charger. A possible design of such a charger is presented in Fig. 5. It is more

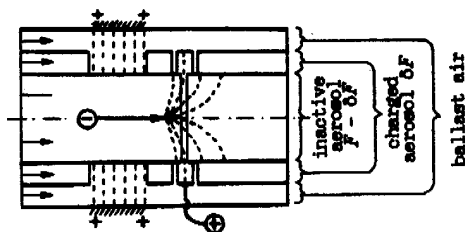


Fig. 5. Diagram of an axial outer charger for measuring capacitor with an inner collector electrode.

complicated to ensure the independence of local charge intensity from the angular coordinate. It is also complicated to use corona discharge as a source of small ions. A compact design can be achieved by the use of α -rays or weak β -rays for the generation of small air ions.

The radioactive preparation should be uniformly spread on the inner surface of a cylindrical electrode. In the described charger a method of deactivation of the air by opposite charging is applied, an inner corona charger is used for it. Compensation charging is carried out similarly to the charging in Fig. 4. An outer ballast layer of air flowing past the measuring capacitor serves to insulate the radioactive preparation and to improve the parameters of the charger.

An inner charger for a measuring capacitor with an outer collector electrode

The arrangement "inner charger and outer collector electrode" does not ensure good discrimination of the granulometer. The arrangement "outer charger and inner collector electrode" should theoretically ensure high discrimination and sensitivity, but the design of an actual granulometer according to this arrangement would run into serious difficulties. High discrimination can be combined with constructional simplicity as shown in Fig. 6. Here the outer cover of

the measurement capacitor serves as the collector electrode which is reasonable, if it is necessary to divide the electrode into several rings insulated from one another.

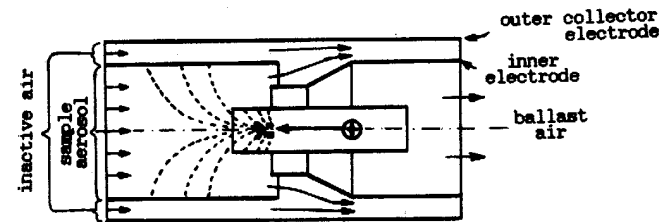


Fig. 6. Diagram of axial inner charger for a measuring capacitor with an outer collector electrode.

Fig. 6 does not include the device for the deactivation of the air and the subsidiary charger for compensation charging. In the case of this arrangement compensation charging is more complicated than in the two preceding cases. Therefore the arrangement "inner charger and outer collector electrode" is most suitable for two-capacitor systems where one measuring capacitor has the regime of dominant diffusion charging, and the other has the regime of dominant field charging.

The modulation method in aerosol granulometry

Numeric synchronous detection and the nature of the modulation method

We speak of the modulation method when the transformation coefficient of the measured signal undergoes periodic variation and the output signal of the device is formed as a result of detection, most frequently synchronous detection. In aerosol measurements it is reasonable to carry out modulation by periodic switching on/off of the measured signal. Here we will not to consider the method of signal modulation inside the amplification circuit.

The optimum period of modulation depends both, on the frequency characteristics of the noises of the measurement system, and on the transition characteristics of the modulator of the air ion flow and the measuring capacitor. For the measurement of small air ions it is useful to have a modulation period ranging from some tenths of a second to

some seconds. In aerosol granulometry air ions of low mobilities are recorded and the measuring capacitor has a long transition time. A modulation period of some tens of a second or longer may be optimal. Certain difficulties occur in the application of traditional analog equipment of synchronous detection.

In the range of low modulation frequencies it is possible to digitize the signal in each half-period of modulation. Detection is then executed with a computer. Numerical processing of the signal is carried out on-line. In this case the process of measurement is outwardly rather similar to the process of measurement with an analog synchronous detector. If it is not possible to use the computer on line, the signal of every half-period can be recorded on magnetic or punched tape, or other storage media, and the computations can be executed later. Then the procedure of measurement is outwardly different from the usual procedure with an analog synchronous detector. It could be argued that this is not the modulation method, but a periodic zero correction to obtain data for the correction of results during the processing of measurement data. This argument gets further support, if for technical reasons an amplifier of direct current is used for the amplification of the signal. However, there is a deeper difference between the methods of modulation and periodic zero correction. In the modulation method the period of modulation is at the same time also the minimum period of measurement. In the periodic zero correction method, the period of measurement is shorter than the period of zero correction, whereas the ratio of the periods can be rather large. Therefore we consider it appropriate to speak of the modulation method, if the signal is amplified with an amplifier of direct current, the period of modulation lasts several minutes, and synchronous detection is postponed until the phase of data processing.

Modulation with a charger

In air ion measurement devices modulation is executed by the switching of the air flow, the voltage of the measuring capacitor, or the voltage on a special preliminary capacitor. All these methods can be used in aerosol granulometry. However, there is a simpler method of modulation through periodic switching on/off of a unipolar aerosol charger.

The method of modulation with a charger has all the advantages of the method of modulation with a preliminary capacitor. Special attention should be paid to an advantage specific for granulometry. In charger modulation the flow of residual air ions in the air which should be inactive is not modulated. This suppresses measurement errors connected with possible imperfection of the device of air deactivation making it possible to simplify the design of this device and there appears a possibility to realize the differential measurement method without the device of air deactivation. For instance, in the device depicted in Fig. 6, the inactive air could be replaced by an uncharged variant of the aerosol which is being analyzed. Modulation here is carried out by periodic switching on/off of high voltage on the corona point.

RC-regime of the measurement of current strength

Let us consider the task of measuring the strength of direct current of air ions in a measuring capacitor and denote the duration of the measurement cycle through δ . Let the transition process of the measuring device be a simple exponential process with the time constant τ

Two measurement regimes are widely spread :

- the regime of measurement of the voltage drop on the resistance or R-regime where $\tau < \delta$,
- the regime of charge cumulation on the capacitance or C-regime where $\tau > \delta$ is assumed.

As is known, R-regime is characterized by a lowered sensitivity, and C-regime requires periodic commutation of the input circuit of the electrometric amplifier. Two variants of C-regime are known:

- the variant of fixed zero,
- the variant of floating zero.

In the case of fixed zero the charge generated by the electrometric commutator will be included in the measurement result as noise. Therefore the electrometric commutator should meet rigorous requirements, and the sensitivity of the electrometer will not be significantly higher than in R-regime. Floating zero makes it possible to realize the highest theoretically possible sensitivity. However, complicated equipment for signal commutation and registration would be necessary in this case.

In practice, for reasons of technical simplicity, R-regime is the most wide-spread one. Therefore the improvement of the sensitivity of R-regime is especially significant. The sensitivity of the electrometer in R-regime to current strength is growing together with the ratio τ/δ . At $\tau/\delta \gg 1$ the sensitivity is approaching that of the electrometer in C-regime. However, a systematic measurement error called the error of inertia occurs, if the condition $\tau > \delta$ is not satisfied. The error of inertia depends on the voltage on the electrometer at the end of the previous cycle. If this voltage is known, then the error of inertia can be unambiguously established and the measurement results can be corrected computationally. In the case of computational correction of the error of inertia, a measurement regime with $\tau \approx \delta$ is quite acceptable. This regime might be called RC-regime.

The correction of the inertia

Let us consider the measurement of the strength of the current in a modulating granulometer. The process in an electrometer with RC-regime is illustrated in Fig. 7.

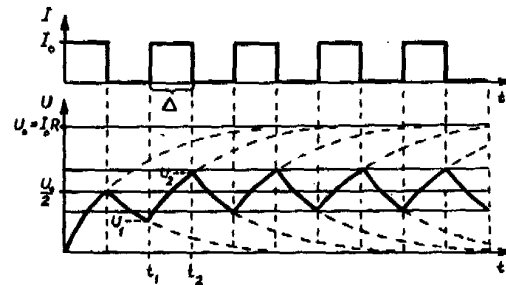


Fig. 7. The process in an electrometer with RC-regime at a rectangular modulation of the measured current.

Let δ , τ , U_1 , and U_2 be known. For the correction of the measurement error we need a computation formula for the level of U_0 which would be valid for any period of modulation, independently of the history of the process. It is easy to derive such a formula from the equation of the transition process, according to which

$$U_0 - U_2 = (U_0 - U_1) \exp\left(-\frac{t_2 - t_1}{\tau}\right). \quad (37)$$

The correction formula will be

$$U_0 = U_2 + \frac{\exp(-\delta/\tau)}{1 - \exp(-\delta/\tau)} (U_2 - U_1). \quad (38)$$

It is expedient to carry out the correction together with synchronous detection. As the factor in formula (38) is an apparatus constant, the correction is simple to execute also if analog synchronous detection is used.

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