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Determination of particle size distribution — Differential electrical mobility analysis for aerosol particles

Détermination de la distribution granulométrique — Analyse de mobilité électrique différentielle pour les particules d'aérosol

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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 15900 was prepared by Technical Committee ISO/TC 24, *Particle characterization including sieving*, Subcommittee SC 4, *Particle characterization*.

Introduction

Differential electrical mobility classification and analysis of airborne particles has been widely used to measure a variety of aerosol particles ranging from nanometre-size to micrometre-size in the gas phase. In addition, the electrical mobility classification of charged particles can be used to generate mono-disperse particles of known size for calibration of other instruments. One notable feature of these techniques is that they are based on simple physical principles. The techniques have become important in many fields of aerosol science and technology, e.g. aerosol instrumentation, production of materials from aerosols, contamination control in the semiconductor industry, atmospheric aerosol science, characterization of engineered nanoparticles, and so on. However, in order to use electrical mobility classification and analysis correctly, several issues, such as the slip correction factor, the ion-aerosol attachment coefficients, the size-dependent charge distribution on aerosol particles and the method used for inversion of the measured mobility distribution to the aerosol size distribution, need due caution.

There is, therefore, a need to establish an International Standard for the use of differential electrical mobility analysis for classifying aerosol particles. Its purpose is to provide a methodology for adequate quality control in particle size and number concentration measurement with this method.

Determination of particle size distribution — Differential electrical mobility analysis for aerosol particles

1 Scope

This International Standard provides guidelines on the determination of aerosol particle size distribution by means of the analysis of electrical mobility of aerosol particles. This measurement is usually called “differential electrical mobility analysis for aerosol particles”. This analytical method is applicable to particle size measurements ranging from approximately 1 nm to 1 µm. This International Standard does not address the specific instrument design or the specific requirements of particle size distribution measurements for different applications, but includes the calculation method of uncertainty. In this International Standard, the complete system for carrying out differential electrical mobility analysis is referred to as DMAS (differential mobility analysing system), while the element within this system that classifies the particles according to their electrical mobility is referred to as DEMC (differential electrical mobility classifier).

NOTE For differential electrical mobility measurements relating to Road Vehicle applications, please refer to relevant national and international standards. ISO Technical Committee TC 22, *Road vehicles*, is responsible for developing International Standards relating to road vehicles, components and measurements.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
aerosol
system of solid or liquid particles suspended in gas

2.2
attachment coefficient
attachment probability of ions and aerosol particles

2.3
bipolar charger
device to attain the equilibrium steady state of charging by exposing aerosol particles to both positive and negative ions within the device

2.4
charge neutralization
process that leaves the aerosol particles with a distribution of charges that is in equilibrium and makes the net charge of the aerosol nearly zero, which is usually achieved by exposing aerosol particles to an electrically neutral cloud of positive and negative gas charges

2.5
condensation particle counter
CPC
instrument that measures the particle number concentration of an aerosol

NOTE 1 The sizes of particles detected are usually smaller than several hundred nanometres and larger than a few nanometres.

NOTE 2 A CPC is one possible detector for use with a DEMC.

NOTE 3 In some cases, a condensation particle counter may be called a condensation nucleus counter (CNC).

2.6
critical mobility

instrument parameter of a DEMC that defines the electrical mobility of aerosol particles that exit the DEMC in aerosol form, which may be defined by the geometry, aerosol and sheath air flow rates, and electrical field intensity

NOTE Particles larger or smaller than the critical mobility migrate to an electrode or exit with the excess flow and do not exit from the DEMC in aerosol form.

2.7
differential electrical mobility classifier

DEMC

classifier that is able to select aerosol particles according to their electrical mobility and pass them to its exit

NOTE A DEMC classifies aerosol particles by balancing the electrical force on each particle with its aerodynamic drag force in an electrical field. Classified particles are in a narrow range of electrical mobility determined by the operating conditions and physical dimensions of the DEMC, while they can have different sizes due to difference in the number of charges that they have.

2.8
differential mobility analysing system

DMAS

system to measure the size distribution of submicrometre aerosol particles consisting of a DEMC, flow meters, a particle detector, interconnecting plumbing, a computer and suitable software

2.9
electrical mobility

mobility of a charged particle in an electrical field

NOTE Electrical mobility can be defined as the migration velocity dependent on the strength of the electrical field, the mechanical mobility and the number of charges per particle.

2.10
electrometer

device that measures electrical current ranging from about 1 femtoampere (fA) to about 10 picoamperes (pA)

2.11
equilibrium charge distribution

charging condition for aerosol particles that is stable after exposure to bipolar ions for a sufficiently long period of time

NOTE Bipolar ions are positive and negative ions which are produced by either a radioactive source or a corona discharge.

2.12
Faraday-cup aerosol electrometer

FCAE

electrometer designed for the measurement of electrical charges carried by aerosol particles

NOTE A Faraday-cup aerosol electrometer consists of an electrically conducting and electrically grounded cup as a guard to cover the sensing element that includes aerosol filtering media to capture charged aerosol particles, an electrical connection between the sensing element and an electrometer circuit, and a flow meter.

2.13
Knudsen number
Kn [ISO]
ratio of gas molecular mean free path to the radius of the particle, which is an indicator of free molecular flow versus continuum gas flow

2.14
laminar flow
gas flow with no temporally or spatially irregular activity or turbulent eddy flow

2.15
migration velocity
steady-state velocity of a charged airborne particle within an externally applied electric field

2.16
particle charge conditioner
device used to establish a known size-dependent charge distribution on the sampled aerosol of an unknown charging state, which is either a bipolar or unipolar charger

2.17
Peclet number
Pe [ISO]
dimensionless number representing the ratio of a particle’s convective to diffusive transport

2.18
Reynolds number
Re [ISO]
dimensionless number expressed as the ratio of the inertial force to the viscous force; for example, applied to an aerosol particle or a tube carrying aerosol particles

2.19
slip correction
S_c
dimensionless factor that is used to correct the drag force acting on a particle for non-continuum effects that become important when the particle size is comparable to or smaller than the mean free path of the gas molecules

2.20
space charge
net charge spatially distributed in a gas

2.21
Stokes' drag
drag force acting on a particle that is moving relative to a continuum fluid in the creeping flow (low Reynolds number) limit

2.22
system transfer function
transfer function defined as the ratio of the particle concentration at the particle concentration measurement detector of a DMAS to the particle concentration at the inlet of the DMAS, which is normally expressed as a function of electrical mobility

2.23
transfer function
ratio of particle concentration at the outlet of a DEMC to the particle concentration at the inlet of the DEMC, which is normally expressed as a function of electrical mobility

2.24
unipolar charger

device to attain a steady-state charge distribution of aerosol particles by exposing them to either positive or negative ions within the device

3 Symbols

For the purposes of this document, the following symbols are applied.

Symbol	Quantity	SI Unit
A, B, C	elements of the slip correction factor defined in Equation (2)	dimensionless
C_N	number concentration of an aerosol	m^{-3}
c	thermal velocity of an ion or molecule	$m\ s^{-1}$
D	diffusion coefficient of a particle or an ion in air	$m^2\ s^{-3}$
d	aerosol particle diameter	m
E	electric field strength in a DEMC	$V\ m^{-1}$
ε	relative error	
e	elementary charge $= 1{,}602\ 177 \times 10^{-19}$ C	
Kn	Knudsen number	
k	Boltzmann constant $= 1{,}381 \times 10^{-23}\ J\ K^{-1}$	
L	effective active length of a DEMC, approximated by the axial distance between the midpoint of the aerosol entrance and the midpoint of the exit slit of a cylindrical DEMC	m
l	mean free path of a molecule	m
M	mass of a molecule	amu
m	mass of an ion	amu
N_A	Avogadro constant $\approx 6{,}022\ 141\ 79(30) \times 10^{23}\ mol^{-1}$	
N_I	number density of ions	m^{-3}
P	atmospheric pressure	Pa
p	number of elementary charges on a particle	(dimensionless)
Pe	Peclet number	(dimensionless)
q_1, q_2, q_3, q_4	flow rates of air (or gas) and of aerosol entering and exiting a DEMC	$m^3\ s^{-1}$
q_a	aerosol air flow rate	
r_1	outer radius of inner cylinder of a cylindrical DEMC	m
r_2	inner radius of outer cylinder of a cylindrical DEMC	m
Re	Reynolds number	(dimensionless)
S	Sutherland constant (=110,4 K at 23 °C and standard atmospheric pressure)	
S_c	slip correction	(dimensionless)
T	absolute temperature	K

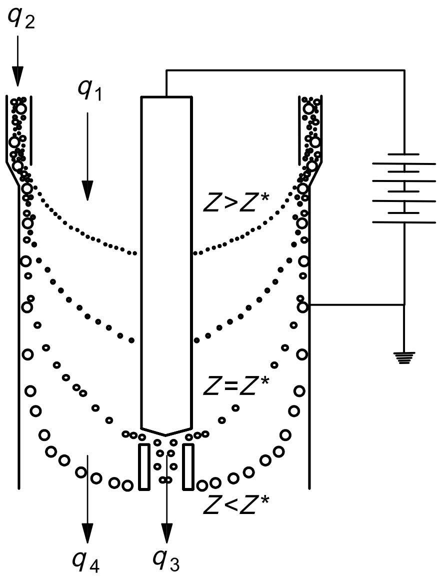
Symbol	Quantity	SI Unit
t	residence time of an ion	s
U	DC voltage used to establish an electrical field in a DEMC	V
V	volume	m^3
Z	electrical mobility of a charged aerosol particle	$m^2\ V^{-1}\ s^{-1}$
Z_1, Z_2, Z_3, Z_4	critical electrical mobilities that describe the transfer function of a DEMC	$m^2\ V^{-1}\ s^{-1}$
β	attachment coefficient of ions onto aerosol particles	$m^3\ s^{-1}$
γ	recombination coefficient of ions	(dimensionless)
δ	radius of a limiting sphere	m
η	coefficient of dynamic viscosity of a gas	$kg\ m^{-1}\ s^{-1}$
ι	ion pair production rate	$m^{-3}\ s^{-3}$
λ	mean free path of an ion	m
ρ	mass density of a particle	$kg\ m^{-3}$

4 General principle

4.1 Particle size classification with the DEMC

The measurement of particle size distributions with a DMAS is based on particle classification by electrical mobility in a DEMC. The DEMC may be designed in many different ways; for example, coaxial cylindrical DEMC, radial DEMC, parallel plate DEMC, etc. The coaxial cylindrical DEMC shown in Figure 1 is an example of a widely used design. It consists of two coaxial, cylindrical electrodes with two inlets. One inlet (marked q_1 in Figure 1) is for filtered clean sheath air. The other inlet (marked q_2) is for the aerosol sample air.

The aerosol sample air, some of whose particles are electrically charged, enters the DEMC as a thin annular cylinder around a core of filtered, particle-free sheath air. By applying a voltage, an electric field is created between the inner and outer electrodes. A charged particle in the presence of an electric field will migrate within the field and reach a terminal migration velocity when the fluid dynamic drag on the particle balances the driving force of the electric field. Charged particles of the correct polarity within the sample air begin to drift across the sheath air flow towards the inner electrode. At the same time, the clean sheath air flow carries the charged airborne particles downward. A small fraction of the charged particles enters the thin circumferential slit near the bottom of the centre electrode and is carried by the air flow to the detector (in the direction marked q_3). By varying the voltage, particles of different electrical mobility are selected.



Z^* critical mobility of particles exiting the DEMC with q_3

Figure 1 — Schematic diagram of coaxial cylindrical DEMC

When used within a DMAS, measurements of relevant parameters such as voltage and flow and their timings need to be combined with other measurements such as the output from the particle detector. These parameters are usually controlled using a system controller as shown in Figure 3.

4.2 Relationship between electrical mobility and particle size

The electrical mobility of a particle depends on its size and its electric charge. The relationship between electrical mobility and particle size for spherical particles can be described by Equation (1):

$$Z(d,p) = \frac{pe}{3\pi\eta d} S_\mathrm{c} \qquad (1)$$

The slip correction, S_c, extends the Stokes' law-based calculation of the drag force on a spherical particle moving with low Reynolds number in a gas phase to nanometre-sized particles. It is approximated by the expression given in Equation (2):

$$S_\mathrm{c} = 1 + Kn\left[A + B\exp\left(-\frac{C}{Kn}\right)\right] \qquad (2)$$

For a detailed discussion of the slip correction, see Annex C.

The dynamic viscosity and the mean free path of gas molecules used within Equations (1) and (2), respectively, depend on both the temperature and the pressure of the carrier gas. Equations (3) and (4) shall be used to calculate the viscosity and the mean free path for temperatures and pressures different from the reference temperature and pressure, T_0 and P_0, specified in Table 1, respectively.

$$\eta = \eta_0 \times \left(\frac{T}{T_0}\right)^{3/2} \times \left(\frac{T_0 + S}{T + S}\right) \qquad (3)$$

$$l = l_0 \times \left(\frac{T}{T_0}\right)^2 \times \left(\frac{P_0}{P}\right) \times \left(\frac{T_0 + S}{T + S}\right) \qquad (4)$$

where S, the Sutherland constant, has the value given in Table 1.

Unless explicitly specified differently in the measurement report, Equations (1) to (4) and the set of parameters given in Table 1 shall be used for the calculation of the relation between electrical mobility and particle size in air.

Table 1 — Values of parameters recommended for the calculation of the electrical mobility from the particle size in air

Parameter	Value	Remarks
η_0	1,832 45 10^{-5} kg·m^{-1}·s^{-1}	For dry air at $T_0 = 296{,}15$ K; $P_0 = 101{,}3$ kPa. All values from: J.H. Kim, G.W. Mulholland, S.R. Kukuck and D.Y.H. Pui (2005).
l_0	$6{,}730 \times 10^{-8}$ m	
S	110,4 K	
A	1,165	
B	0,483	
C	0,997	

4.3 Measurement and data inversion

For a given supply voltage, U, the response, $R(U)$, of the particle detector to aerosol particles entering the DEMC is given by Equation (5), which is called the basic equation for the response of the electrical mobility measurement:

$$R(U) = q_2 \sum_{p=1}^{\infty} \int_{d=0}^{\infty} n(d) \cdot f_p(d) \cdot \Omega\left[Z(d,p), \Delta\Phi(U)\right] W(d,p)\,\mathrm{d}d \tag{5}$$

where

$W(d, p)$ is the factor relating the detector response to the rate of particles;

For condensation particle counters (CPCs), the response is particle number concentration and $W(d, p) = \eta_{\mathrm{CPC}}(d)\, q_{\mathrm{CPC}}^{-1}$, where $\eta_{\mathrm{CPC}}(d)$ is the size-dependent detection efficiency of the CPC and q_{CPC} is the measuring flow rate of the CPC.

For Faraday-cup aerosol electrometers (FCAEs), the response is current and $W(d, p) = p\, e\, \eta_{\mathrm{FCAE}}(d)$, where $\eta_{\mathrm{FCAE}}(d)$ is the size-dependent detection efficiency of the FCAE.

$n(d)\,\mathrm{d}d$ is the number concentration of aerosol particles in the diameter interval dd around d;

$f_p(d)$ is the charging probability function (see 4.5 and Annex A);

$\Omega\left[Z(d,p), \Delta\Phi(U)\right]$ is the transfer function of the DEMC (see 4.4 and Annex E);

$Z(d, p)$ is the electrical mobility (see 4.2);

$\Delta\Phi(U)$ is a function of the supply voltage and the geometry of the DEMC (see 4.4 and Annex E).

If the transfer function, Ω, the charge distribution function, $f_p(d)$, and the maximum particle size (see 5.2.1) are known, the particle size distributions can be calculated based on the measurements with a DEMC. Details of some methods of data inversion are described in Annex D.

4.4 Transfer function of the DEMC

The transfer function, Ω, of a DEMC is defined as the probability that an aerosol particle which enters the DEMC at the aerosol inlet will leave via the detector outlet. It depends on the particle's electrical mobility, Z, on the four volumetric flow rates, on the geometry of the DEMC and on the electrical field. The influence of the geometry and the electrical field on the transfer function is expressed by the term $\Delta\Phi$, which is a function of the geometry and the supply voltage of the DEMC. For a given supply voltage, $\Delta\Phi$ is constant.

If particle inertia, Brownian motion, space charge and its image forces are neglected, the transfer function of a DEMC can be described as a truncated isosceles triangle with the half-width, ΔZ, centred around the electrical mobility, Z^*, as in Figure 2.

A detailed discussion of the transfer function for the example of a coaxial cylindrical DEMC can be found in Annex E.

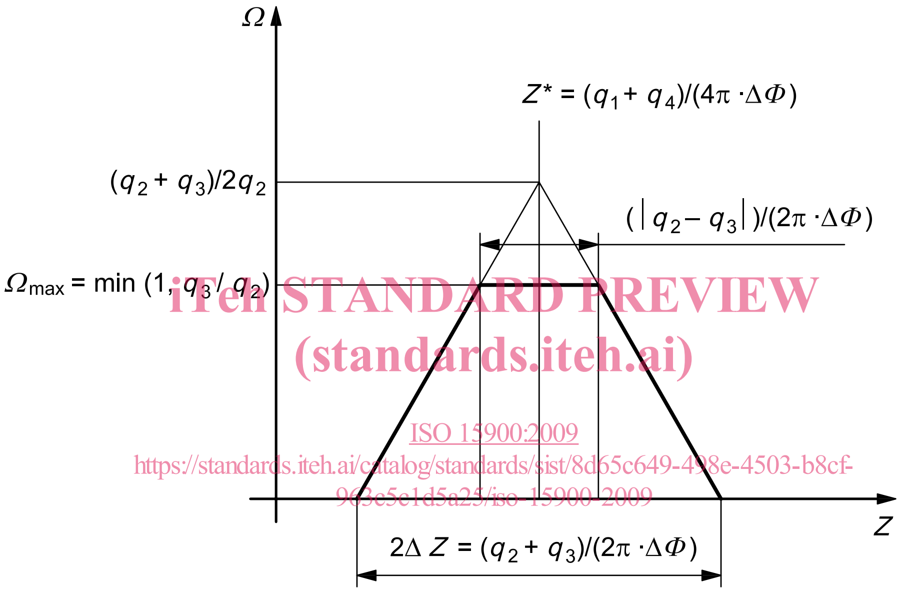


Figure 2 — Transfer function of a DEMC

4.5 The charge distribution function

As stated in 4.3, the particle size-dependent charge distribution function, $f_p(d)$, must be known to calculate the particle size distribution of particles measured by a DEMC. In principle, a known charge distribution function can be established either by bipolar or by unipolar charging. An aerosol particle charge conditioner (5.2.2) is used for this purpose.

For unipolar charging, the achieved charge distribution depends on the technical design of the charger. Therefore, the charge distribution function, $f_p(d)$, must be evaluated for each specific unipolar charger design. The particle concentration to be charged must be limited in such a way that the depletion of the ion concentration due to ion attachment to the particles does not lead to significantly reduced charges on the particles. The instrument manufacturer or the user shall, by design or by measurement, ensure that the method performs correctly and does not produce artefact particles. Unipolar charging is discussed further in Annex A.

In a gaseous medium containing aerosol particles and a sufficiently high concentration of bipolar ions produced e.g. by a radioactive source, an equilibrium charge distribution will develop on the aerosol as a result of the random thermal motion of the ions and the frequent collisions between ions and aerosol particles. The bipolar equilibrium charge distribution depends on the ion properties (ion mobility and ion mass), gas-dynamic properties (diffusion coefficient of the ions and mean free path of the ions) and the ion-aerosol attachment coefficient. Details are described in Annex A.

The bipolar charging probability for spherical particles in air (293,15 K, 101,3 kPa) can also be calculated using the approximation by Wiedensohler (1988) [50] in combination with a result from Gunn (1956) [24], given in Annex A. This approximation compares well both with other theoretical calculations and experimental results. Table 2 shows the results of this calculation.

Unless explicitly specified differently in the measurement report, values in Table 2 shall be used for the determination of the charge distribution function, $f_p(d)$, for aerosol particles in air.

Table 2 — Bipolar charging probability $f_p(d)$ for spherical particles in air (293,15 K, 101,3 kPa), from Equations (A.10) and (A.11)

d_p	Charging probability												
nm	**−6**	**−5**	**−4**	**−3**	**−2**	**−1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**
1	0	0	0	0	0	0,004 8	0,999 3	0,004 5	0	0	0	0	0
2	0	0	0	0	0	0,008 3	0,974 2	0,007 5	0	0	0	0	0
5	0	0	0	0	0	0,022 5	0,969 3	0,018 9	0	0	0	0	0
10	0	0	0	0	0	0,051 4	0,912 4	0,041 1	0	0	0	0	0
20	0	0	0	0	0,000 2	0,109 6	0,793 1	0,084 6	0,000 1	0	0	0	0
50	0	0	0	0	0,011 4	0,222 9	0,581 4	0,169 6	0,006 6	0	0	0	0
100	0	0	0,000 1	0,003 7	0,056 1	0,279 3	0,425 9	0,213 8	0,031 7	0,001 7	0	0	0
200	0	0,000 5	0,005 3	0,034 0	0,121 1	0,264 1	0,299 1	0,204 3	0,071 9	0,015 3	0,001 8	0,000 1	0
500	0,006 7	0,020 7	0,050 4	0,098 0	0,149 0	0,181 6	0,181 8	0,140 3	0,089 1	0,044 0	0,017 3	0,005 4	0,001 4
1 000	0,035 7	0,058 4	0,085 4	0,111 3	0,126 1	0,138 5	0,123 5	0,103 9	0,075 4	0,050 0	0,029 3	0,015 4	0,007 2

5 System and apparatus

5.1 General configuration

A complete DMAS for the measurement of particle size distributions based on differential electrical mobility analysis typically has the following fundamental components (see Figure 3):

a) pre-conditioner;

b) particle charge conditioner;

c) DEMC with flow control and high voltage control;

d) aerosol particle detector;

e) system controller with data acquisition and data analysis (typically built-in firmware or dedicated software on a personal computer).