INTERNATIONAL STANDARD

ISO 15900

Second edition
2020-10

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

Reference number
ISO 15900:2020(E)

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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

This second edition cancels and replaces the first edition (ISO 15900:2009), which has been technically revised.

The main changes compared to the previous edition are as follows:

— subclauses on particle losses due to Brownian diffusion, effects due to non-spherical particles, and measurement of particles below 10 nm have been added in Clause 5;

— traceability diagrams for DEMC and DMAS have been added in Clause 5;

— calibration for size measurement in Clause 8 has been refined;

— Clause 9 for “Using a DEMC at a fixed voltage to generate particles of a chosen size” has been added;

— Annex D for “Data inversion” has been rewritten completely;

— Annex F for “Example certificate for a DMAS particle size calibration” has been added;

— former Annex G for “Uncertainty” in the previous edition has been deleted;

— new Annex G for “Good practice for measurements at particle sizes below 10 nm” has been added;

— Annex H for “Examples for overall system tests” has been added;

— Annex I for “Comparison of different approaches to calculate diffusion loss in laminar tube flow” has been added;

— Annex J for “Corrections for effects due to non-spherical particles” has been added.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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 particle 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 document provides guidelines and requirements for the determination of aerosol particle number 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 document 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 document, 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 This document does not include technical requirements and specifications for the application of DMAS, which are defined in application specific standards or guidelines, e.g. for road vehicle applications (ISO/TC 22), environmental measurements (ISO/TC 146) or nanotechnologies (ISO/TC 229).

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
aerosol
system of solid and/or liquid particles suspended in gas

3.2
attachment coefficient
attachment probability of ions and aerosol particles

3.3
bipolar charging
process which attains a conditioned charge distribution of both positive and negative charges on aerosol particles

3.4
bipolar charge conditioner
device which attains a conditioned charge distribution of both positive and negative charges on aerosol particles

3.5
charging
processes that leave aerosol particles with size dependent specific distributions of unipolar or bipolar electrical charges

3.6
charge conditioner
device (or component of a DMAS) which establishes a known conditioned size dependent charge distribution on aerosol particles which are passed through it

3.7
charge distribution function
mathematical and/or empirical description of a conditioned particle size dependent charge distribution

3.8
condensation particle counter
CPC
instrument that measures the particle number concentration of an aerosol

Note 1 to entry: The sizes of particles detected are usually smaller than several hundred nanometres and larger than a few nanometres.

Note 2 to entry: A CPC is one possible detector for use with a DEMC.

Note 3 to entry: In some cases, a condensation particle counter may be called a condensation nucleus counter (CNC).

3.9
conditioned charge distribution
distribution of unipolar or bipolar electrical charges on aerosol particles defined by a charge distribution function, which is in a steady state for a sufficiently long period of time in an aerosol instrument downstream of a unipolar or bipolar charge conditioner

3.10
critical mobility
instrument parameter of a *DEMC* (3.11) that defines the electrical mobility of aerosol particles that exit the DEMC in aerosol form, which may be defined by the geometry, sample and sheath flow rates, and electrical field intensity

Note 1 to entry: 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.

3.11
differential electrical mobility classifier
DEMC
classifier able to select aerosol particles according to their electrical mobility and pass them to its exit

Note 1 to entry: 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.

Note 2 to entry: Another common acronym for the DEMC is DMA.

3.12
differential mobility analysing system
DMAS
system to measure the size distribution of submicrometre aerosol particles consisting of a charge conditioner, a DEMC, flow meters, a particle detector, interconnecting plumbing, a computer and suitable software

Note 1 to entry: Another common acronym for the DMAS is MPSS (mobility particle size spectrometer).

3.13
electrical mobility
ratio of *migration velocity* (3.18) to electrical field for particles and ions in a gas

3.14
equivalent diameter
d
diameter of a sphere with defined characteristics which behaves under defined conditions in exactly the same way as the particle being described

Note 1 to entry: Particle diameter (or simply diameter) used throughout this document always refers to the electrical mobility equivalent diameter, which defines the size of charged particles with the same electrical mobility or the same terminal migration velocity in still air under the influence of a constant electrical field.

3.15
Faraday cup aerosol electrometer
FCAE
electrometer designed for the measurement of electrical charge concentration carried by an aerosol

Note 1 to entry: 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. An FCAE measures electrical current ranging from about one femtoampere (fA) to about ten picoamperes (pA).

3.16
Knudsen number
Kn
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

3.17
laminar flow
gas flow with no temporally or spatially irregular activity or turbulent eddy flow

3.18
migration velocity
steady-state velocity of a charged airborne particle within an externally applied electric field

3.19
particle diameter
electrical mobility equivalent diameter

Note 1 to entry: Also, just called diameter.

3.20
plateau detection efficiency
mean detection efficiency of a CPC in the size range which is not biased by particle size

[SOURCE: ISO 27891:2015, 3.27, modified — term “plateau efficiency” has been changed to "plateau detection efficiency.]

3.21
Reynolds number
Re
dimensionless number expressed as the ratio of the inertial force to the viscous force

Note 1 to entry: For example, applied to an aerosol particle or a tube carrying aerosol particles

3.22
slip correction
S_C
dimensionless factor 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

3.23
Stokes's drag
drag force acting on a particle that is moving relative to a continuum fluid in the creeping flow limit (low Reynolds number)

3.24
transfer function
ratio of particle concentration at the outlet of a DEMC to the particle concentration at the inlet of the DEMC

Note 1 to entry: It is normally expressed as a function of electrical mobility.

3.25
unipolar charge conditioner
device which attains a conditioned charge distribution of either positive or negative charges on aerosol particles

3.26
unipolar charging
process which attains a conditioned charge distribution of positive or negative charges on aerosol particles

4 Symbols

For the purposes of this document, the following symbols apply.

Symbol	Quantity	SI Unit
A, B, C	elements of the slip correction factor defined in Formula (2)	dimensionless
c	thermal velocity of an ion or molecule	m s^{-1}
D	diffusion coefficient	m^2 s^{-1}
d	aerosol particle diameter	m
E	electric field strength in a DEMC	V m^{-1}
e	elementary charge = 1,602 176 634 × 10^{-19} C	
Kn	Knudsen number	(dimensionless)
k	Boltzmann constant = 1,380 649 × 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_{Tube}	length of a tube	m
M	molecular mass of air	amu
m	mass of an ion	amu
N	number concentration of aerosol particles, note that C_N is widely used as well.	m^{-3}
N_A	Avogadro constant = 6,022 140 76 × 10^{23} mol^{-1}	
N_I	number concentration of ions	m^{-3}
P	atmospheric pressure	Pa
p	number of elementary charges on a particle	(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	m^3 s^{-1}

Symbol	Quantity	SI Unit
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
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	$m^2\ V^{-1}\ s^{-1}$
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
ε	relative error	
μ_{gas}	coefficient of dynamic viscosity of a gas	$kg\ m^{-1}\ s^{-1}$
λ	mean free path	m
ρ	mass density	$kg\ m^{-3}$

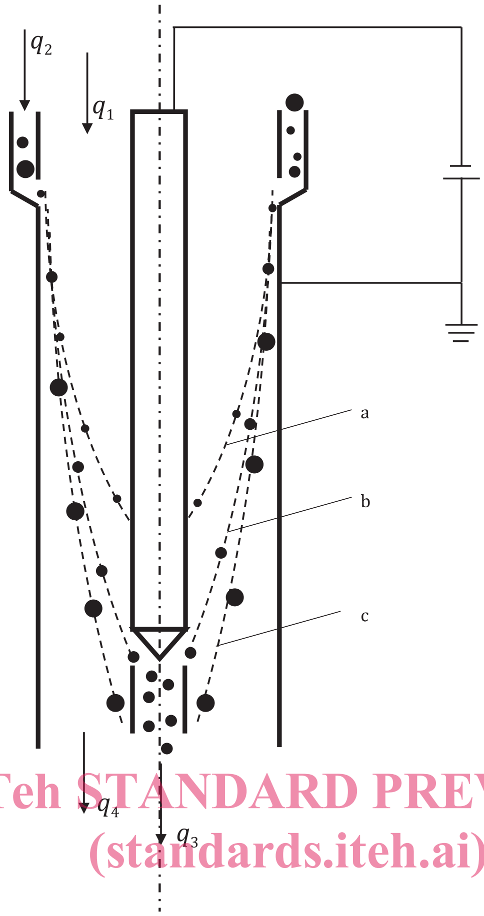
5 General principle

5.1 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 sample aerosol.

The sample aerosol, 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 aerosol 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. The remaining (not extracted) air flow leaves the DEMC as excess flow (q_4).

When used within a DMAS, measurements of relevant parameters such as voltage, 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 5.



Key

q_1 sheath flow

q_2 sample aerosol flow

q_3 mobility selected aerosol flow

q_4 excess flow

a Trajectory of particles trapped in the DEMC due to high electrical mobility.

b Trajectory of particles leaving the DEMC with q_3.

c Trajectory of particles trapped in the DEMC due to low electrical mobility.

Figure 1 — Schematic diagram of coaxial cylindrical DEMC

5.2 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 Formula (1):

$$Z(d,p)=\frac{pe}{3\pi\mu_{\text{gas}}d}S_{\text{C}} \tag{1}$$

The slip correction, S_{C}, extends the Stokes's 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 Formula (2):

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

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

The dynamic viscosity and the mean free path of gas molecules used within Formulae (1) and (2), respectively, depend on both the temperature and the pressure of the carrier gas. Formulae (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.

$$\mu_{\text{gas}} = \mu_{\text{gas},0} \cdot \left(\frac{T}{T_0} \right)^{\frac{3}{2}} \cdot \left(\frac{T_0 + S}{T + S} \right) \tag{3}$$

$$\lambda = \lambda_0 \cdot \left(\frac{T}{T_0} \right)^2 \cdot \left(\frac{P_0}{P} \right) \left(\frac{T_0 + S}{T + S} \right) \tag{4}$$

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

Unless explicitly specified differently in the measurement report, Formulae (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 for the calculation of the electrical mobility from the particle size in dry air at T_0 = 296,15 K and P_0 = 101,3 kPa [33]

Parameter	Value
$\mu_{\text{gas},0}$	1,832 45 × 10^{-5} kg m^{-1} s^{-1}
λ_0	6,730 × 10^{-8} m
S	110,4 K
A	1,165
B	0,483
C	0,997

5.3 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 Formula (5), which is called the basic equation for the response of the electrical mobility measurement:

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

For condensation particle counters (CPCs), the response is particle number concentration, while it is charge concentration for Faraday cup aerosol electrometers (FCAEs).

$W(d, p)$ describes the detector response;

For CPCs, $W(d, p) = \eta_{\text{CPC}}(d)\ q_{\text{CPC}-1}$, where $\eta_{\text{CPC}}(d)$ is the size-dependent detection efficiency of the CPC and q_{CPC} is the detection flow of the CPC.

For FCAEs, $W(d, p) = p\ e\ \eta_{\text{FCAE}}(d)\ q_{\text{FCAE}-1}$, where p is the number of elementary charges on a particle, e is the elementary charge, $\eta_{\text{FCAE}}(d)$ is the size-dependent detection efficiency of the FCAE, and q_{FCAE} is the detection flow of the FCAE.

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

$P(d)$ is the penetration which accounts for diffusion losses (see 5.6 and Annex I).

$f_p(d)$ is the charge distribution function (see 5.5 and Annex A);

$\Omega[Z(d,p),\Delta\Phi(U)]$ is the transfer function of the DEMC (see 5.4 and Annex E), which uses the functions $Z(d, p)$ and $\Delta\Phi(U)$ below as arguments;

$Z(d, p)$ is the electrical mobility of a particle with diameter d carrying p elementary charges (see 5.2);

$\Delta\Phi(U)$ is a function of the supply voltage and the geometry of the DEMC (see 5.4 and Annex E). For a cylindrical DEMC, $\Delta\Phi(U)$ is given in Formula (E.2).

If the transfer function, Ω, the charge distribution function, $f_p(d)$, and the maximum particle size (see 6.2.1) are known, the particle size distributions can be calculated based on the measurements with a DEMC. An example calculation is given in Annex D.

NOTE 1 Formula (5) applies to the case when the DEMC classifies positively-charged particles, since the range of the summation is from $p = +1$ to $+\infty$. For the mode of classifying negatively-charged particles, the range is from $p = -1$ to $-\infty$.

NOTE 2 A DEMC can be (electrically) described as a capacitor. $\Delta\Phi(U)$ can then be linked to the DEMC's capacitance, C_E, where $\Delta\Phi(U) = U \cdot C_E/(2 \cdot \pi \cdot \varepsilon_0)$, $\varepsilon_0 = 8{,}854 \times 10^{-12}$ F m^{-1}.

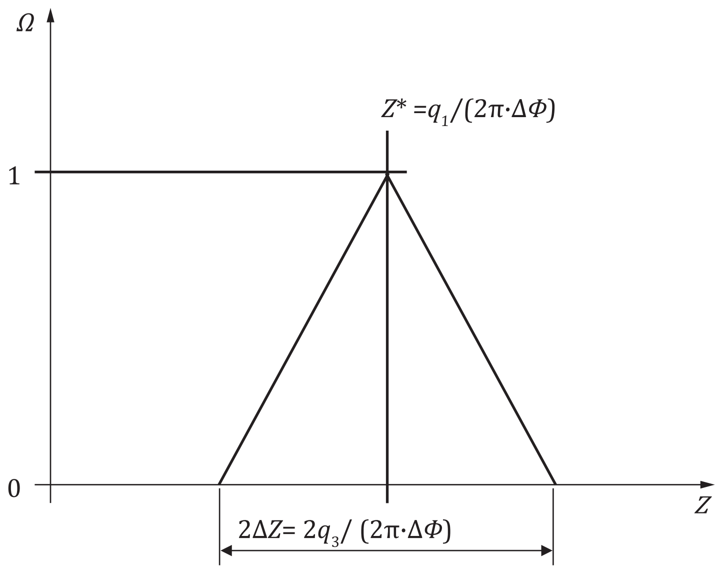
5.4 Transfer function of the DEMC

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 can, mathematically, easily be described in the mobility regime. Therefore, this approach is taken here. The transfer function 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 strength. The influence of the geometry and the electrical field strength on the transfer function is expressed by $\Delta\Phi$, which is a function of the geometry and the variable supply voltage, U, of the DEMC. For a given supply voltage, $\Delta\Phi$ is constant.

If particle inertia, gravimetric sedimentation, Brownian motion, space charge and its image forces are neglected, and if the sheath flow in the DEMC is recirculated ($q_1 = q_4$, also resulting in $q_2 = q_3$), the transfer function of a DEMC can be described as an isosceles triangle with the half-width, ΔZ, centred around the electrical mobility, Z^*, as in Figure 2.

When particle diffusion due to Brownian motion is significant, the resolution of the DEMC classification is reduced, which corresponds to a broader and shorter transfer function.

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



Key

Z electrical mobility

Ω transfer function

Z^* centre electrical mobility of the transfer function

ΔZ half-width of the transfer function

Figure 2 — Transfer function of a DEMC with sheath flow re-circulation (q_1 = q_4 and q_2 = q_3)

5.5 Charge distribution function

5.5.1 General

As stated in 5.3, the particle size-dependent charge distribution function, $f_p(d)$, shall be explicitly known to calculate the size distribution of airborne particles classified in a DEMC. A charge conditioner is used at the entrance of a DEMC to achieve a conditioned charge distribution which is independent of the initial charge state of the aerosol particles and which is - at least for typical aerosol residence times in a DEMC - in a steady-state or stable. $f_p(d)$ may then be given by a set of formulae or tabulated data, approximating the size-dependent charge distribution by theoretical models and/or empirical data.

There are several types of bipolar or unipolar charge conditioners which are described in more detail in 5.5.2. Bipolar charge conditioners produce positively and negatively charged particles while unipolar charge conditioners produce particles of one polarity (positive or negative) only.

5.5.2 Charge distribution function for radioactive bipolar charge conditioners

For commercially available radioactive bipolar charge conditioners the charge distribution function under standard conditions (spherical particles in air (293,15 K, 101,3 kPa) is given by Formula (6) in combination with the coefficients given in Table 2 and Formula (7) which are derived from an approximation (Wiedensohler (1988) [50] to theoretical models in combination with a result from Gunn (1956) [24]).

$$\log\left[f_p(d)\right]=\sum_{i=0}^{5} a_i(p)\cdot(\log d)^i \qquad (6)$$

NOTE 1 In Formula (6), d is given in nanometres.

Formula (6) is valid for the size range:

1 nm ≤ d ≤ 1 000 nm for p = {-2, −1, 0, +1, +2}