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**Colloidal systems — Methods for zeta  
potential determination —**

**Part 3:  
Acoustic methods**

*Systèmes colloïdaux — Méthodes de détermination du potentiel  
zêta —*

*Partie 3: Méthodes acoustiques*



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# Contents

|                                                                                     | Page      |
|-------------------------------------------------------------------------------------|-----------|
| <b>Foreword</b> .....                                                               | <b>iv</b> |
| <b>Introduction</b> .....                                                           | <b>v</b>  |
| <b>1 Scope</b> .....                                                                | <b>1</b>  |
| <b>2 Normative references</b> .....                                                 | <b>1</b>  |
| <b>3 Terms, definitions and symbols</b> .....                                       | <b>1</b>  |
| 3.1 Electric double layer (EDL).....                                                | 1         |
| 3.2 Electrokinetic phenomena.....                                                   | 3         |
| 3.3 Electroacoustic phenomena.....                                                  | 4         |
| <b>4 Symbols</b> .....                                                              | <b>6</b>  |
| <b>5 Principle</b> .....                                                            | <b>7</b>  |
| <b>6 Zeta potential probe design elements</b> .....                                 | <b>8</b>  |
| <b>7 Determination of the dynamic electrophoretic mobility</b> .....                | <b>8</b>  |
| 7.1 Subtracting background electroacoustic signal generated by ions.....            | 9         |
| <b>8 Calculation of zeta potential</b> .....                                        | <b>10</b> |
| 8.1 General.....                                                                    | 10        |
| 8.2 Isolated double layers.....                                                     | 10        |
| 8.3 Overlapped double layers.....                                                   | 13        |
| <b>9 Operational procedures</b> .....                                               | <b>13</b> |
| 9.1 Requirements.....                                                               | 13        |
| 9.2 Verification.....                                                               | 14        |
| 9.3 Sources of measurement error.....                                               | 15        |
| <b>Annex A (informative) Electroacoustics: high frequency electrokinetics</b> ..... | <b>16</b> |
| <b>Annex B (informative) Verification of electroacoustic theories</b> .....         | <b>17</b> |
| <b>Bibliography</b> .....                                                           | <b>20</b> |

## 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](http://www.iso.org/directives)).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 24, *Particle characterization including sieving*, Subcommittee SC 4, *Particle characterization*.

ISO 13099 consists of the following parts, under the general title *Colloidal systems — Methods for zeta potential determination*:

- *Part 1: Electroacoustic and electrokinetic phenomena*
- *Part 2: Optical methods*
- *Part 3: Acoustic methods*

## Introduction

Zeta potential is a parameter that can be used to predict the long term stability of suspensions and emulsions, and to study surface morphology and surface adsorption of particles and other surfaces in contact with a liquid. Zeta potential is not a directly measurable parameter. It can be determined using appropriate theoretical models from experimentally determined parameters, which depend on electric charge separation at interfaces. “Electrokinetic phenomena” encompass such experimentally observed effects. A group of electrokinetic phenomena at high frequency on MHz scale is referred to as “electroacoustics”.<sup>[1]</sup> Each classical electrokinetic phenomenon at DC or low AC conditions has electroacoustic analogue. These electroacoustic phenomena have been widely used to determine electrophoretic mobility of various concentrated particulates without sample dilution. The purpose of this part of ISO 13099 in methods for Zeta potential determination is description of general features of such electroacoustic methods that should be common for all instrumental implementation for measuring electrophoretic mobility using electroacoustics and following calculation of zeta potential of particulates.

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# Colloidal systems — Methods for zeta potential determination —

## Part 3: Acoustic methods

### 1 Scope

This part of ISO 13099 describes in general electroacoustic effects that can be defined as high frequency electrokinetic phenomena.

Particular attention is given to two methods of measurement of electrophoretic mobility of particles suspended in a liquid at high concentration above 1 % v/v, colloid vibration current (CVI)<sup>[2]</sup> and electric sonic amplitude (ESA),<sup>[3]</sup> <sup>[4]</sup> respectively.

Estimation of surface charge and determination of zeta potential can be achieved from measured electrophoretic mobility using proper theoretical models, which are described in detail in ISO 13099-1.

### 2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13099-1, *Colloidal systems — Methods for zeta-potential determination — Part 1: Electroacoustic and electrokinetic phenomena*

ISO 13099-2, *Colloidal systems — Methods for zeta-potential determination — Part 2: Optical methods*

### 3 Terms, definitions and symbols

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

#### 3.1 Electric double layer (EDL)

The electric double layer (EDL) is a spatial distribution of electric charges that appears on and at the vicinity of the surface of an object when it is placed in contact with a liquid.

##### 3.1.1

##### Debye-Hückel approximation

model assuming small electric potentials in the electric double layer

##### 3.1.2

##### Debye length

$\kappa^{-1}$

characteristic length of the electric double layer in an electrolyte solution

Note 1 to entry: The Debye length is expressed in nanometres.

### 3.1.3

#### **diffusion coefficient**

$D$

mean squared displacement of a particle per unit time

Note 1 to entry: The diffusion coefficient is expressed in metre squared per second.

### 3.1.4

#### **Dukhin number**

$Du$

dimensionless number which characterizes contribution of the surface conductivity in electrokinetic and electroacoustic phenomena, as well as in conductivity and dielectric permittivity of heterogeneous systems

### 3.1.5

#### **dynamic viscosity**

$\eta$

ratio of the applied shear stress and the rate of shear of a liquid

Note 1 to entry: For the purpose of this part of ISO 13099, dynamic viscosity is used as a measure of resistance of a fluid which is being deformed by shear stress.

Note 2 to entry: Dynamic viscosity determines the dynamics of an incompressible Newtonian fluid.

Note 3 to entry: Dynamic viscosity is expressed in pascal seconds.

### 3.1.6

#### **electric surface charge density**

$\sigma$

charges on interface per area due to specific adsorption of ions from the liquid bulk, or due to dissociation of the surface groups

Note 1 to entry: Electric surface charge density is expressed in coulombs per square metre.

### 3.1.7

#### **electric surface potential**

$\psi^s$

difference in electric potential between the surface and the bulk liquid

Note 1 to entry: Electric surface potential is expressed in volts.

### 3.1.8

#### **$\zeta$ - potential**

#### **electrokinetic potential**

#### **zeta potential**

$\zeta$

difference in electric potential between that at the slipping plane and that of the bulk liquid

Note 1 to entry: Electrokinetic potential is expressed in volts.

### 3.1.9

#### **Gouy-Chapman-Stern model**

model describing the electric double layer

### 3.1.10

#### **isoelectric point**

condition of liquid medium, usually the value of pH, that corresponds to zero zeta-potential of dispersed particles

**3.1.11****slipping plane  
shear plane**

abstract plane in the vicinity of the liquid/solid interface where liquid starts to slide relative to the surface under influence of a shear stress

**3.1.12****Stern potential**
 $\psi_d$ 

electric potential on the external boundary of the layer of specifically adsorbed ions

Note 1 to entry: Stern potential is expressed in volts.

**3.2 Electrokinetic phenomena**

Note 1 to entry: Electrokinetic phenomena are associated with tangential liquid motion adjacent to a charged surface.

**3.2.1****electroosmosis**

motion of liquid through or past a charged surface, e.g. an immobilized set of particles, a porous plug, a capillary or a membrane, in response to an applied electric field, which is the result of the force exerted by the applied field on the countercharge ions in the liquid

**3.2.2****electroosmotic counter-pressure**
 $\Delta p_{eo}$ 

pressure difference that is applied across the system to stop the electroosmotic flow

Note 1 to entry: The electroosmotic counter-pressure value is positive if the high pressure is on the higher electric potential side.

Note 2 to entry: Electroosmotic counter-pressure is expressed in pascals.

**3.2.3****electroosmotic velocity**
 $v_{eo}$ 

uniform velocity of the liquid far from the charged interface

Note 1 to entry: Electroosmotic velocity is expressed in metres per second.

**3.2.4****electrophoresis**

movement of charged colloidal particles or polyelectrolytes, immersed in a liquid, under the influence of an external electric field

**3.2.5****electrophoretic mobility**
 $\mu$ 

electrophoretic velocity per unit electric field strength

Note 1 to entry: Electrophoretic mobility is positive if the particles move toward lower potential (negative electrode) and negative in the opposite case.

Note 2 to entry: Electrophoretic mobility is expressed in metres squared per volt second.

**3.2.6****electrophoretic velocity**
 $v_e$ 

particle velocity during electrophoresis

Note 1 to entry: Electrophoretic velocity is expressed in metres per second.

### 3.2.7

#### **sedimentation potential**

$U_{\text{sed}}$

potential difference sensed by two electrodes placed some vertical distance apart in a suspension in which particles are sedimenting under the effect of gravity

Note 1 to entry: When the sedimentation is produced by a centrifugal field, the phenomenon is called centrifugation potential.

Note 2 to entry: Sedimentation potential is expressed in volts.

### 3.2.8

#### **streaming current**

$I_{\text{str}}$

current through a porous body resulting from the motion of fluid under an applied pressure gradient

Note 1 to entry: Streaming current is expressed in amperes.

### 3.2.9

#### **streaming current density**

$J_{\text{str}}$

streaming current per area

Note 1 to entry: Streaming current density is expressed in coulombs per square metre.

### 3.2.10

#### **streaming potential**

$U_{\text{str}}$

potential difference at zero electric current, caused by the flow of liquid under a pressure gradient through a capillary, plug, diaphragm, or membrane

Note 1 to entry: Streaming potentials are created by charge accumulation caused by the flow of countercharges inside capillaries or pores.

Note 2 to entry: Streaming potential is expressed in volts.

### 3.2.11

#### **surface conductivity**

$K_{\sigma}$

excess electrical conduction tangential to a charged surface

Note 1 to entry: Surface conductivity is expressed in siemens.

## **3.3 Electroacoustic phenomena**

Electroacoustic phenomena arise due to the coupling between the ultrasound field and electric field in a liquid that contains ions. Either of these fields can be primary driving forces. Liquid might be a simple Newtonian liquid or complex heterogeneous dispersion, emulsion, or even a porous body. There are several different electroacoustic effects, depending on the nature of the liquid and type of the driving force.

### 3.3.1

#### **colloid vibration current**

CVI

a.c. current generated between two electrodes, placed in a dispersion, if the latter is subjected to an ultrasonic field

Note 1 to entry: Colloid vibration current is expressed in amperes.

**3.3.2****colloid vibration potential**

CVU

a.c. potential difference generated between two electrodes, placed in a dispersion, if the latter is subjected to an ultrasonic field

Note 1 to entry: Colloid vibration potential is expressed in volts.

**3.3.3****electrokinetic sonic amplitude**

ESA

amplitude is created by an a.c. electric field in a dispersion with electric field strength,  $E$ ; it is the counterpart of the colloid vibration potential method

Note 1 to entry: See References [3] and [4].

Note 2 to entry: Electrokinetic sonic amplitude is expressed in pascals.

**3.3.4****ion vibration current**

IVI

a.c. electric current created from different displacement amplitudes in an ultrasound wave due to the difference in the effective mass or friction coefficient between anion and cation

Note 1 to entry: See Reference [5].

Note 2 to entry: Ion vibration current is expressed in amperes.

**3.3.5****seismoelectric effect**

SEI

non-isochoric streaming current that arises in a porous body when an ultrasound wave propagates through

Note 1 to entry: See References [6] and [7].

Note 2 to entry: A similar effect can be observed at a non-porous surface, when sound is bounced off at an oblique angle. [11]

Note 3 to entry: Seismoelectric effect is expressed in amperes.

**3.3.6****electroseismic effect**

ESI

non-isochoric electroosmotic pressure wave that arises in a porous body under influence of high frequency electric field

Note 1 to entry: See References [6] and [7].

Note 2 to entry: Electrostatic effect is expressed in pascals.

**3.3.7****dynamic electrophoretic mobility** $\mu_d$ 

electrophoretic velocity per unit electric field strength in high frequency (MHz) electric field

Note 1 to entry: Traditional electrophoretic mobility is low frequency asymptotic of the dynamic electrophoretic mobility.

Note 2 to entry: Electrophoretic mobility is expressed in metres squared per volt second.

## 4 Symbols

|                  |                                                                                   |
|------------------|-----------------------------------------------------------------------------------|
| $a$              | particle radius                                                                   |
| $c$              | electrolyte concentration in the bulk                                             |
| $D_+$            | diffusion coefficient of cations                                                  |
| $D_-$            | diffusion coefficient of anions                                                   |
| $D_{\text{eff}}$ | effective diffusion coefficient of the electrolyte                                |
| $Du$             | Dukhin number                                                                     |
| $e$              | elementary electric charge                                                        |
| $F$              | Faraday constant                                                                  |
| $K_m$            | conductivity of the dispersion medium                                             |
| $K_p$            | conductivity of the dispersed particle                                            |
| $K_s$            | conductivity of the dispersion                                                    |
| $K^\sigma$       | surface conductivity                                                              |
| $k_B$            | Boltzmann constant                                                                |
| $m$              | parameter characterizing electroosmotic flow contribution to surface conductivity |
| $N_A$            | Avogadro's number                                                                 |
| $P$              | pressure                                                                          |
| $R$              | ideal gas constant                                                                |
| $r$              | radial distance from the particle centre                                          |
| $T$              | absolute temperature                                                              |
| $U_{\text{st}}$  | streaming potential                                                               |
| $\mu$            | electrophoretic mobility                                                          |
| $\mu_d$          | dynamic electrophoretic mobility                                                  |
| $X$              | distance from the particle surface                                                |
| $Z$              | acoustic impedance                                                                |
| $z_i$            | valence of the $i$ th ion species                                                 |
| $z_{\pm}$        | valences of the cations and anions                                                |
| $\epsilon_m$     | relative permittivity of the medium                                               |
| $\epsilon_p$     | relative permittivity of the particle                                             |
| $\epsilon_0$     | vacuum permittivity                                                               |
| $\eta$           | dynamic viscosity                                                                 |

|               |                                               |
|---------------|-----------------------------------------------|
| $\varphi$     | volume fraction                               |
| $\kappa$      | reciprocal Debye length                       |
| $\rho_m$      | medium density                                |
| $\rho_p$      | particle density                              |
| $\rho_s$      | density of the dispersion                     |
| $\sigma^d$    | electric charge density of the diffuse layer  |
| $\sigma$      | electric surface charge density               |
| $\omega$      | rotational frequency                          |
| $\omega_{MW}$ | Maxwell-Wagner relaxation frequency           |
| $\omega_{hd}$ | critical frequency of hydrodynamic relaxation |
| $\zeta$       | electrokinetic potential, zeta potential      |
| $\Psi(x)$     | electric potential in the double layer        |
| $\psi^d$      | Stern potential                               |
| $\Omega$      | drag coefficient                              |

## 5 Principle

Any instrument designed for characterizing  $\zeta$ -potential should contain three essential components for achieving three distinctive purposes.

- means for generating motion of the liquid phase relative to the dispersed phase (either solid or liquid);
- means for monitoring response induced by such motion;
- means for calculating  $\zeta$ -potential from the measured response.

The first purpose is usually achieved by manipulating one of the two fields that are responsible for electrokinetic phenomena (electrical and mechanical). For instance, in optical electrophoretic methods (see ISO 13099-2) an electric field generates mechanical motion of particles relative to the liquid. This field is usually constant in time or oscillates with low frequency up to KHz range.

Similarly, one can go to a higher frequency electric field (MHz range) for generating relative motion of phases. There is a special term for such high frequency electrophoresis (electric sonic amplitude reflecting the fact that the wave nature of the mechanical motion at such high frequency becomes dominant). This mechanic effect is an ultrasound wave. There is also a reversible effect: propagation of an ultrasound wave through the concentrated particulate system generates an oscillating electric field and related current (colloid vibration current). These effects are symmetrical according to the Onsager principle.<sup>[8]</sup> Both of them can be used for generating a relative motion of phases. The field used for such purposes is called “driving force”.

The second purpose of monitoring relative phase motion is often achieved by optical means as described in ISO 13099-2.

It turns out that at a high frequency range, there is no need to use an additional “monitoring” field. Instead, the field complementary to the driving force can be measured. If the electric field is the driving force,

then the ultrasound response can be measured using the ESA method. Alternatively, if an ultrasound wave is the driving force then electric current can be measured using the CVI mode.

Both these methods yield raw experimental data for calculating electrophoretic mobility from the magnitude of the response field and sign of the surface charge from its phase. This electrophoretic mobility becomes frequency-dependent due to a number of factors. There are well verified theories for extracting  $\zeta$ -potential from such “dynamic electrophoretic mobility” described in ISO 13099-1. The simplest one is practically identical to the well-known Smoluchowski theory that usually serves as the basis for optical methods.<sup>[9]</sup>

There are no known advantages of one electroacoustic method over the other.

Electroacoustic phenomena exist not only in particulates systems but in porous materials saturated with liquid as well. There are two known electroacoustic effects in porous media introduced by Frenkel.<sup>[6] [7]</sup> Seismoelectric effect is a high frequency analogy of the streaming current/potential. Electroseismic effect is a high frequency analogy of electroosmosis. [Annex A](#) presents the relationship between classical electrokinetic effects and high frequency electroacoustics.

Electroacoustics effects in porous materials can be measured with modern devices,<sup>[10] [11] [12]</sup> but it is still at the stage of research. This part of ISO 3099 is dedicated to the electroacoustic methods in particulates only.

All electroacoustic instruments that have been designed to date are built as a probe. Such probe design includes elements for generating (measuring) ultrasound and elements for generating (measuring) electric field (current). There are common features for all existing instruments, presented in the next section.

## 6 Zeta potential probe design elements

An electroacoustic instrument contains an electronic block that generates electric pulses of certain frequency. A pulse technique is an essential feature of all electroacoustic instruments. The frequency range of these pulses is from 1 MHz to 20 MHz.

The same block is used for analysing either electric (CVI mode) or ultrasound (ESA mode) pulses generated by a sample in response to the initial driving pulse.

The electronic block is supplied with a probe that contains elements required for transmitting pulses to the sample and receiving generated response. Such a sensing probe contains piezo-electric devices which are able to convert electric energy into ultrasound and vice versa. All piezo-electric devices shall contain a delay rod that separates pulses in time. There shall be also an additional insert that provides for matching of acoustic impedances between the probe and a sample.

There is also a system of two electrodes used either for launching electric pulse in the sample or measuring electric response.

An initial electric pulse can be applied directly to the dispersed system for generating relative phase motion by the electrode system. This motion generates ultrasound that is measured with the piezo-electric device. This approach is used in the ESA mode.

The CVI approach uses a piezo-electric device first, converting the initial electric pulses into ultrasound that then are launched into the dispersed system. This ultrasound generates a relative phase motion and electric current that is then measured with the electrode system.

## 7 Determination of the dynamic electrophoretic mobility

Electroacoustic devices measure the magnitude and phase of the electroacoustic signal, which might be either ESA or CVI depending on the nature of the driving force. This is the raw experimental data that might vary for different instruments. It shall be converted to some other parameters that would be universal for all instruments and methods. Such a parameter was suggested by O'Brien<sup>[4]</sup> and is

currently in use in all electroacoustic devices ("dynamic electrophoretic mobility"). This parameter ( $\mu_d$ ) is the generalization of the electrophoretic mobility concept for high frequency oscillating particle motion.

According to the O'Brien relationship, the average dynamic electrophoretic mobility,  $\mu_d$ , is defined as:

$$\mu_d = (A_{\text{ESA}} \text{ or } A_{\text{CVI}}) \left[ \frac{\rho_m}{\phi(\rho_p - \rho_m)} \right] \left[ \frac{1}{A(\omega)F(Z)} \right] \quad (1)$$

where

- $A_{\text{ESA}}$  and  $A_{\text{CVI}}$  are the magnitudes of ESA and CVI electroacoustic signals normalized with corresponding driving forces;
- $A(\omega)$  is an instrument constant found by calibration;
- $F(Z)$  is a function of the acoustic impedances of the transducer and the dispersion under investigation describing reflection of ultrasound on the surface of the electroacoustic probe.

The densities of the medium and particles,  $\rho_m$  and  $\rho_p$ , are required, as well as the volume fraction of particles  $\phi$ .

According to O'Brien, a complete functional dependence of electroacoustics on key parameters, such as zeta potential, particle size and frequency, is incorporated into the dynamic electrophoretic mobility. For all considered cases, the coefficient of proportionality between electroacoustic signal and dynamic electrophoretic mobility is frequency independent and independent of particle size and zeta potential. This feature makes the dynamic electrophoretic mobility an important and central parameter of the electroacoustic theory. It can be used for comparing results produced by different instruments.

## 7.1 Subtracting background electroacoustic signal generated by ions

Electroacoustic probes measure the total electroacoustic signal, which is the sum of the signal produced by particles and signal produced by ions. Historically, the electroacoustic signal from ions was the first electroacoustic effect predicted theoretically by Debye in 1933.<sup>[5]</sup>

The electroacoustic signal from ions is normally much smaller than the signal produced by particles and can be neglected. Its role increases with increasing ionic strength due to a larger number of ions. Increasing ionic strength causes a decay in  $\zeta$ -potential, which also enhances the relative contribution of ionic background.

Another factor that controls relative contribution of ions and particles in the measured electroacoustic signal is the volume fraction of particles. The contribution from ions becomes more important in dilute systems due to the smaller particles contribution.

The next factor is particle size. Increasing particle size leads to a reduction of the particles contribution which, in turn, amplifies the role of the ionic background.

The last factor is density contrast that also affects particles contribution.

It is impossible to provide exact thresholds for individual parameters because the total effect depends on multiplicative contributions of individual factors. It is possible to provide approximate values for individual parameters causing sufficient reduction of the particles contribution for making ionic background important. These empirical thresholds are: ionic strength exceeding 0,1 M, volume fraction below 1 %, particle size above 10 microns, and density contrast below 0,1.

The electroacoustic signal generated by equilibrium supernate should be measured if one of the mentioned above parameters is below the specified threshold. It is quite possible that large values of

some parameters would compensate for low value of others and the particles contribution would still be much larger than the ionic background.

If the ionic background signal becomes comparable with total measured electroacoustic signal for a particular sample, then it shall be subtracted. This subtraction is not trivial due to the fact that both electroacoustic signals (total and ionic background) are vectors, which is the usual presentation of AC electric effects.

## 8 Calculation of zeta potential

### 8.1 General

Dynamic electrophoretic mobility, same as classical electrophoretic mobility, depends first of all on the degree of the individual particles or pores double layers interaction. This interaction is usually negligible in aqueous solutions due to a very small Debye length,  $\kappa^{-1}$ , as compared to the particle size dimension  $a$ . That is why double layers in aqueous solutions are usually assumed to be isolated and not interacting, even at rather high volume fraction of particles  $\phi$ . ISO 13099-1 contains the following formula for critical volume fraction,  $\phi_{\text{over}}$ , that limits the range of isolated double layers model.

$$\phi_{\text{over}} \approx \frac{0,52}{\left[1 + (1 / \kappa a)\right]^3} \quad (2)$$

Parameter,  $\kappa a$ , is usually quite large in aqueous solutions. As a result, critical volume fraction that limits applicability of the isolated double layers model is also high and this limitation is not very important.

Nevertheless, this factor might become more important for nano-dispersions due to the small particle size that leads to  $\kappa a$  decay. In fact, this is valid for classical electrokinetics as well.

Overlap of the particle double layer becomes much more important in non-aqueous systems, especially in non-polar ones where Debye length becomes much large due to the low ionic strength.

There are dynamic electrophoretic mobility theories for both isolated and overlapped double layers.

Overlap of double layers is just one of the mechanisms that affect particle dynamic electrophoretic mobility due to their interaction. Particles generate hydrodynamic and electric fields when they participate in electroacoustic phenomena, as well as in the classical electrokinetic one. These fields could affect motion of neighbouring particles. Electroacoustic theory shall take into account this interaction. Otherwise, it would be valid only for dilute systems, where such interactions are negligible.

### 8.2 Isolated double layers

Where there are isolated double layers, dynamic electrophoretic mobility is proportional to the  $\zeta$ -potential, similarly to the classical electrophoretic mobility. There are several theories allowing calculation of the  $\zeta$ -potential from the dynamic electrophoretic mobility. They are valid for different ranges of several parameters, such as  $\kappa a$ , surface conductivity, volume fraction, particle conductivity. Some of them take into account particles interaction (others do not), which would limit the volume fraction range of applicability.

#### 8.2.1 O'Brien theory for dilute systems

The electroacoustic theory for dilute systems with negligible particle-particle interaction is valid for spherical particles only but with no restriction on the particle size. It is called the "O'Brien theory for

dynamic electrophoretic mobility”[4]. It yields the following expression for the dynamic electrophoretic mobility:

$$\mu_d = \frac{2\varepsilon_0\varepsilon\zeta}{3\eta} G(s) [1 + F(\omega')] \quad (3)$$

where

$$G(s) = \frac{1 + (1+j)s}{1 + (1+j)s + j \frac{2s^2}{9} \left( 3 + 2 \frac{\rho_p - \rho_m}{\rho_m} \right)} \quad (4)$$

$$F(\omega') = \frac{1 + j\omega' \left( 1 - \frac{\varepsilon_p}{\eta} \right)}{2 + j\omega' \left( 2 + \frac{\varepsilon_p}{\varepsilon} \right)} \quad (5)$$

$$s^2 = \frac{a^2 \omega \rho_m}{2\eta} ; \omega' = \frac{\omega}{\omega_{MW}}$$

$s^2$  and  $\omega'$  are two factors that determine the frequency dependence of dynamic electrophoretic mobility and  $j$  is the square root of  $-1$ . The factor  $G(s)$ , reflects the frequency dependence related with the inertia effects, whereas the factor  $F(\omega')$ , represents the influence of the Maxwell-Wagner polarization of the EDL.[13] [14]

For aqueous colloids, the inertia factor,  $G(s)$ , plays a more important role than the EDL polarization factor,  $F(\omega')$ . The inertia factor dramatically reduces the magnitude of the dynamic mobility of larger particles at high frequencies. In addition to reducing the amplitude, the inertia factor also causes a lag in the particle motion relative to the external driving force, and this interposes a phase shift on the dynamic electrophoretic mobility. This phase shift reaches a maximum value of  $45^\circ$  at the high frequency limit.

Neither of these two factors is important at low frequency when the  $G(s)$  and  $F(\omega')$  factors approach to 1 and 0,5 respectively. This means that at sufficiently low frequency, dynamic electrophoretic mobility would depend only on those factors that are taken into account by Smoluchowski theory for electrophoresis. It is known that Smoluchowski theory for electrophoresis is valid for any volume fraction, any shape of the particles. That is why Smoluchowski theory is so popular.

## 8.2.2 Smoluchowski theory for CVI in concentrates, including particles interaction

It is important to have Smoluchowski theory for electroacoustics as well. Such theory was developed for CVI mode [4]. This theory effectively takes into account particles hydrodynamic and electrodynamic interaction. It yields the following expression for the dynamic electrophoretic mobility measured in CVI mode:

$$\mu_d = \left( \frac{\varepsilon\varepsilon_0\zeta}{\eta} \right) \left[ \frac{K_s (\rho_p - \rho_s) \rho_m}{K_m (\rho_p - \rho_m) \rho_s} \right] \quad (6)$$

This theory was verified with the equilibrium dilution experiment, see [Annex B](#).

It is more limited than Smoluchowski theory for electrophoresis. There are two critical frequencies that determine the valid range of this theory. The critical frequency of hydrodynamic relaxation ( $\omega_{hd}$ )

determines the range of the particle inertia and that of the factor  $G(s)$  influence. This factor becomes negligible when frequency  $\omega$  satisfies the following condition:

$$\omega \ll \omega_{hd} = \frac{\eta}{\rho_m a^2} \quad (7)$$

This condition is valid for particles with sizes under 300 nm assuming that the frequency is 1 MHz. This critical size increases with decreasing density contrast and becomes much higher for emulsions and soft particles.

The critical frequency of EDL electric polarization  $\omega_{MW}$  presents a frequency range where the second factor, function  $F(\omega')$ , becomes negligible:

$$\omega \ll \omega_{MW} = \frac{K_m}{\epsilon_0 \epsilon} \quad (8)$$

Both theories presented above have been derived assuming a thin double layer:

$$\kappa a \gg 1, \quad (9)$$

and a negligible contribution of the surface conductivity, expressed in terms of small Dukhin number: [1] [2] [3] [4] [5] [6] [7] [8]

$$Du \ll 1 \quad (10)$$

The theory given in 8.2.3 eliminates restriction specified with Formula (10).

### 8.2.3 CVI theory in polydisperse concentrates with surface conductivity and particles interaction

There is also version of CVI theory that takes into account particles interaction and eliminates restriction on the Dukhin number, see Reference [15].

$$\mu_d = \frac{\sum_{i=1}^N \frac{9\rho_s \phi_i h(s_i)}{4j\phi(1-\phi)s_i I(s_i) \left\{ \rho_p - \rho_m \left[ \frac{3H_i}{2I(s_i)} + 1 \right] \right\}} \frac{3}{2+\phi+2Du_i(1-\phi)}}{3\eta(\rho_p - \rho_m)\rho_m + 1 - \frac{\rho_p}{1-\phi} \sum_{i=1}^N \frac{\left[ \frac{3H_i}{2I(s_i)} + 1 \right] \phi_i}{\rho_p - \rho_m \left[ \frac{3H_i}{2I(s_i)} + 1 \right]}} \quad (11)$$

where

Index  $i$  corresponds to fraction with size  $a$  in polydisperse system with  $N$  fractions.

$Du_i = \kappa \sigma / K_m$   $a_i$  is the Dukhin number for the  $i$ th fraction of the polydisperse colloid.

$s_i = \alpha_i \sqrt{\omega \rho_m / 2\eta}$ , and special functions  $h$ ,  $H$ , and  $I$  are given in Section 2.5.2 of Reference [2].

It is assumed that all fractions have the same  $\zeta$ -potential.

This theory was verified with the equilibrium dilution experiment, see Annex B.

### 8.2.4 ESA theories for concentrates with particles interaction

There are several papers of the same type and about the same range of parameters[17] [18] [19] dedicated to the ESA effect in concentrated dispersions.

### 8.3 Overlapped double layers

Both theories mentioned above assume isolated non-overlapped DLs. This condition might not be valid in concentrated systems, especially with nano-size range and/or low ionic strength. There is a theory developed for overlapped DLs.[16] It exists so far only for the CVI mode:

$$\mu_d = \frac{2\sigma a}{3\eta\Omega} \frac{\rho_m}{\rho_s + i\omega(1-\phi)\frac{\phi}{\gamma}\rho_p\rho_m} \quad (12)$$

where

$$\gamma = \frac{9\eta\phi\Omega}{2a^2} \quad (13)$$

$\Omega$  is a drag coefficient introduced according to the Stokes law,  $F = 6\pi\eta a\Omega v$ , and reflecting hydrodynamic particles interaction.

It is important to stress that this approximation of the electroacoustic method makes possible direct measurement of the electrokinetic charge in nano-colloids and non-polar dispersions without the need to know the Debye length.

## 9 Operational procedures

### 9.1 Requirements

#### 9.1.1 Instrument location

The instrument should be located in a clean environment that is free from excessive electrical noise.

Mechanical vibrations are not important.

Temperature fluctuations are important. It is desirable to prevent temperature variations over 1 °C during measurement period for maintaining specified precision level.

#### 9.1.2 Sample handling

Samples can be stirred, mixed, or pumped for eliminating the possible sedimentation influence and ensure stability of results. Otherwise, there is not general requirement for sample being agitated.

Bubbles do not affect results unless they are attached to electrodes.

The electrophoretic mobility measured in a sample is only valid for a batch of material if the test sample is representative for that batch.

#### 9.1.3 Preparation

Sample can be measured without dilution.

Samples exhibiting sedimentation and deposit formation shall be homogenized before the measurement.

#### 9.1.4 Sample volume fraction requirement

Sample volume fraction should be above 1 % v/v. Contribution of particles exceeds contribution of ions and precision of the measurement.

### 9.2 Verification

#### 9.2.1 Reference materials

Electroacoustic instruments perform better for systems with higher density contrast. That is why traditional latex standards are not appropriate for verifying and calibrating electroacoustic instruments. Reference materials are used in two different stages of the measurement process:

**Calibration:** Reference materials used for calibration should meet the requirements specified for certified reference materials, namely being homogeneous and stable and having value assigned according to a metrologically valid procedure. These materials shall be used to either calibrate the instrument or to verify trueness of the measured results.

**Daily quality control:** Reference materials shall be used with every measurement series to ensure correct performance of the instrument system. This control is most suitably done using quality control charts. Reference materials for this purpose need to be homogeneous and stable, but do not have to have a metrologically valid assigned value.

Different reference materials shall be used for calibration and for daily quality control.

**NOTE** At the time of the publication of this standard, no certified reference materials for zeta potential existed. Non-certified reference materials with assigned values are available from several suppliers. Another currently frequently used option is using Ludox®<sup>1)</sup> This is a 50 % silica suspension and is usually diluted with a 0,01 KCl solution to a mass fraction of 10 %. There is reported value of  $\zeta$ -potential for these particles calculated using Smoluchowski approximation as -38 mV, which corresponds to electrophoretic mobility -4 ( $\mu\text{m/s}$ ) (cm/V). [2] This value of the electrophoretic mobility measured with CVI methods agrees within 10 % with independent measurement of the same material conducted using ESA method (paper). [24] These materials are well suited for the daily quality control, but are insufficient for calibration and/or instrument verification. However, in the absence of certified reference materials, these have to be used. Priority should be given to materials with clearly stated values by the producers.

#### 9.2.2 Repeatability

To achieve the desired repeatability of electrophoretic mobility measurement, the following steps need to be followed:

- Set up the instrument adequately, select the proper settings for operating conditions and allow all parts sufficient warm-up time.
- Follow the measurement protocol given for the material.
- Perform at least six consecutive measurements with the same aliquot.

An instrument is considered as meeting the requirement of this standard if the CV for the mean electrophoretic mobility value of six measurements for a reference material is less than 3 % if the absolute value of the reference material mobility is higher than 1  $\mu\text{m}\cdot\text{cm}/\text{V}\cdot\text{s}$ .

#### 9.2.3 Intermediate precision

The test of intermediate precision shall follow the procedure set out in 9.2.2 except that six different sample aliquots at an appropriate concentration shall be used.

**NOTE** Care must be taken that the material used is stable after opening.

1) Ludox® is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

An instrument is considered as meeting the requirement of this standard if the CV for the mean electrophoretic mobility value of six measurements for a reference material is less than 4 % if the absolute value of the reference material mobility is higher than  $1 \mu\text{m}\cdot\text{cm}/\text{V}\cdot\text{s}$ .

#### 9.2.4 Trueness

The accuracy of operation of instruments shall be determined using certified reference materials meeting the definition of ISO Guide 30 and having been produced in compliance with ISO Guide 34. In the absence of certified reference materials, non-certified reference materials meeting the definitions of ISO Guide 30, of hard spheres from a reliable source, homogenous and stable having a defined electrophoretic mobility determined by optical means at specified conditions can be used, bearing in mind that the use of non-certified reference materials precludes absolute demonstration of accuracy. The test of accuracy shall follow the procedure set out in [9.2.3](#).

An instrument is considered to meet this standard if the mean electrophoretic mobility value for the six measurements is in agreement with the assigned value of the reference material. For checking the agreement both the uncertainty of the reference material and an uncertainty of the six results shall be taken into consideration.

### 9.3 Sources of measurement error

The main source of the errors in the reported values of  $\zeta$ -potential are errors in input parameters, such as volume fraction of solids, densities, viscosity of liquid, dielectric permittivity of the liquid.

Usually, high values of  $\zeta$  -potential exceeding 100 mV occur due to

- lower input volume fraction values than in reality,
- lower input density contrast, than in reality,
- lower input dielectric permittivity, than in reality, or
- higher viscosity, than in reality.

Wrong particle size calculated from the electroacoustic phase can be also a source of the error in the  $\zeta$ -potential. The phase of the electroacoustic signal depends on several parameters, not only particle size. For instance, particles and particle aggregates porosity affect the phase. Particles shape is another factor. If these and contributions from others factors are attributed to the influence of the particles size, then it would be wrong and calculated  $\zeta$ -potential would be wrong as well.

Sedimentation of particles on the surface of the electroacoustic probe leads to increasing volume fraction in the vicinity of sensing elements. This effect would be reported as increasing  $\zeta$ -potential, instead of increasing volume fraction, unless recognized by the user.

## Annex A (informative)

### Electroacoustics: high frequency electrokinetics

Electroacoustics is a family of electrokinetic effects that occur at high frequency oscillating either electric or acoustic fields. Both, electroacoustics and electrokinetic phenomena arise due to the spatial distribution of electric charges at the vicinity of the object interface when it is placed in contact with a liquid. Both electroacoustics and electrokinetics are result of the electric and mechanical fields coupling.

Every traditional electrokinetic effect has its electroacoustic analogue as shown in [Table A.1](#).

**Table A.1 — Electroacoustic analogues of electrokinetic phenomena**

| Electrokinetics                                                                                                                            | Electroacoustics                                                                                                                 |
|--------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| <b>Electrophoresis:</b><br>Motion of particles in electric field DC, AC KHz                                                                | <b>Electric sonic amplitude:</b><br>Ultrasound generated by particles motion in the electric field, AC MHZ                       |
| <b>Sedimentation potential, Dorn effect:</b><br>Electric field generated by particle sedimentation, DC conditions                          | <b>Colloid vibration current:</b><br>Electric field generated by particle motion in ultrasound wave, AC conditions               |
| <b>Electroosmosis:</b><br>Liquid motion through a porous material induced by electric field, DC, AC KHz                                    | <b>Electroseismic effect:</b><br>Liquid motion through a porous material induced by electric field, AC MHZ                       |
| <b>Streaming current/potential:</b><br>Electric field/current generated by gradient of pressure applied to the porous material, DC, AC KHz | <b>Seismoelectric effect:</b><br>Electric field/current generated by gradient of pressure applied to the porous material, AC MHZ |

There are number of differences between electroacoustic and traditional electrokinetic phenomena that justify introduction of electroacoustics as a separate group of experimental phenomena.

First of all, a wavelength of mechanical (sound) field becomes comparable with system-sample dimensions at MHz range. It is 1,5 mm at 1 MHz in water. That is why mechanical force needs to be described in wave terminology at MHz range, in contrast to traditional electrokinetic phenomena. At the same time, wavelength is still much longer than particle size. This “long wavelength limit” leads to tremendous theory simplifications, which allow introduction of Smoluchowski theory analogues for all electroacoustic effects.

Secondly, a liquid behaves as compressible on macroscopic scale, which opens up completely new avenues for instrument design.