Co-Nanomet

Co-ordination of Nanometrology in Europe

Workshop

'Instruments, standard methods and reference materials

for traceable nanoparticles characterisation'

Nuremberg, 28./29.04.2010

SUMMARY OF THE WORKSHOP FINDINGS

and

DETAILED REPORT OF
THE CLOSING DISCUSSION SESSION

Objectives

General objectives of the workshop:

- To assess the current metrology status with regard to:
  - relevant measurands (depending on the context of the measurement)
  - available measurement techniques, their limits and fields of application
  - the dissemination of such techniques to science, industry and public authorities
  - traceability and measurement uncertainty
  - standardisation
  - reference materials

- reveal current and future needs for engineered nanoparticles (ENP[1]) metrology

Specific objectives of the discussion

- To collect the stakeholders/participants opinions and ideas about what NEEDS to be done to improve the reliability of nanoparticles characterisation, for example in terms of interlaboratory comparisons and new documentary standards.

How Co-Nanomet will disseminate the results of the discussion

- Co-Nanomet will collect, extract and transform the received feedback into

  1) a scoping paper for the area of metrology for engineered nanoparticles (see www.nanoparticle-metrology.de and www.co-nanomet.eu).

  2) a strategy paper to inspire the community of people measuring nanomaterials and at the nanoscale, and – in particular – the EC departments that funded Co-Nanomet and that can fund research and innovation in this area (see www.co-nanomet.eu).

Structure of the discussion

1. Environment – Health – Safety, and related regulatory demands

2. Demands from industry

3. Generic metrology issues

[1] ENP = engineered nanoparticles: the workshop focused on ENPs; the acronym will be used throughout the text.

Summary of the Workshop Findings

The workshop findings are given here in a structure corresponding with the structure of the workshop objectives (see previous page).

- assess the current metrology status with regard to:
  This 2-days workshop could obviously not yield a complete survey on the current metrology status for nanoparticle characterisation. However it tackled the general aspects of nanoparticle metrology and gathered expertise from all fields involved in nanoparticle characterisation (NPs production, EHS testing, developers and manufacturers of characterisation methods, scientists from material characterisation and metrology, particle measurement engineers, …). It focussed on sizing of **dispersed nanoparticles**, but explored related topics like concentration measurement and interfacial characterisation as well.

  - relevant measurands (depending on the context of the measurement):
    Considering the potentially relevant measurands most techniques and metrology tools exist for measurands related to morphology, hydrodynamics or optics – most often expressed as "size". That is, because a) "size" decides on the status as nanoparticle, b) many product or EHS related properties are determined by size, c) there is already a multitude of commercial sizing instruments available.
    Fewer techniques are available for concentration measurement, shape description or zeta potential measurement. For these measurands there is a clear need for new measurement techniques.
    …

  - available measurement techniques, their limits and fields of application:
    The currently most widely used sizing techniques were presented and their limitations and field of applications discussed. There is certainly a lack for each of the methods on how reliable the measurement results are in the range below 10 nm (sampling losses, lack of reference materials, …).

  - the dissemination of such techniques to science, industry and public authorities
    is okay

  - traceability and measurement uncertainty
    Even though the traceability and measurement uncertainty of the different sizing techniques are in general known or at least can be derived on standardised procedure, little is known on the instrument performance (accuracy, uncertainty, resolution of size distributions/information content) at the nanoscale (despite electron microscopy, …). This is partly due to a lack of reference materials; accordingly instrument validation has been traditionally conducted in the range above 100 nm.

  - standardisation
    international standards exists or are currently being developed for most presented sizing (and counting) techniques

- reference materials
  very few reference materials for particle size < 100 nm are currently available. The existing RMs generally consist of suspensions of a nominal (often very low) particle concentration;
  due to the laws of nature, there is no reference aerosol

- reveal current and future needs for ENP metrology
  - for a detailed discussion of the ENP metrology needs, we refer to the following chapter, which provides a detailed summary of the workshop closing discussion session.

Summary of the Workshop Findings

EHS and related regulatory demands

1) There is a need to better identify the relevant measurands.

All participants agreed that *size matters*, but *not only* size.

The discussion showed that an initially proposed list of potentially relevant measurands (size, shape, surface chemistry) is not exhaustive and additional measurands were mentioned. These measurands are proposed to be grouped as shown below.

The list of measurands mentioned is extensive, and it must be reminded that only a few measurands are usually required to enable a specific application or to understand a specific effect. There is no indication that all ENPs have to be systematically characterised for each of the mentioned measurands.

On the other hand, until there is a better understanding of the relation between the nanoparticles basic physico-chemical characteristics and their behaviour, R&D has a natural interest in exploring and measuring a maximum of measurands for particle systems. A thorough characterisation of ENPs used in EHS studies is strongly recommended.

- morphology (*topology/geometry*):
  - characteristic lengths and areas in 2D-projection, e.g. x_{Feret}, x_{Perim}, $a_{Legendre,1/2}$, …
  - parameters describing aggregates/agglomerates, e.g. x_{Gyr}, N_{agg}
  - shape parameters from morphology data, e.g. sphericity, aspect ratio, fractal dimension for x_{Gyr}

- size related properties based on hydrodynamics and/or interaction with external fields
  - diffusion coefficient, hydrodynamic diameter (of translation)
  - settling velocity, Stokes diameter
  - aerodynamic diameter
  - acoustophoretic mobility
  - (partial) scattering or extinction cross section → e.g. x_{Gyr}, $x_{projection}$

- surface area of the dispersed phase
  - via adsorption of gases e.g., S_{BET}
  - via SAXS
  - via titration experiments, with surfactants, polyelectrolytes etc.
    - since these methods are not yet mature techniques, and partly only possible with calibration, there is need for prenormative research and standardisation.

- chemical composition and phase
  - crystallinity (amorphous fraction vs crystalline fraction)
  - phase (fractions of different crystallographic phases)

- concentration of particles
  - Mass, surface, number concentration (see below)
  - Total or fractional concentration

- interfacial properties (which depend on whether the ENP is in polar and non-polar solvents, or in gas):
  - surface charge
  - zeta-potential
  - surface conductivity
  - *pristine* point of zero charge and iso-electric point (for different charge determining ions)

- interaction with continuum/solvent
  - solubility and dissolution kinetics
  - ROS (radical oxidising species) potential
  - wettability

2) There is a need for better explaining the limitations of nanoparticle characterisation

The workshop participants agree that particle characterisation experts and manufacturers of particle sizing instruments should give more attention on exploring and explaining the limitations of the techniques (detection limits, calibration procedures, etc.) they develop and use. The question was raised how users and manufacturers should cope with the fact, that their instruments can not (always) cover the complete nanoscale (i.e. from 1 nm to 100 nm [CEN ISO TS 27687:2009]).

3) There is a need to develop measurement techniques and corresponding metrology tools (interlaboratory comparisons, standard methods, reference materials) for:

3.1 dosimetry / concentration metrics

The workshop has confirmed the lack of reliable and traceable methods for the determination of nanoparticle concentration, especially in complex matrices.

At the same time, in EHS it is often not clear which concentration metrics (number, surface, mass, …) determines the effect of nanoparticles. It can be reasonably expected that there will never be a single metric that fits for all EHS issues of ENPs.

Reference was made to a VCI statement: “A disperse system is a nanomaterial, if it contains 10 % (m/m) nanoparticles". The importance of accurate and reliable concentration measurement methods is perfectly illustrated in this statement.

The following needs were explicitly addressed:

- need to traceably measure number concentration
  - in aerosols: progress has been made recently in development, calibration and standardisation of Condensation Particle Counting (CPC) instruments (via comparison with traceably calibrated electrometer); both ISO/TC 24/SC 4 and the chemistry metrology community (CCQM, Consultative Committee on Quantity of Matter, CIPM) are working on this issue.
  - in liquid dispersions: there is no 'liquid-CPC'; also the Nanoparticle Tracking Analysis requires calibration. Since there is no reference material for NP number concentration, calibration methods are no option (yet).

<u>3.2 surface area measurement in suspension</u>

- Progress is expected in the field of SAXS (ref. Presentation by M. Krumrey)
- Possibilities are suspected in methods working via adsorption of molecules (e.g. CTAB – see comment above) and NMR (which is sensitive for the difference in state between atoms/molecules in the bulk or at the nanoparticles surfaces).

<u>3.3 distinction btw. natural and engineered nanoparticles</u>

- specific solutions: subtract particle background (workplace measurement) or chemical analysis (ICP-MS) of fractionated particle samples (background must be known as well)

<u>3.4 detection of NPs in complex matrices</u>

- there are no easy, robust, broadly applicable methods available to detect nanoparticles adsorbed on larger particles or surfaces
  - specific solutions, such as AFM in resonance mode, exist
- it is not possible to detect all nanoparticles in a waste water
  - a specific but limited solution is the investigation of the fate of nanoparticles in model sewage plants (with a defined liquid phase)

<u>4) There is a need for traceable methods characterising the nanoparticle release from surfaces and agglomerates</u>

The workshop likes to see better methods. And there is a need for reference material for the strength of adhesion forces of NPs on surfaces and for the strength of agglomerates.

<u>5) There is a need for nanoparticle classification / identification systems</u>

A system of nanoparticle “classes” (e.g. compact vs high-aspect-ratio nanoparticles) needs to be developed. However, the functionalisation of nanoparticles will make a simple classification difficult.

Demands from industry

The measurands relevant for product performance are sometimes different from the measurands required for EHS. This simple fact can make harmonisation of measurement methods and communication of measurement results a particular challenge. For example, in the production of ENPs there is an increasing demand for the simultaneous determination of two or more measurands on a particle system. Such a combination of simultaneously measured measurands may justify lower accuracy requirements for the individual measurands, as the simultaneous measurements can avoid the creation of differences between particle test systems stemming from different sample preparation procedures.

Several of the measurement needs listed in the previous (EHS) section, are equally relevant for the industrial application of ENPs. In this section we describe the additional, industry-specific requirements that were detected during the workshop and its closing discussion.

1) There is a need for (more) on-line/in-line process control instrumentation

Such instrumentation has to meet the following requirements:
- high temporal resolution and robustness (fouling, incorrect operation, …)
- high concentration, harsh environments (pH, temperature, pressure, …)

In process control one needs to focus on the characterisation of disperse systems in specific environments (determined by the process conditions); this is an approach which goes beyond the study of individual particles, and has consequences for the validation of instruments and techniques and for the requirements for reference materials.

2) There is a need for methods to assess the structure and the composition of the nanoparticles at the nanoscale

Real, industrial particles are often different from the pure and spherical particles used to calibrate instruments. Therefore, better methods are needed to assess at the nanoscale the complex structures and composition of nanoparticles (systems).

- particle structure: porosity, fractal dimension

- “composition of the material”: core-shell, hybrid, janus-like

3) There is a need to address the relevance of sample preparation

The state of dispersion is an important property of an ENP system. That means sample preparation should reproduce that state of dispersion, which is relevant for the technical / EHS / … problem. Hence, sample preparation determines the significance of a measurement result and affects – sometimes even dominates – its accuracy and uncertainty. For that reason sample preparation procedures have to be validated (for reproducibility, …).

Related to this is the issue of dispersion stability. Both for the industrial use of a dispersed material, as well as for the measurement of a test sample of dispersed material, the stability of the dispersion during use or measurement is important. Stability can be defined - and therefore investigated and measured - in many different ways, depending on the parameter that is supposed to keep a stable value.

4) There is a need to develop product and process models / property and process functions

We need to develop the functions which relate the parameters of the production process, with the nanoparticles properties and the product functionality, based on measurement results obtained at different stages of processing and use.

Generic metrology issues

1) There is a need to improve dissemination of basic metrology concepts

Very frequently, the importance of the basic metrological concepts (e.g. measurand, method-defined property, traceability, uncertainty) is not recognised, or the concepts are used in an intuitive way and depending on the user's educational background. Different interpretations exist between metrologists, instrument manufacturers and process engineers. Regarding measurement uncertainty, the workshop participants express different (awareness for) support by their national standardisation bodies. There is a clear need for harmonisation. The following measures are proposed:

- *translation* of the basic metrology concepts into illustrative examples from the particle characterisation field, by and for particle characterisation experts.
- promotion of the estimation and reporting of measurement uncertainty by imposing it in the new versions of the existing documentary standards.
- Insertion of examples of uncertainty budgets in annexes to existing documentary standards (job for the standardisation bodies)
- wider application of quality assurance measures such as control charts, calibrations, training, …
- for each standard method, there should be a basic agreement about the best-case 'intrinsic' uncertainty of the method (e.g. precision and bias statements in ASTM documentary standards).

2) There is a need for methods to measure the basic material properties of particles

Several particle properties can only be derived from equations which include more basic properties of the material(s) the ENPs consist of, such as:

- (mass) density
- complex refractive index / complex permittivity (depending on wavelength)
- phase (solid, liquid; amorphous, crystallinity, micro-gel, …)
- chemical composition

Contrary to what happens in practice, one cannot always use values of the material properties which are not determined on the nanoparticles themselves. There is a need to develop and refine the methods which assess these basic material properties to make them applicable at the nanoscale.

3) There is a need for more reference materials

There is a general need for reference materials for method development, for interlaboratory studies and for validation or calibration of existing methods.

The development and supply of reference material is a matter of resources. Due to the large number of potentially relevant measurands and the multitude of measurement techniques, international collaboration is highly desirable.

Special needs mentioned during the workshop and the closing discussion:

- reference materials in larger volumes (for example for use in ecotoxicity studies)
- reference materials with certified shapes
- multimodal or polydisperse reference materials (ref. presentation prof. Mori)
- reference materials consisting of ENPs in a matrix matching real-life samples
- zeta-potential RM/CRM (not likely for near future)

The question was raised why there seems to be a complete absence of ENP related measurement capacity claims in the CIPM CMC database. It is believed that this is due to the fact that the ENP measurement area is relatively young.