Advantages and limits of aerosol spectrometers for the particle size and particle quantity determination stables and air exhaust ducts

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Abstract

For a reliable particle size and particle quantity determination in particle concentrations up to 10^5 p/cm³ optical aerosol spectrometers (OAS) offer many advantages. However, they must fulfil certain technical requirements in order to ensure significant measurement results. This essay imparts important basics for reliable particle measurement with optical aerosol spectrometers. The technical set-up and the function of an OAS are described and possible sources of error are also mentioned.

In order to avoid errors, a new OAS was developed whose measuring procedures are based on the "true" Mie-scattering, i. e. on the scattering at the spherical single particle. This measuring instrument offers clear calibration curves and very good device characteristics such as size resolution and classification accuracy, measures without border zone errors and has coincidence detection. The sensors can be used into temperatures of – 90° to 70°C. With a special cuvette, particles can be measured in overpressure up to 10 bar and in hot gases up to 120°C.

With this OAS an isothermal particle measurement is possible. Therefore, the system offers special advantages for the clear and economic characterisation of MDI, DPI, inhalers or jet mills as well as of separators even in highly explosive environments or in badly accessible places.

Keywords: high particle concentration, function OAS, explanation and influence of device parameters on particle size distribution, calibration curve, border zone error, coincidence

1 Introduction

At the particle size analysis, counting measuring methods are naturally used for numerous applications, because measurements at the particle collective or gravimetric procedures, which come from the total mass as valuation criterion, do not supply all desired information depending upon the application. Thus e.g. a photometer cannot differentiate between a particle size and a particle concentration variation. With counting measuring methods however, a time resolution of the particle sizes and the particle concentration and thus a clear determination of these measurable variables is possible.

For the determination of the fractional separation efficiency of separators, the size and the number of particles both in raw gas and in clean gas must be determined accurately, e.g. at blow-by in-situ measurements, at tests of interior filters or engine filters according to ISO 5011. Here the use of optical aerosol spectrometers (OAS) is recommended (Hess W. F. et al. 2005, Mölter L. et al. 2003, Baron P. et al. 2001, Hinds W. C. 1999, Hemmer G. et al. 1999, Umhauer H. et al. 1995), which can measure also in high particle concentrations up to 10^5 P/cm³ without dilution. OAS offer special advantages also for the characterisation of MDI, DPI and nebulisers in pharmacy, the production monitoring of active substances, the cut off determination of impactors, cyclones (Binnig J. et al. 2005), impingers or the measurement of atmospheric aerosols (e.g. bio aerosols in stables, compost, fog or tunnel), particularly for the measurement of droplet aerosols.

An aerosol spectrometer is not to be mixed up with a so-called "clean room counter". The latter is to determine the number of particles in clean rooms - thus in low concentrations - within a short time, whereby the particle size determination does not have to be accurate.

An aerosol spectrometer however is used if a highly concentrated aerosol is to be characterised concerning the particle size and the particle number as clearly as possible. At present an ISO standard for optical aerosol spectrometers (ISO/CD-21501-1) and for clean room counters (ISO/FDIS 21501-4) is worked out.

In this essay, we will describe the technical set-up and the function of an optical aerosol spectrometer and we will explain the effects of the device characteristics on the particle size and particle concentration determination.

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The particle measurement in environments with varying particle size distributions and varying particle concentrations makes special demands on the used measuring method. Examples for this are outside air measurements or measurements at objects with strongly varying raw gas concentrations such as cooling agent oil separators, in-situ measurements of the car engine or measurements of the lung function (inhale/exhale). In addition, measurements in very high particle concentrations or in environments accessible with difficulty and/or explosive environments require the employment of a measuring method particularly suitable for this purpose. Another application would be the quality assurance of a jet mill during the production of active substances.

With an optical aerosol spectrometer, which can measure at two different measuring points quasi simultaneously, there are completely new possibilities for the applications specified above. The new modular particle measuring system welas® 3000 measures with two sensors, which are connected to only one light source and only one photomultiplier, and obtains that way particularly quick and accurate results.

Thus, during filter testing, one of the sensors can be used for example in raw gas and the other can be used quasi simultaneously for clean gas measurement. Furthermore, unwanted factors, e.g. the influence of temperature and humidity on the particle size distribution, can be minimised with this measuring instrument. Due to the flexible selection of the sensors concerning their measuring volumes, this measuring system can be used for different particle concentration ranges. That way, it can be adapted optimally to the respective application.

2 Selection criteria for an appropriate measuring method

In particle measurement, counting procedures are suitable in particular if – from the beginning on – there are small sample quantities to be analysed, if there are not to high particle concentrations (number concentrations of less than 10^6 P/cm³) or if one has to measure in very small concentrations.

Counting aerosol measuring instruments are e.g.:

- OAS (Optical Aerosol Spectrometer),
- PDA (Phase Doppler Anemometer),
- Relaxation Time Spectrometer (Time of Flight Spectrometer),
- SMPS (Scanning Mobility Particle Sizer).

For the correct selection of the appropriate measuring method it is helpful to first visualise the requirements of the application to the measuring instrument to be used.

One has to expect e.g. at outside air measurements with a particle diameter of 0.2 µm a concentration of approx.

2000 particles per cm³. In such concentrations, the particle distance is clearly smaller than 1 mm (table 1).

Table 1:

Distances of the particles as a function of the concentration

Number N [m⁻³]	Number N [cm⁻³]	particle distance [cm]	particle distance [mm]	particle distance [µm]
1	10^{-6}	100	1000	
10^3	10^{-3}	10	100	
10^6	1	1	10	
10^9	10^3		1	1000
10^{12}	10^6		0,1	100
10^{15}	10^9		0,01	10
10^{18}	10^{12}		0,001	1

From this, one can conclude that e.g. an optical aerosol spectrometer with an optical measuring volume of approx. 1 mm³ cannot determine concentrations above 1 000 p/cm³ without coincidence errors, since with a particle distance of less than 1 mm there has to be allways more than one particle in the measuring volume.

By calculation, it can be observed that the particle distance in a concentration of 10^6 particles per cm³ amounts to 100 µm (table 1). Thus, if a particle concentration of 10^5 particles per cm³ is to be measured, then the border length of the optical measuring volume should be naturally not larger than 100 µm. The indication of the measuring volume size is very helpful for the user in order to be able to estimate in which maximum concentrations he can measure coincidence-freely. These examples show how important it is to know the theoretical basics for the selection of the appropriate counting procedure.

3 Theoretical basics of optical aerosol spectrometers

3.1 Lorentz-Mie theory

The measuring method of optical aerosol spectrometers is based on the Lorentz-Mie theory. The particle characteristic, the diameter, is determined by the impulse height analysis of the scattered light at the spherical single particle. The particle number is determined at the same time by the number of scattered light impulses.

Does light with the wavelength λ meet on a spherical particle with the diameter x and the refractive index m, then the light is scattered in different directions (figure 1).

The scattering of light at the particle is caused by diffraction, refraction and reflection. The polarisation plane of the incident light wave is also turned.
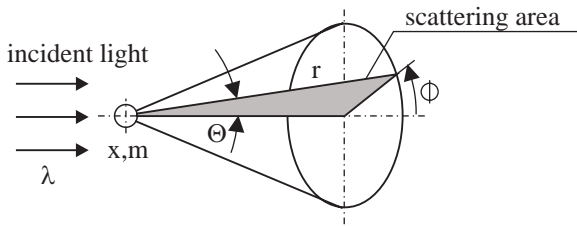
Figure 1:

Principle of incident light scattering

The intensity *I* of the light scattered at the single particles depends on the incident light intensity I_0, the polarisation angle Φ, the detection angle of the scattered light Θ, the refractive index n, the light wave length λ and the particle diameter *x*.

$$I = I_0 \cdot f(\Phi, \Theta, n, \lambda, x)$$

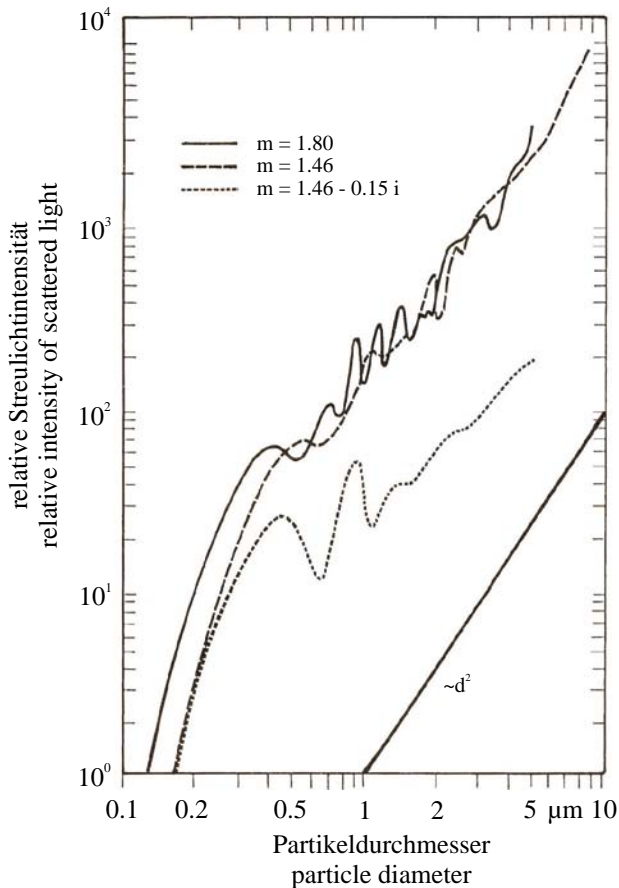By means of the scattering parameter introduced by Mie (Mie G. 1908)

$$\alpha = \frac{\pi \cdot x}{\lambda}$$

the relation between the sphere circumference $\pi \cdot x$ to the wave length λ is used into the above mentioned equation:

$$I = I_0 \cdot f(\Phi, \Theta, n, \alpha)$$

With regard to the particle-size-depending scattering power one can differ between three ranges due to the introduction of the scattering parameter α:

a) **Rayleigh-range:** $\alpha \ll 1$; here the scattering power rises with the sixth power of the particle diameter and the scattered light will be proportional to d^6/λ^4. This means: If in the Raleigh-range one should be able to measure a half so large particle as before (lower detection limit), then the double supplied quantity of light
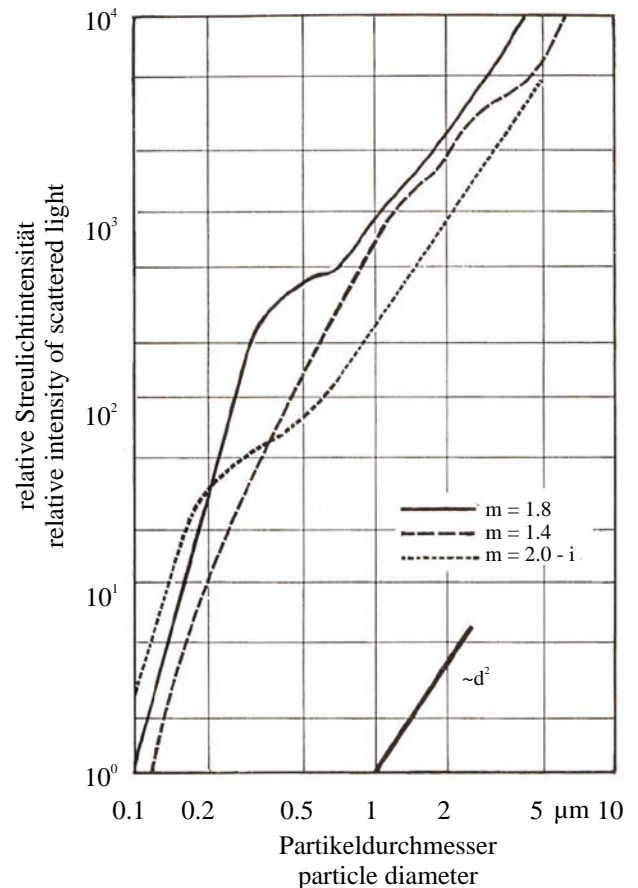

Figure 2:

Relative scattered light intensity for monochromatic light, e.g. laser light;

mean scattering angle $\theta 0 = 45°$; receiver aperture $\upsilon = 14$;

light wave length $\lambda = 0{,}436\ \mu m$; refractive index m

Source: VDI 3489 [13]

Figure 3:

Relative scattered light intensity for white light and 90° scattering;

mean scattering angle $\theta 0 = 90°$

receiver aperture $\upsilon = 24°$

Source: VDI 3489 [13]

is not enough. The necessary quantity of light must be possibly 64-times stronger than at a twice as large particle.

b) **Mie-range**: $0.1 \leq \alpha \leq 10$; here the correlation between the scattered light intensity and the particle size is not clear (figure. 2). Whereas with white light and 90° scattered light detection this correlation is clear (figure 3).

c) **Fraunhofer- resp. geometrical range**: $\alpha \gg 1$ (from $\alpha \approx 10$); here the quadratic correlation between the scattering power and particle diameter is valid.

In order to be able to determine with an aerosol spectrometer the particle size distribution as accurately as possible, a clear calibration curve (figure 3) is an important condition. OAS are usually calibrated by the manufacturer with monodisperse latex-aerosols with a refractive index of $m = 1.59$. Further suitable calibration procedures, e.g. the aerodynamic calibration, are described by Friehmelt (Friehmelt R. 1999).

3.2 Technical set-up of optical aerosol spectrometers

For the better understanding of the measuring method including the device characteristics, the set-up in principle of an OAS in forward scattering is represented in figure 4.

During forward scattering the light scattered by particles (figure 1) toward 180° is collected by the light source with a light-sensitive detector, e.g. a photomultiplier. At the 90°

scattered light detection, the photomultiplier is attached orthogonally to the image plane. The height of the scattered light impulse is a measure for the particle diameter, while the number of impulses supplies the information on the concentration since the volume flow is known.

With the help of a lens system the light is focused on the desired measuring volume size. Before the receiver optics there must be installed a light collector in forward scattering, which protects the light detector against direct irradiation. Due to diffraction actions of the light and of the scattered light, this light collector leads to an ambiguous calibration curve, also when using white light. However, a source of white light in connection with a 90° scattered light detection secures a clear calibration curve for many refractive indices.

An advantage of a small measuring volume defined and projected with white light is that this one - in contrast to the laser beam - is homogeneously illuminated over the cross section. In the figure 5 and 6, real scattered light signals are represented from which the particle size is determined by detection of the impulse height. It is easily conceivable that the signal from figure 6 can be detected more easily and reliably than the signal in figure 5. Friehmelt points out in his dissertation (Friehmelt R. 1999; see also Friehmelt R. et al., 1998) that the particle size of irregularly shaped particles is determined with white light better than with laser light.

For the quality of the evaluated scattered light impulses, not only the optical set-up is responsible, but also the quality of the opto-electronic elements.
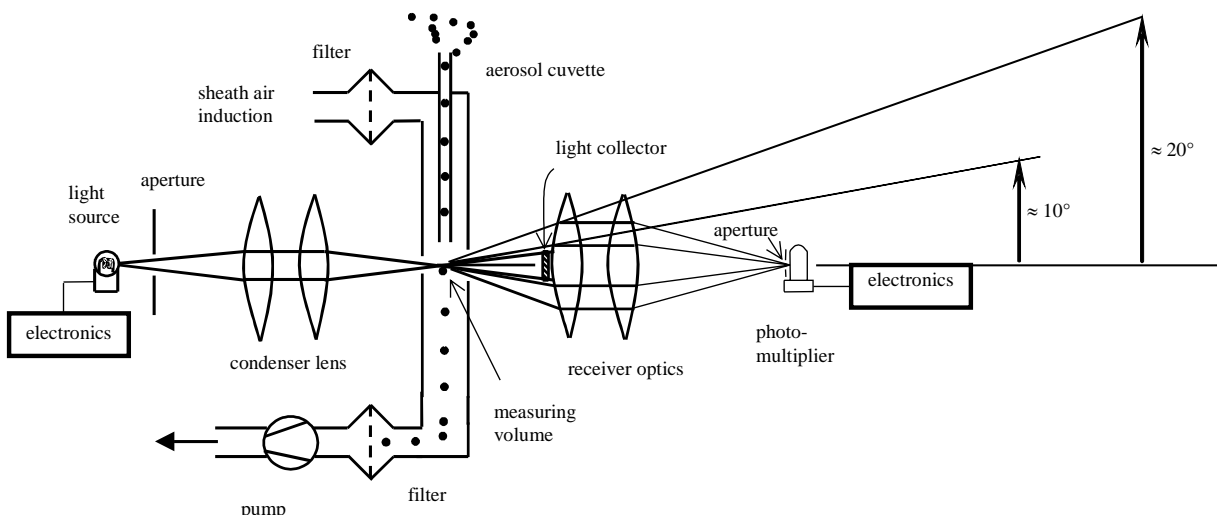

Figure 4:
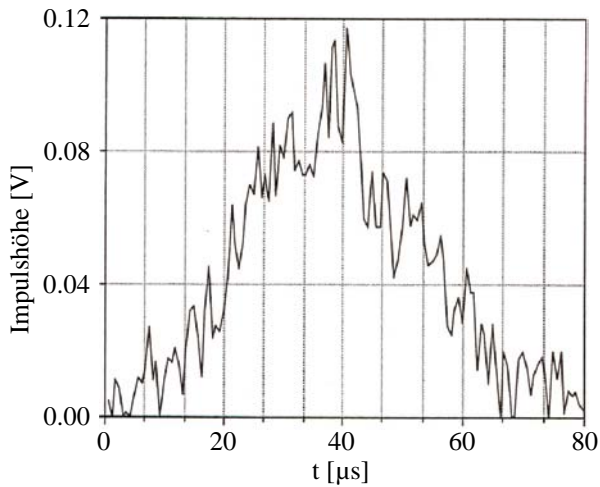Optical aerosol spectrometer (forward scattering)

Figure 5:

Real scattered light signal at laser measuring devices: Signal of a 0,5 μm
SiO2-sphere (monosphere, company Merck);
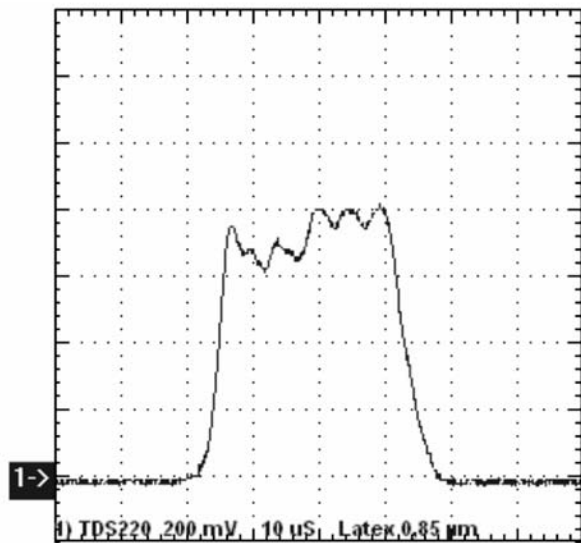
Source: H. Mühlenweg (Diss.)

Figure 6:

Real scattered light signal at an homogeneously illuminated T-shaped
measuring volume (white light source and 90° scattered light detection);

Source: Palas® GmbH

4 About the measuring accuracy of counting measuring methods

Independently of which counting method is used, usually one or more physical values must be known for the clear measurement of the particle size. Depending upon the counting method, these values are the following:

- the refractive index,
- the particle material density,
- the surface texture or the chemical composition,
- the electrical charge.

A particle measurement without the taking into consideration of the necessary physical values leads to different measuring results at different measuring methods. If different measuring instruments with the same measuring method supply different measuring results under the same test conditions, even when knowing the concerned physical values, then the cause might have to be found in the detail set-up and/or in the selection of the components of these measuring instruments. The shape influence of the particles plays a large role, too.

As generally in the measurement technique, it is meaningful also in the particle measuring technique to give information on the measurement uncertainty of the used measuring method and/or the concerned measuring instrument.

In the on-line particle measuring technique - in contrast to the mechanical measuring technique - it is practically impossible to determine measuring errors exactly with the help of a fixed tolerance (in the mechanical measuring technique for example the hole diameter of a drilling H7). Therefore, in the particle measuring technique, one has defined for the error consideration important device characteristics, which are specified in the VDI guide line 3489 and the ISO 13323-1 and will be described in the future in the VDI 3867 and the ISO/DIS 21501-1-4, too.

For a clear quantitative comparison of measurement results, which are won with different measuring methods, the used measuring instruments should be calibrated - if possible - with the same calibration procedure.

4.1 Particle size resolution and particle size classification accuracy

The particle size resolution gives information about which particle sizes can be differentiated from each other. The particle size classification accuracy indicates how exactly the particles are determined concerning their size.

4.2 Sources of error when measuring with optical aerosol spectrometers

Optical measuring volume limitations are used in practice in order to be independent of the Gauss intensity distribution of the laser light or to be able to determine as coincidence-free as possible the particle size distribution in high concentrations. The following possible sources of error must be considered:

4.2.1 Border zone error

Figure 7 shows the detail set-up of the measuring volume of an OAS with laser light and without optical measuring volume limitation.

from the side

aerosol nozzle

aerosol flow

light beam

measuring volume

suction nozzle

from the top
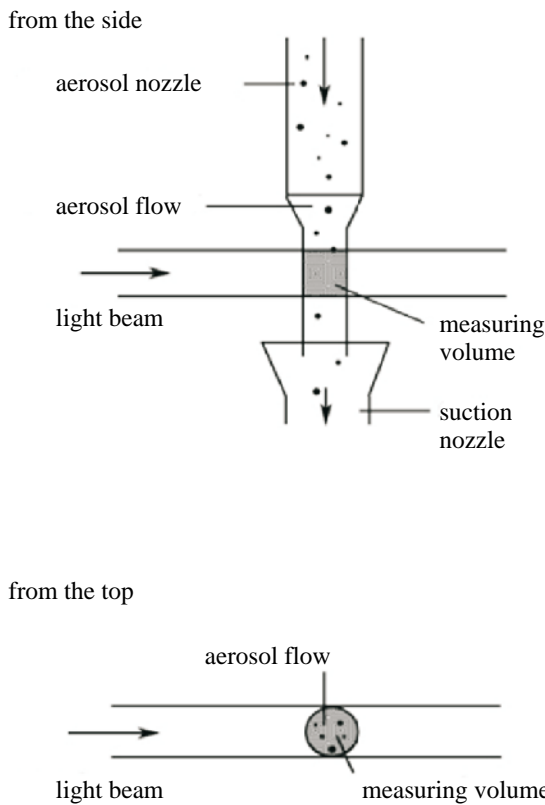
aerosol flow

light beam   measuring volume

Figure 7:
Measuring principle: laser beam

The light intensity of a laser light beam is distributed Gauss-shaped over the beam diameter (figure 8).

A particle at the border of the laser beam scatters substantially fewer light than an equally large particle in the center of the laser beam. This so-called border zone error has been already known since 1970 and is described in (Helsper C. 1981, Blattner J. 1995, Mölter L. et al. 1995). This error can be minimised also by an aerodynamic focussing of the aerosol beam.
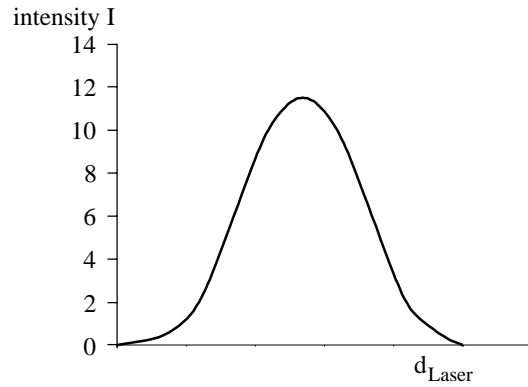
intensity I

d_{Laser}

Figure 8:
Schematic representation of the intensity distribution of the laser beam (Gauss-shape)

If an optical measuring volume limitation is selected in order to minimise e.g. the effect of the Gauss distribution of a laser beam, then a further border zone problem arises. In figure 9 an optical measuring volume limitation is represented at which the problem of the border zone error can be made clear. A particle which is lighted only to 50% in the border zone scatters only half of the light of an equally large particle which is in the measuring volume center. Thus, the border zone error leads to the fact that particles are measured too small. In filter testing this leads to the fact that the separation efficiency is measured better than it really is because the fine parts of the particle size spectrum in the raw gas are measured too high.

from the side

aerosol channel

light beam

measuring volume

from the top

aerosol channel

light beam
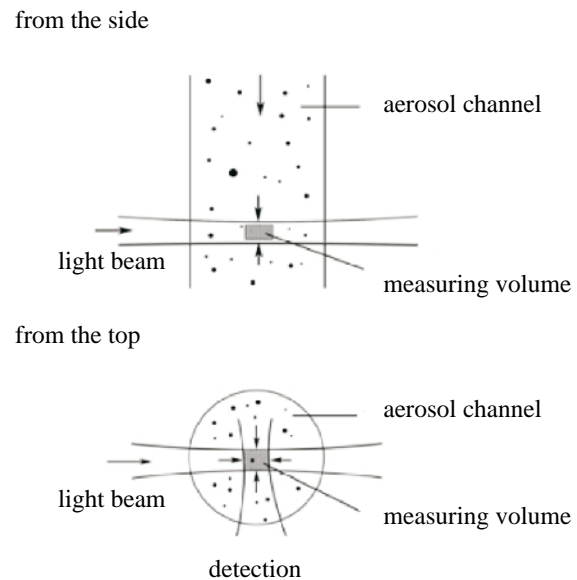
measuring volume

detection

Figure 9:
Measuring principle: optical volume limitation, 90° scattered light detection

Figure 10 shows through the example of monodisperse test aerosols that the size of the border zone error is dependent on the particle size. The wider is the particle size distribution to be measured, the larger is also the border zone error.
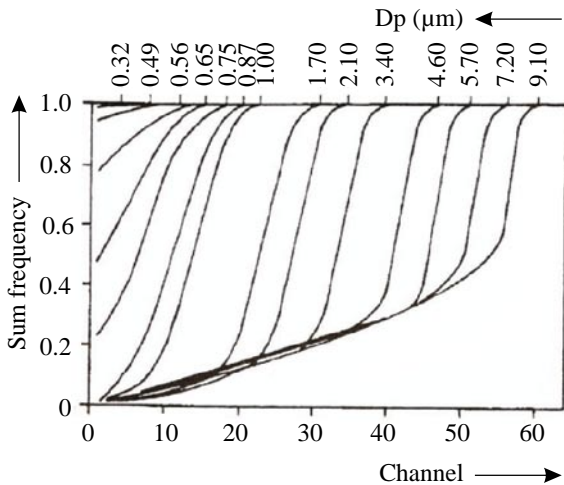

Figure 10:

Border zone error at optical measuring volume limitation (sum distribution of different mono-disperse aerosols)

Source: Helsper 1981 (Diss.)

4.2.2 Coincidence

One speaks about coincidence error if there is more than one particle at the same time in the measuring volume. If e.g. a laser beam diameter amounts to 1 mm, then one can measure with it maximally in a concentration of 1 000 particles per cm³ with negligible coincidence error, since, theoretically, the particle distance amounts here to 1 mm (table 1). Several particles in the measuring volume supply a higher scattered light impulse. Therefore the coincidence-afflicted particle measurement leads to two errors: The particles are measured too large and the concentration too low (Raasch J. et al. 1984, Szymanski W. W. 1996, Mölter L. 1995). At the conversion of the number distribution into the volume distribution these errors affect particularly strongly. In filter testing this leads to the fact that the separation efficiency is measured worse than it really is.

Thus, measurements without border zone error and with coincidence detection are an important precondition for an accurate and reliable filter testing.

5 Particle measurement without border zone error and with coincidence detection

The new **white-light-aerosol-spectrometer system we-las®** has a clear calibration curve due to the white light source and the 90° scattered light detection (figure 3). Six different calibration curves for different refractive indices can be supplied with the welas® if desired. With the optical set-up of the system and its patented T-shaped measuring volume, with which it can be measured practically without border zone errors, a clear particle size determination with very good size resolution and very good classification accuracy is ensured (Lindenthal G. et al. 1998, Keusen G. 2003).

The measuring chamber is optionally heatable in order to avoid cross sensitivities and changes of particle size as a function of the relative humidity – an important point, because by a change of the relative humidity from approx. 40 % to 90 % e.g. hydrophilic particles such as NaCl particles can increase to around the factor 2 (Ebert E. et. al. 2002).
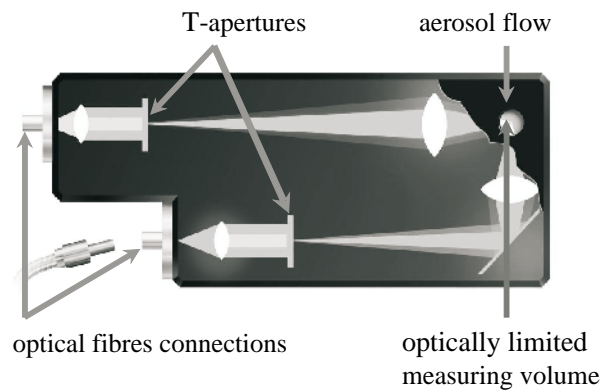

Figure 11:

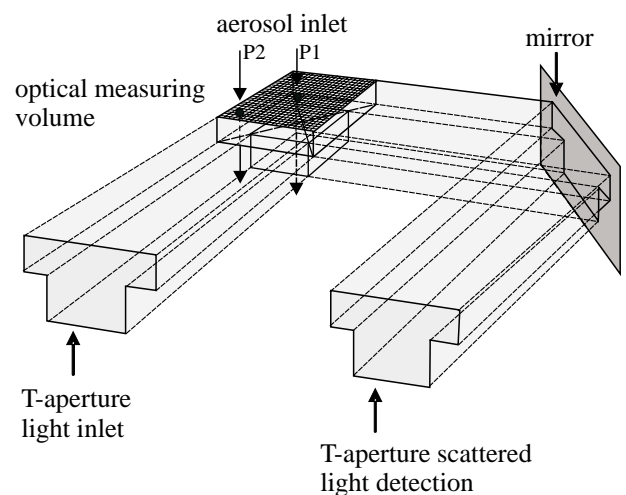Cross section through the welas® sensor

Figure 12:

Three-dimensional T-shaped measuring volume

In figure 11 one can see the compact set-up of the welas®-sensor. White light is injected over optical fibres into the aerosol sensor and focused with a T-aperture in a T-shaped way in the measuring volume. The scattered light is ob-

served over a T-aperture in an angle of 90° to the incident light. One receives a three-dimensional T-shaped measuring volume by the T-shaped light beam and the T-shaped observation level (figure 12). Since the aerosol is sucked with a vacuum pump through the sensor, one knows the runtime between inflow and outflow of the particles into the measuring volume.

5.0.1 No border zone error due to T-aperture technology

Figure 13 shows different particle positions in the T-shaped measuring volume as well as the corresponding scattered light impulse.

The pulse width analysis is used beyond that also for co-incidence detection.

5.0.2 Coincidence signal by means of T-aperture technology

If several particles fly at the same time through the measuring volume (figure 14), then one can easily imagine that the impulse height is higher than at only one particle of comparable size. Without coincidence detection the particles would be measured too large and the concentration too low.
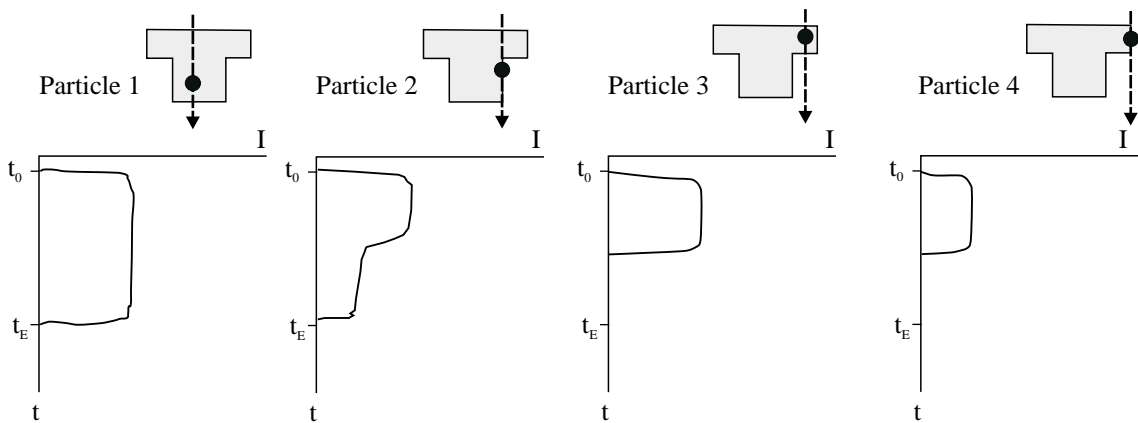

Figure 13:

Border zone error correction of the white light aerosol spectrometer welas®

Particles, which pass both the upper and the lower part of the measuring volume in a central place, generate a rectangular scattered light impulse as represented in case 1 of figure 13.

Case 2 represents a particle, which is still completely seized in the upper, larger part of the measuring volume, but is subject to a border zone error in the lower part of the measuring volume. The corresponding scattered light impulse shows a step-decrease with the passage of the particle from the upper to the lower part of the measuring volume. This particle is included with the higher impulse height into the evaluation.

In case 3 a particle is illuminated and seized measurement-technologically only in the upper part of the measuring volume. The signal evaluation recognizes this by the shorter impulse duration and rejects this impulse.

In case 4 a particle at the border of the upper part of the measuring volume is illuminated only to 50%. In this case the particle is measured around 50% too small. The measuring instrument rejects the signal of case 4, since the running time is too short.
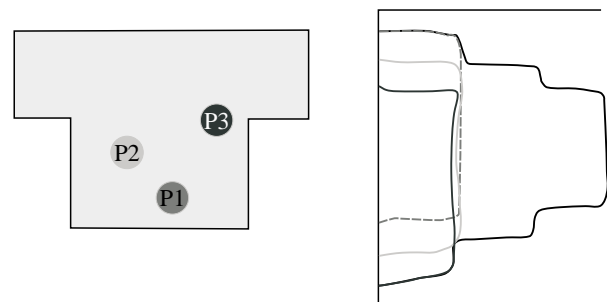

Figure 14:

Coincidence detection: particle flow through the optical T measuring volume and evaluation of the signal height and signal length

At the welas®-system (figure 14) the coincidence error is detected by the runtime measurement (the impulse is too long) and indicated by an acoustical and/or optical warning signal. Only a coincidence free particle measurement allows a reliable particle size and particle number determination of the aerosol. The user is responsible to use in accordance with the measuring task a particle measuring

instrument with the correct measuring volume size in order to measure as coincidence-free as possible. Due to the patented modular set-up of the welas®-system one can select depending upon measuring problem the optimal sensor with the optimal measuring volume size (border length 100, 200 or 300 µm) concerning the particle concentration to be measured (table 2).

Table 2:

Particle size range and maximum concentration range of the welas®-systems

	welas® 1100	welas® 1200	welas® 2100	welas® 2200
measuring ranges [µm]	0.18 – 40	0.18 – 40	0.3 – 40	0.3 – 40
concentration				
Cmax [p/cm³]	10^5	10^4	10^5	10^4

5.1 Evaluation of the scattered light signals

The evaluation of the scattered light impulses is done with the fundamental formulas of the error calculation and/or of the statistics known in the technology. The scattered light

generated by the single particles supplies at the same time information about the number (single particle analysis) and the size of the particles, whereby the height of the scattered light impulse is a measure for the diameter and the number of impulses is a measure for the quantity of particles.

The better are the classification accuracy and the resolution of a particle measuring instrument, the narrower can be selected the characteristic category. Therefore, at the welas®-system the characteristic categories can be selected very closely. In principle, 4096 size classes are available for evaluation. The size classes are summarised into 32 channels per decade. The user can have the size distributions indicated in 32, 16, 8 or 4 size classes at the PC.

Due to this high resolution, with the welas® 1100 even tri-modal particle size distributions of highly concentrated droplet aerosols $d_p < 2$ µm can be measured as represented in figure 15. Here, this concerns the oil mist of a cooling agent lubricant.

For the representation of the particle size distribution neither complicated mathematics nor intransparent algorithms are used. The particles are assigned directly to the size classes (figure 15). Thus, e.g. the cumulative distribution is calculated according to the following formula:
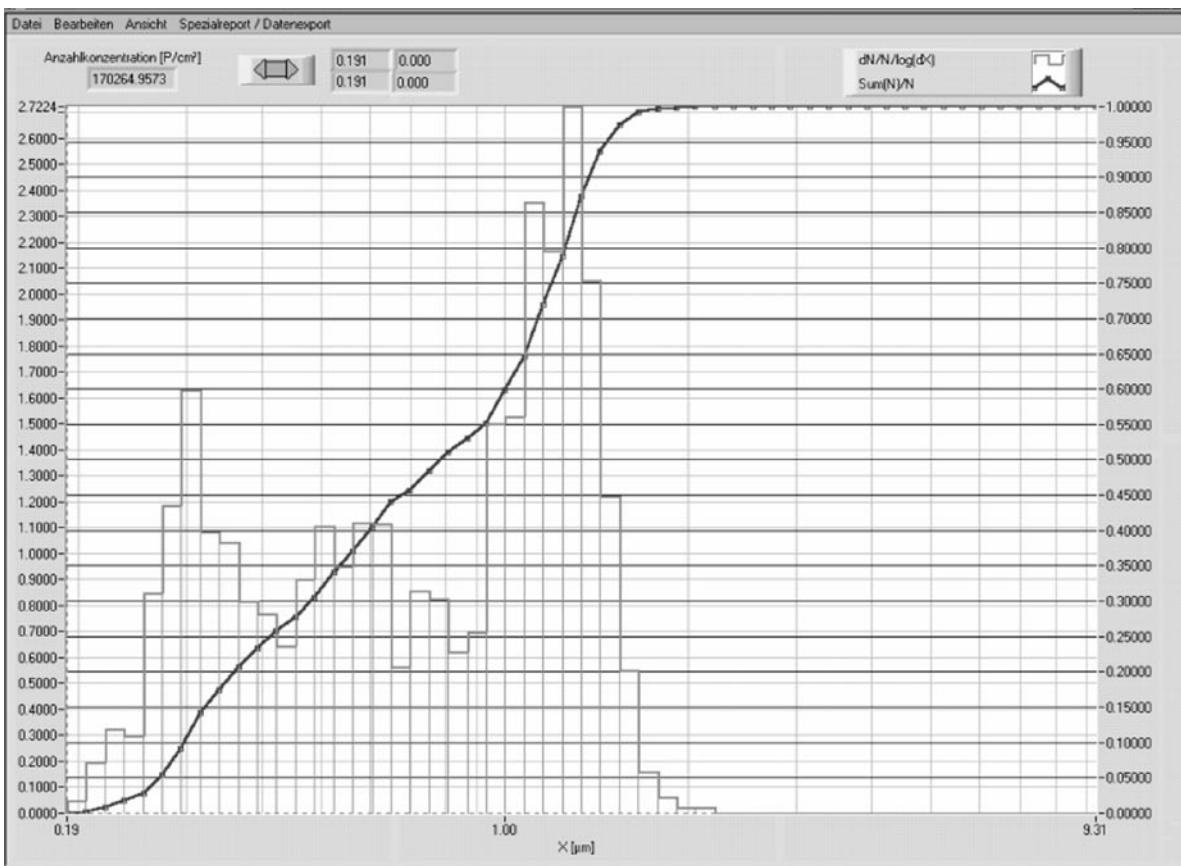

Figure 15:

Tri-modal particle size distribution

Cumulative distribution $Q_r(x)$

The following is valid formally mathematically:

$$Q_r(x) = \frac{\text{quantity q of measured particles} \leq x}{\text{total quantity of particles } q_{ges}}$$

$$q_r(x) = \frac{dQ_r(x)}{dx} \qquad Q_r(x') = \int_{x_{min}}^{x'} q_r(x)dx$$

$$Q_r(x_i) = \frac{\sum\limits_{i=1}^{n} q_i}{q_{ges}}$$

Quantity type: $r = 0$: number
$r = 1$: length
$r = 2$: face
$r = 3$: volume

x = particle size
r = quantity measure

Calculation of the density distribution $q_r(x)$:

$$q_r(x) = \frac{\text{quantity } \Delta q \, (dq) \text{ of the measured particles in the interval} \Delta x \, (dx)}{\text{total quantity of the measured particles } q_{ges} \cdot \text{intervall width } \Delta x \, (dx)}$$
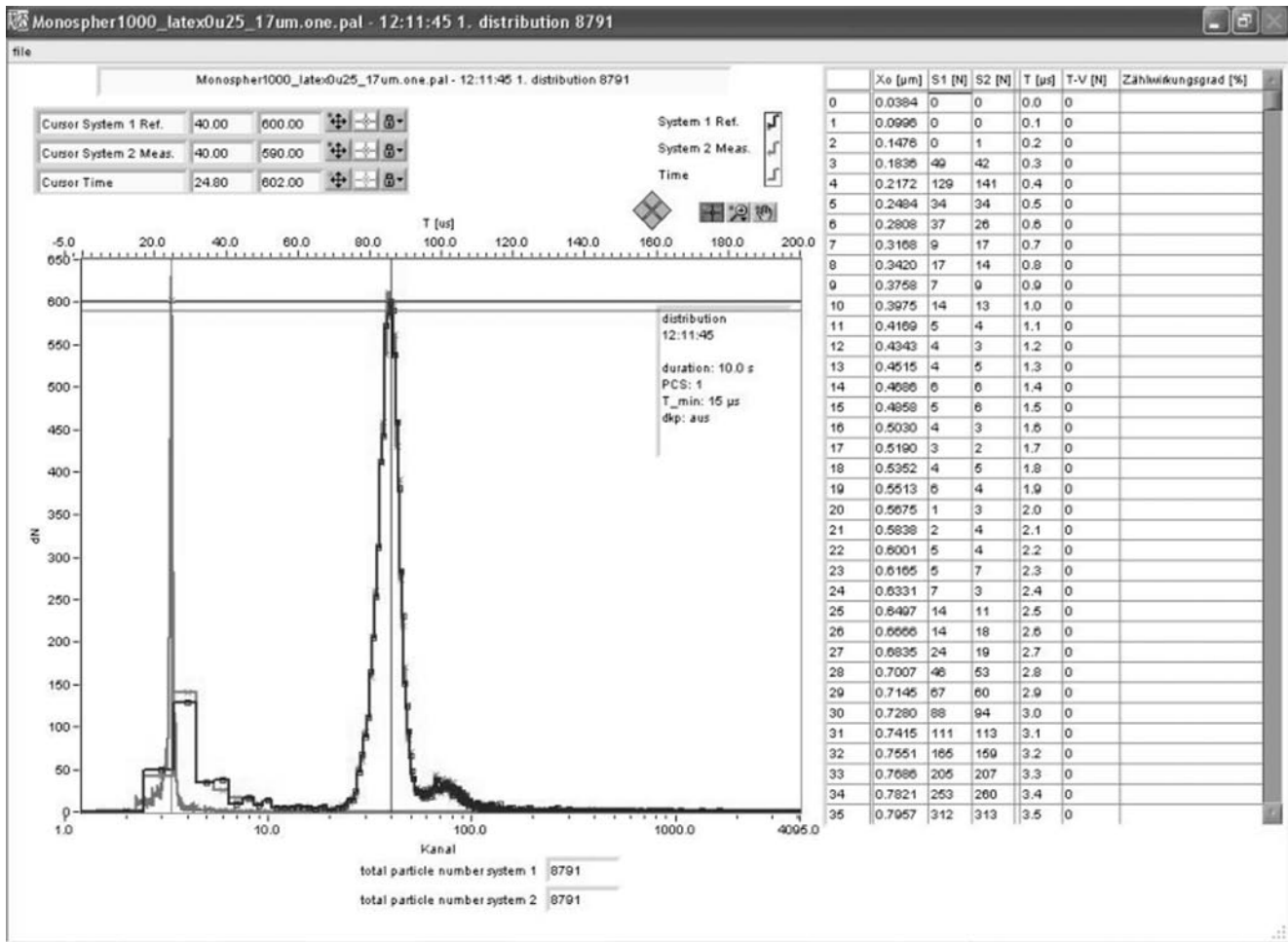

Figure 16:

Raw data analysis in the welas® software

5.2 Calibration

It was already mentioned how important is the calibration of a particle measuring instrument for a clear comparison of measurement results. Possibilities for the generation of test aerosols are represented in (Hochrainer S. 1998, Helsper C. et al. 1989, Peters C. et al. 1991).

Optical aerosol spectrometers are calibrated with latex (m = 1.59). One measures with such methods the scattered light equivalent diameters related to latex.

In the following, the importance of the correct calibration procedure will be shown considering as example the particle size characterisation of the aerosol spectrometer welas®.

As described in chapter 5, at the welas®-system – due to the evaluation of the flying time of the particles through the T-shaped measuring volume – all scattered light impulses are rejected automatically, whose evaluation with conventional measuring instruments would cause a border zone error. Due to the same technology, measurements in coincidence are indicated optically and/or acoustically.

For these reasons, the evaluation software of the welas® offers an analysis of the raw data concerning the particle size and particle velocity distribution as represented in figure 16.

The condition of the exact concentration determination is the accurate size of the measuring volume which is determined with a tolerance of ± 1.5 %.

Figure 16 shows the raw data saved during a measurement. One measured quasi monodisperse SiO_2-particles with a scattered light equivalent diameter of 0.87 µm related to Latex.

On the Y-axis the number of particles is represented. On the lower X-axis the raw data channels (raw size classes) are shown, on the upper X-axis the flying time in µs. In table of figure 16 one can read the corresponding values.

Since the welas®-system is supplied, depending upon application, with differently large measuring volumes and differently highly adjustable volume flows, the respective minimum permitted flying time T_{min} must be set by computer.

From the indication of the mean flying time of the particles and the length of the measuring volume one can clearly determine the mean particle velocity in the measuring volume for monosphere (figure 17).

$$\bar{v}_{particle} = \frac{L_{measuringvolume}}{\bar{t}_{particle}}$$

$$\dot{V}_{measuringvolume} = A_{measuringvolume} \bullet \bar{v}_{particle}$$

$\bar{t}_{particle}$: *mean flying time of particles through the measuring volume*

$\bar{v}_{particle}$: *mean velocity of particles through the measuring volume*

$\dot{V}_{measuring volume}$: *volume flow in the measuring volume*

$A_{measuring volume}$: *passage surface of measuring volume*

$L_{measuring volume}$: *length of measuring volume*

Only the accurate determination of the particle velocity in connection with an accurate indication of the passage surface in the measuring volume leads to an accurate calculation of the measured particle concentration.

$$c_n = \frac{N_{analysed particles} \bullet t_{measuring time}}{\dot{V}_{measuring volume}}$$

c_n = *number concentration*

$N_{analysed particles}$ = *number of measured particles*

$t_{measuring time}$ = *measuring duration*

The raw data distribution is used also for the exact adjustment of the sensor with monodisperse particles. This calibration concerning the particle size can be accomplished by the customer himself.

5.2.1 Characterisation of the device parameters – border zone error, resolution and classification accuracy

The characterisation of the welas® 1200, which is equipped with a cuvette, was accomplished in the Leibniz-Institut für Troposphärenforschung e. V. (IFT) in Leipzig, Germany. In the figures 18 and 19 the measuring data of three different latex aerosols are represented. The latex suspensions (0.2 µm; 0.34 µm; 0.5 µm) were generated in each case in a separate Palas® latex generator and were supplied directly to the welas® system.

It can be clearly taken from the run of the cumulative distribution in figure 19 that besides latex there are also finer particles in the aerosol. As it is well known, one does not receive an exclusive mono-disperse aerosol when nebulising latex suspensions, since the stabilisers of the suspension are also nebulised and measured. This fact supplies an explanation for the fines recognisable in figure 19. However, it can not be excluded that the fines represented in the curve could also be due to a remainder border zone error of the measuring system.
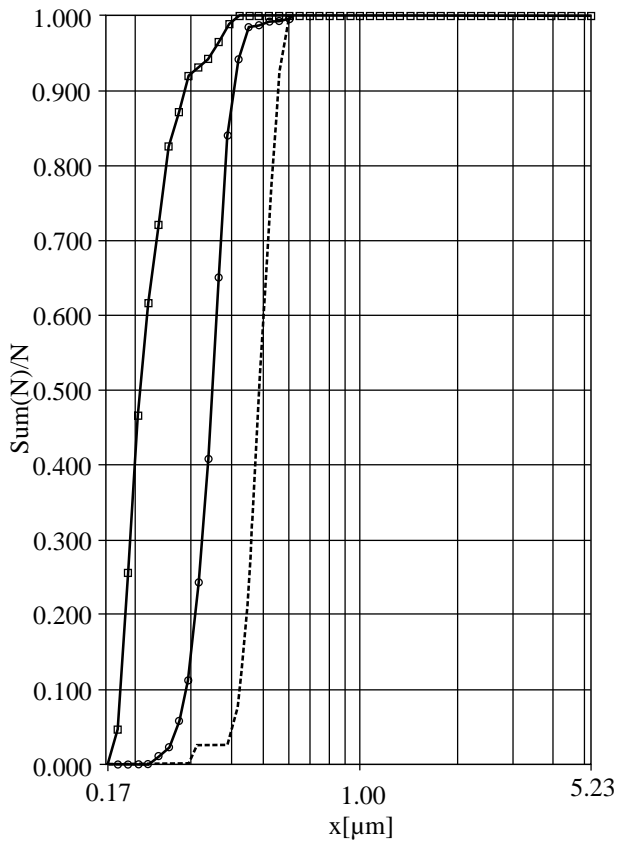
Cursor System 1 Ref.	40.00	600.00			
Cursor System 2 Meas.	40.00	590.00			
Cursor Time	24.80	602.00			

mean flight time in µs

Figure 17:

Raw data analysis – detail

Figure 18:

Latex aerosols dp = 0.2; 0.34; 0.5 µm with fines separated by a DMA

Figure 19:

Latex aerosols dp = 0.2; 0.34; 0.5 µm with fines nebulised by the stabilisers of the suspension

For the clear characterisation of the aerosol spectrometer, the three different latex aerosols were led through a company-owned Differential Mobility Analyser (DMA) of the IFT. The DMA was switched between the latex generator and the welas®-system. In figure 18 it can be clearly recognised that the fines of the aerosol were separated by the DMA and that they are therefore not measured and indicated by the welas®-system. Thus, it can be concluded that the T-aperture-technology supplies practically border-zone-error free measurement results. Therefore, the curve in figure 19 was measured correctly with the welas®, since the latex aerosol was soiled with fines. The curves show clearly the high resolution and the good classification accuracy of the welas®-system. One recognises the resolution by the rate of rise of the cumulative distribution. The classifying accuracy is read off from the d_{50}-value of the cumulative distribution.
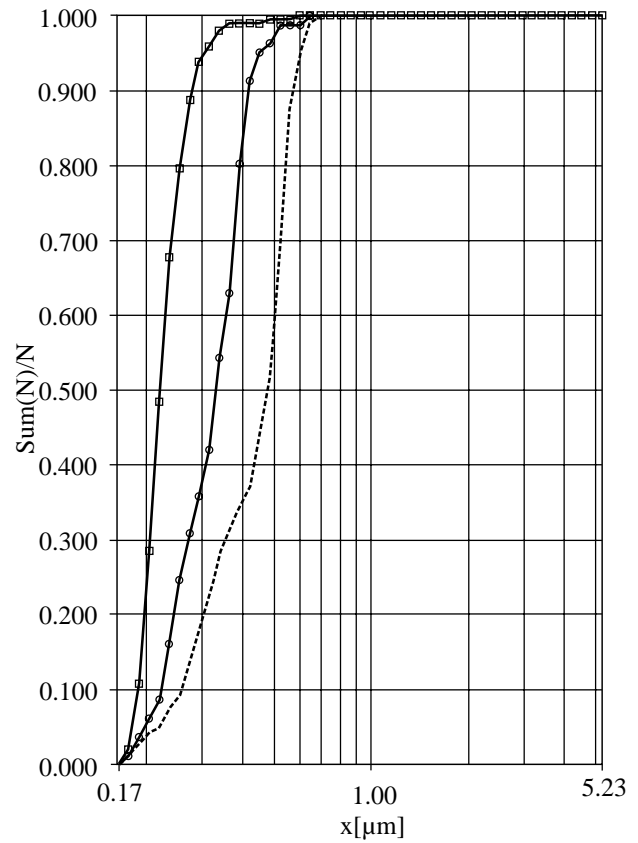
6 Summary and future prospects

Counting optical aerosol spectrometers are suitable for the meaningful particle size and particle number determination; they must however fulfil certain technical conditions. Among them there are the high resolution and the good classification accuracy, i.e. a measuring method which has a clear calibration curve and measures without border zone errors. Coincidence-free measurements are ensured by coincidence detection.

The insight into the theoretical basics of the counting optical particle measurement explains the significance of the device parameters and the importance of a clear calibration curve. The explanation of the operational principle of optical measuring methods demonstrates the advantages of a measurement with white light and 90° scattered light detection compared to laser light or forward scattering.

The white light source and the 90° scattered light detection provide a clear calibration curve. A specific feature is the patented T-aperture-technology: The T-shaped measuring volume projected and limited with white light allows for the first time a border-zone-error free measurement.

In addition, the measuring system possesses coincidence detection. The heatable measuring chamber and the optical fibre technology offer special advantages, too. Due to the modular set-up the sensors with the optimal measuring volume size can be selected depending upon application. Beyond that, the welas®-system offers an innovative specific feature which pays off particularly with special applications, for example measurements in strongly varying or very high raw gas concentrations or measurements in badly accessible environments: For the first time one can measure with two sensors at one control unit quasi simultaneously at different places in different concentrations.

The evaluation of the scattered light signals generated by the particles is done by software tested in practical applications. This software does not only allow different representation possibilities of the particle size distribution, but also records the environment conditions such as air pressure, relative humidity, temperature and velocity, which were measured with other sensors. The data can be recalled also over the internet.

An important advantage of the welas®-system is - in particular also with view to the future - the possibility to combine the measurements with other measuring methods (Mölter L. et al. 2004).

7 References

Baron P., Willeke K. (2001). Aerosol Measurement – Principles, Techniques and Applications, Chapter 15 and 16. Wiley-Interscience Publication. 2nd edition, New York 2001.

Binnig J., Meyer J., Kasper G. (2005). Integration of cyclones and an optical particle counter into a filter tester VDI-3926 / Type1 to characterize PM2.5 emissions from pulse-jet cleaned filter media. In: Gefahrstoffe - Reinhaltung der Luft 65/ No. 4, 2005.

Blattner J. (1995). Filtrieren und Separieren. Fraktionsabscheidegradbestimmung mittels Streulichtpartikelzähler mit einem optisch begrenzten Messvolumen. Frankfurt/M. 1995.

Ebert E. et. al. (2002). Environmental scanning electron microscopy as a new technique to determine the hygroscopic behavior of individual aerosol particles. In: Atmospheric Environment 36 (2002), S. 5909-5916.

Friehmelt R. (1999). Aerosol-Messsysteme. Vergleichbarkeit und Kombination ausgewählter online-Verfahren. Diss. 1999.

Friehmelt R., Büttner H., Ebert F. (1998). On-line Measurement of Particle Sizes and Number Concentrations: Establishment of a Combined Measuring System. In: Proceedings of Partec 1998.

Helsper C. (1981). Bestimmung, Simulation und Korrektur des nichtidealen Übertragungsverhaltens klassifizierender Aerosolmessverfahren. Diss. Universität Duisburg 1981.

Helsper C., Mölter L. (1989). Erzeugung von Prüfaerosolen für die Kalibrierung von optischen Partikelmessverfahren nach VDI 3491. In: Technisches Messen – tm 56 (1989), Nr. 5, S. 229-234.

Hemmer G., Umhauer H., Kasper G., Berbner S. (1999). The Separation Efficiency of Ceramic Barrier Filters Determined at High Temperatures by Optical Particle Size and Concentration Measurement. In: High Temperature Gas Cleaning Vol. II, ed. by A. Dittler, G. Hemmer, G. Kasper, Karlsruhe 1999.

Hess W. F., Matschke C. (2005). Comparison of two Scattered Light Particle Counters in practical application in a dust removal test stand. In: Filtrieren & Separieren International Edition, May 2005.

Hinds W. C. (1999). Technology – Properties, Behaviour and Measurement of Airborne Particles, Chapter 16. Wiley-Interscience Publication, 2nd edition, New York 1999.

Hochrainer S. (1998). Quality Assurance in Particle Measurement Technology and Filter Test Technology: Calibration Systems for Particle Counters and Particle Size Analysers. In: Advances in Filtration and Separation Technology, Vol. 12 (1998).

ISO 13323-1: Determination of particle size distribution – single particle light interaction methods, Part 1: Light interaction considerations

ISO/CD 21501-1: Light-scattering aerosol spectrometer

ISO/DIS 21501-4: Light-scattering air-bone particle counter for clean spaces

Keusen G. (2003). Anwendung der Streulicht-Partikelgrößen-Zählanalyse zur Charakterisierung von Tropfenkollektiven bei der Dieselöl-Hochdruckzerstäubung. Diss. 2003.

Lindenthal G., Mölter L. (1998). New White-Light Single-Particle Counter – Border Zone Error nearly eliminated. In: Proceedings of Partec 1998.

Mie G. (1908). Beugung an leitenden Kugeln. In: Annalen der Physik 15, 1908, S. 377-445.

Mölter L. (1995). In-Situ Particle Size Analysis at high Concentrations. In: Proceedings of Partec 1995.

Mölter L., Lindenthal G. (1995). How to measure the fractional grade efficiency correctly for ISO 9000. In: Filtration & Separation, Sept. 1995.

Mölter L., Schütz S. (2003). Accurate Particle Counting of Vacuum Cleaner Emissions. In: Filtration & Separation No. 9/ 2003.

Mölter L., Kessler P. (2004). Partikelgrößen- und Partikelanzahlbestimmung in der Außenluft mit einem neuen optischen Aerosolspektrometer. In: Gefahrstoffe – Reinhaltung der Luft 10 (2004).

Peters C., Gebhardt J., Roth C., Sehrt S. (1991). Test of high sensitive laser particle counters with PSL-Aerosols and CNC reference. Journal of Aerosol Science, Vol. 22, Suppl.1, 1991.

Raasch J., Umhauer H. (1984). Errors in the Determination of Particle Size Distributions caused by Coincidence in Optical Particle Counters. In: Particle & Particle Systems Characterization No. 1/ 1984.

Szymanski W.W. (1996). Applicability of Optical Particle Counters for Determination of Filter Efficiencies. In: Proceedings of International Symposium Filtration and Separation of Fine Dust, 24.-26. April 1996, ed. by W. Höflinger, Vienna 1996.

Umhauer H. (1989). Streulicht-Partikelgrößen-Zählanalyse als Methode für In-Situ-Messungen in Gas-Partikel-Strömungen. In: Technisches Messen tm 56 (1989) 5 VDI 3489, Particulate Matter Measurement.

Umhauer H., Berbner S. (1995). Optical In-Situ Size Analysis of Particles Dispersed in Gases at Temperatures of up to 1000°C. In: Proceedings of Partec 1995.

VDI 3489, Particulate Matter Measurement.