B2 Measurement of Particle Properties

Journal:	*Wiley-VCH Books*
Manuscript ID:	VCHMR-32449-073
Wiley - Manuscript type:	Handbook of Combustion
Date Submitted by the Author:	07-Apr-2009
Complete List of Authors:	Gaderer, Matthias; Technical University of Munich, Institute for Energy Systems
Abstract:	
Note: The following files were submitted by the author for peer review, but cannot be converted to PDF. You must view these files (e.g. movies) online.	
Measurement of particle properties.doc	

HANDBOOK ON COMBUSTION

Measurement of particles properties: concentration, size distribution, density

Dr.-Ing. M. Gaderer[1], Dipl.-Ing. R. Kunde[2], Dipl.-Ing. Ch. Brandt[2]

[1] Technical University of Munich, Institute for Energy Systems, Boltzmannstr. 15, D-85748 Garching, gaderer@tum.de

[2] Bavarian Center for Applied Energy Research (ZAE Bayern), Walther-Meißner-Str. 6, D-85748 Garching, kunde@muc.zae-bayern.de

1 Content

2 Notation

PM … particulate matter
STP … standard temperature and pressure

3 Abstract

For the investigation of particular emissions on combustion processes various methods are available. A survey of typical measuring methods of particle diagnostics on combustion is presented in this chapter.

At the flue gas of combustion units the particle number concentration is measured continuously by using nucleus counters (condensation particle counters – CPC) or light

scattering instruments. The particle mass concentration is typically measured discontinuously by using filtering systems.

Particle size distributions are determined by adding useful fractioning methods to the aforementioned concentration measuring methods.

According to this, size classified particle number distributions or mass distributions may be measured. Typical fractioning methods distinguish between aerodynamic separation on the basis of inertia (impactor, cyclone) and the separation on the basis of the electrical mobility of the particles.

By comparing the size distributions according to the aerodynamic diameter with that of the mobility diameter the effective density of the particle collective may be calculated.

A dilution system is usually required for continuous measurement of particle concentrations on combustion flue gases. It is needed for the reduction of the dew point (avoiding condensation) and for adapting the concentration to the instrument range. Ejector diluters, porous tubes and dilution tunnels are typically used on investigation of stationary combustion processes.

For the analysis of the particle collective it is essential to draw a representative sample. In order to avoid errors on the sampling, certain criteria like isokinetic sampling or transport losses have to be respected.

4 Introduction

A suspension of particles and droplets in the size range of 0.001 µm and 100 µm in a surrounding gas phase is referred to as aerosol. The total mass of particles and droplets is indicated as particulate matter (PM).

The total of all particles in the ambient air is called Total Suspended Particulate Matter (TSP). It is split into two modes, the coarse mode and the fine mode. Coarse mode means larger particles with more than 1 µm in diameter. Fine mode are particles smaller than 1 µm.

Coarse mode particles typically originate from abrasion (wheels, brakes, etc.) and road dust re-suspension, from handling of bulk cargo, agricultural work and last but not least other industrial processes.

Fine mode particles typically originate from particle emissions of industrial processes, vehicle emissions, energy production and house heating. They usually originate from all kinds of combustion processes with solid or liquid fuels .

Particles smaller than 10 µm are almost not precipitated in the nose. Particles smaller than 1 µm (PM1) may trespass deeply into the lung and reach the alveoli. They may stress the human lung and finally cause respiratory disease [1] because they are breathable [see also chapter A19, Volume 1].

Hence the particle fraction PM10 is commonly used for the definition of immission limits in Europe. PM10 means all particles with an aerodynamic diameter smaller than 10 µm according to a separation efficiency of 50 % in the sampling system. PM2.5 (smaller 2.5 µm) and PM1 (smaller 1 µm) are also used.

5 Measurement techniques for particle measurement

In this section general particle measurement techniques are shown. They are common for all kinds of analyzers described in the following sections.

Usually a partial sample flow of the flue gas (aerosol) is taken for analysis. This sample flow is drawn from the stack through a nozzle by a vacuum pump. By that the whole measurement setup is under negative pressure. The particles follow the aerodynamics through the whole setup until they reach the particle analyzing tool for example a filter, impactor or any device. Afterwards the sample flow is dried, cooled and its volume flow rate, pressure and temperature are measured. Some applications require a dilution before the aerosol probe enters the particle analyzer. Therefore different techniques are typically used on analyzing the flue gas of combustion processes.

For additional and more detailed information on aerosol measurement see [2] or [15] for example.

5.1 Common remarks

The most important property of particulate matter from (biomass) combustion is still the mass concentration. Thereby it is distinguished between total mass concentration and mass concentrations of special particulate matter fractions like PM10 or PM2.5 for example.

The second important property of an aerosol is its number concentration. It is usually measured online with optical counters. For particle number counting condensation prevention is essential.

The third important property of a particle is its size. In an aerosol there is a huge amount of particles with different sizes which cause a size distribution, which is a fundamental property of an aerosol.

Since particles usually are not spherical, their size is described by equivalent diameter. Therefore the properties of regularly formed particles are compared to not regularly formed real particles.

5.1.1 Equivalent Diameter

Aerodynamic diameter

The aerodynamic diameter corresponds to the diameter of a spherical particle of unit density (1 g/cm³) that has the same gravitational settling velocity as the particle in question.

It is practical for particles > 0.5 µm because their motion is intended by inertia forces.

Diffusion equivalent diameter

Particles < 0.5 µm follow the Brownian diffusion and are characterized by the diffusion equivalent diameter. This corresponds to the diameter of a spherical particle of unit density (1 g/cm³) that has the same diffusion rate (Brownian motion) as the particle in question.

Mobility diameter

The electrical mobility equivalent diameter corresponds to a diameter of a unit-density (1 g/cm³) spherical particle moving with the same velocity in an electric field as the particle in question.

The Stokes' law describes the constant motion of a particle in a gaseous fluid. The force interacting to a particle depends on the viscosity of the surrounding fluid, the particles diameter and its velocity. The relation of velocity to acting force is called mobility. This relationship is only valid for the particle's diameter is much larger than the mean free path. For smaller particles, the Cunningham correction factor has to be used.

Optic equivalent diameter

The optic equivalent diameter is defined as the diameter of a calibration particle that has the same optical scattering characteristics to light as the particle in question.

5.1.2 Common Units

Mass concentrations usually are given in the raw measured units: weighing gives a mass in the unit of milligram (mg) for example. This mass is related to the sample volume, given in cubic meter (m³). So the raw unit for mass concentration is mg / m³. Comparing of different results is easier, if the mass is related to normal cubic meter. If the fuel amount that is converted into energy in the combustion during a time interval is known as well as its heating value, the particle mass concentration may be related to the fuel energy amount. Common units are mg / kWh or mg / MJ.

Instruments for measuring particle number concentration are analyzing a small partial sample volume in the range of cubic centimeter, so number concentrations usually are given in particles per cubic centimeter (# / cm³) STP.

Size distributions usually are displayed on a logarithmic diameter scale because the data range on the diameter-axis is very small but very large (from only a few up to billions) on the y-axis. To get a nice looking shape of the distribution the number displayed on the y-axis has to be

related to the logarithm of the corresponding diameter. So the unit of the y-axis is $dN / d\log D_p$. N means number, D_p means particle diameter. Thus only distributions with the same diameter unit are comparable, otherwise the distributions are shifted by the factor from the exponent of the unit. For example, one distribution is given by diameter in µm, the other in nm. So they are shifted by factor 3, because 1 µm is 10^3 nm.

In the following, only number distributions are presented because they are usually the raw measuring value. Volume or mass distributions for example are easily calculated from the number distribution.

5.1.3 Difficulties

Comparing results of different measuring methods based on different physical or chemical properties is complicated. Even the German guideline VDI 3491-1 [4] makes a distinction between 19 different particle diameters. Combined with different dimensions (e.g. number, volume, mass) a lot of different methods for presenting size distributions are possible.

No method covers the entire size distribution, no diameter definition can be used for the whole one. Usually a volume equivalent diameter is calculated from the mobility diameter by using a form factor. Still all particles have different forms and the real form is unknown. Also the form factor is unknown and so far it is usually based on assumption.

5.1.4 Sampling

In addition to the measurement method itself the way of sampling has an important influence on the measurement result. A sampling system consists of the probe, a transport line and storage volumes if needed to handle short sampling times and long measurement times. To collect and measure representative samples, care has to be taken of the following issues:

Homogeneity

The location of sample extraction has to be chosen in a way to obtain a representative sample if sampling from pipes with an inhomogeneous flow regime or any other poorly mixed volume. Standards for probe grid arrangements for sample taking from large ducts have been defined by ANSI [3] and VDI guideline 2066 [5]. VDI guideline 2066 recommends four measuring points per square meter and a sufficient maximum of 20 measuring points in the cross sectional plane of a duct.

Isokinetic sampling

The inlet conditions of the sampling probe have to be set in a way that a uniform aspiration efficiency over the particle diameter range of interest is achieved. Samples have to be taken isokinetic, i.e. in the angle and velocity of the examined gas flow, to avoid de-mixing of the

aerosol by inertial forces. Sub-isokinetic sampling leads to an overestimation of the concentration of large particles, super-isokinetic sampling underestimates the larger size fractions. The following Figure 1 shows this relation.

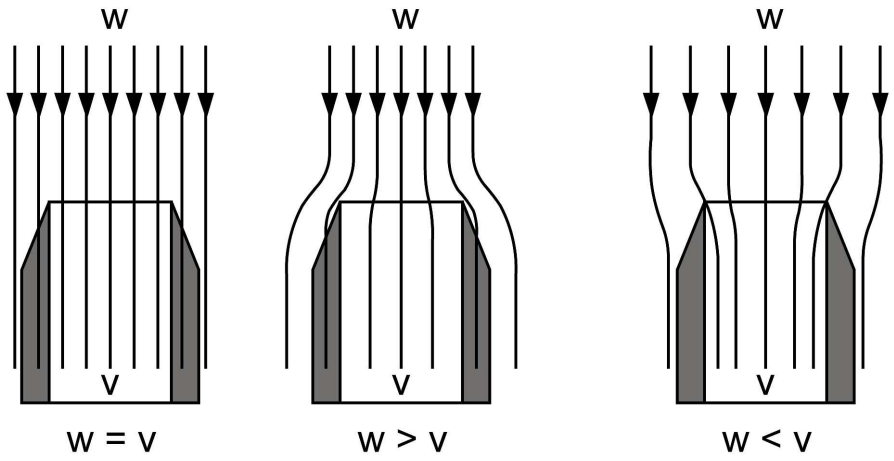


Figure 1: isokinetic (left), sub- (middle) and super-isokinetic sampling (right),

with w = flow velocity and v = extraction velocity

If the combination of available measurement devices and nozzles doesn't allow isokinetic sampling, super-isokinetic sampling is to be preferred. An isokinetic sample error increases with particle size, but is not of great concern for particles smaller than 1 – 2 µm [2].

Transport losses

The sample transport line may contain bends, inclines, contractions, storage containers like bags and other elements. The flow may be laminar or turbulent. On the transport line from the probe inlet to the measuring device, particles may be deposited by gravitational, inertial and diffusion effects. The aerosol characteristics may also be changed by particle agglomeration or re-entrainment of deposited particles. Loss mechanisms for each part of the sample transport have to be characterized as good as possible. Poorly understood loss mechanisms with only little documentation in literature should be avoided when designing the transport line.

Transport losses can be described by the particle size dependent transport efficiency for each flow element and loss mechanism. The transport efficiency is the number of particles of a certain size leaving the flow element divided by the number of particles that entered the flow element. The total transport efficiency for a given particle size is the product of all occurring transport efficiencies [2]:

$$\eta_{transport} = \prod_{flowelements} \prod_{mechanisms} \eta_{flowelement,mechanism}$$

formula 1: transport efficiency [2]

Humidity

Humidity can distort the measurement through condensation on or evaporation from the aerosol particles, nucleation or loss of particles into condensate at the tube walls. Appropriate measures can be setting the temperature of the sampling path over the dew point or lowering the dew point by dilution with clean dry air. In general, the influence of humidity on the measurement has to be kept low by minimizing the retention time of the sample in the sampling system.

Calibration

Whenever possible, the measurement system has to be calibrated fully assembled under measurement conditions. A calibration of component sections at measurement conditions may often be sufficient. If a calibration can only be arranged at conditions different from the intended measurement, reliable models and correlations from literature need to be applied to predict the performance of the measurement setup under working conditions.

For sampling in large power plants it is also referred to volume 2, chapter B19.

5.1.5 Dilution techniques

There are several common dilution techniques for the measuring of aerosols from combustion processes.

Depending on the favored effects during dilution the dilution air might be heated or cooled. Hot and dry dilution air avoids condensation depending on its temperature and the dew point temperature of the flue gas. Cool dilution air enforces condensation in order to find particular volatile organic compounds (VOC).

Table 1: Overview on common dilution techniques

	type	**dilution range**	**remarks**	**references**
Dilution tunnel	stationary	typically up to 10	high volume flow air	[16], [32]
Ejector diluter	portable	typically 10, in cascades 100 or more	pressurized air	[17], [18]
Porous tube diluter	portable	typically up to 10	high pressure drop	[17]
Rotating disc diluter	portable	typically up to 200	no gravimetric measurements	[7], [19]

Dilution tunnel

Originally from the particle measurement in the automotive industry the dilution tunnel offers a simple way for flue gas dilution. Either the entire flue gas stream or only a partial sample stream are diluted by adding cool air. Typical dilution ratios are from 3 to 10. Depending on the designated dilution ratio and the amount of the sample stream a lot of dilution air is necessary.

For example, the total flue gas amount of 25 kW biomass combustion is about 75 m³/h at 13 % O_2. If a dilution ratio of 10 is desired, 750 m³/h dilution air is necessary. So in this case ambient air will be used for dilution, because its particle load is some magnitudes smaller than in the flue gas. So the error will be small. If taking only a small partial sample flow it might be possible to use particle-free and dry dilution air.

One advantage of a dilution tunnel is that unsteady burnout conditions are smoothed. So one gets an average particle concentration without sharp peaks.

However, dilution tunnels are only used in laboratories with a fixed installation due to their large dimension.

The dilution ratio has to be calculated for example by the ratio of tracer gas concentrations in the non diluted and diluted flue gas (CO_2). Therefore two high resolution instruments are required. Dilution tunnels often are self made.

Dilution tunnel standards for particle sampling from biomass combustion are known (e.g. Norwegian standard NS 3058-2, in [32]). There is also an European guideline containing construction details of dilution tunnels but only used for diesel engines [16]. The determination of emission factors e.g. for wood stoves within different countries from measurements in dilution tunnels were shown by Nussbaumer [32].

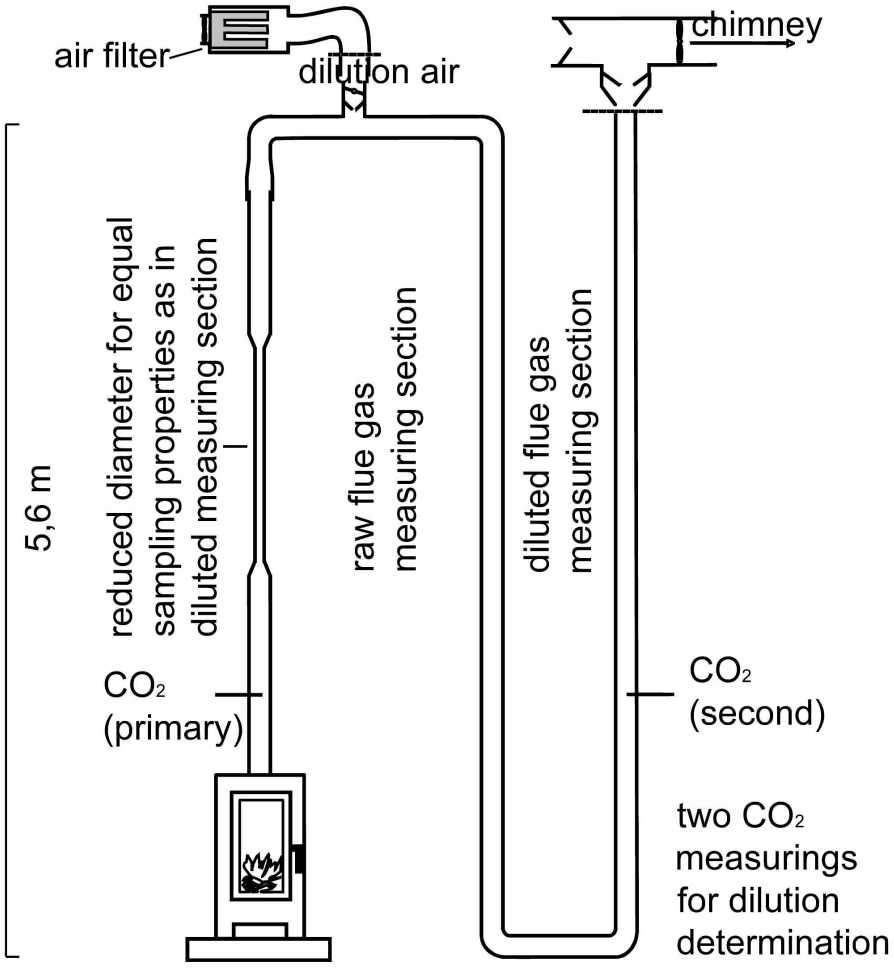


Figure 2: schematic diagram of a dilution tunnel with solid fuel single room firing, dilution air T-fitting and top down sampling line at the laboratory of the TFZ (technology and advancement center) Straubing, Germany.

Ejector diluter

Another dilution technique is the ejector diluter. In the ejector nozzle pressurized dilution air (particle-free, dry, pre-heated or cooled) is accelerated and according to the principle of the venturi nozzle flue gas is aspirated. In an ejector diluter there is a highly turbulent flow mixing the partial sample flow with dilution air. Only particles smaller than a few microns can pass the ejector diluter because they are less inertial than larger particles. The flow rate depends on the pressure of the dilution air, the dilution ratio is independent of these pressures and fixed by the geometry and the gas temperatures.

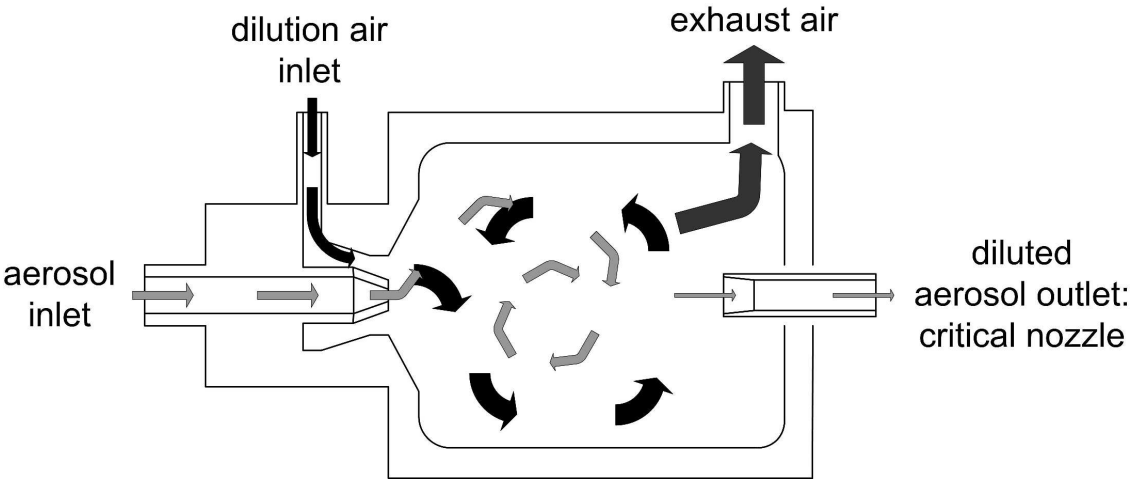


Figure 3: function chart of an ejector diluter

A typical dilution ratio of an ejector diluter is 10, cascading several diluters is practice to reach higher dilution. More detailed information about ejector diluters can be found e.g. at Dekati Ltd. [17] or Palas GmbH [18].

Porous tube diluter

For example in multi stage dilution systems porous tubes (first dilution stage) are combined with an ejector diluter (e.g. DEKATI FPS4000^{TM} [17]). A porous tube can be described as a tube with a lot of radial drills. Also porous materials such as sintered ceramics are in use.

The partial sample flow through the tube is diluted by dilution air which is supplied from the outside through the porous material (holes). The dilution ratio depends on the flow rates of both the aerosol sample and the dilution air. The pressure drop of the porous material constrains the range of usage.

Advantages of porous tube diluters are no particle losses because the sample flow has no contact with the tube wall. The porous tube diluter

Rotating disc diluter

Rotating disc diluters are not yet used for particle measurements on biomass combustion analysis. They are used in the automotive research and manufactured e.g. by TSI Inc. [21], Matter engineering [19] or Cambustion Ltd. [24]. They reach dilution ratios up to 200 depending on the rotation speed.

Advantages are a small construction and a constant dilution ratio, but rotating disc diluters are not applicable for gravimetric analysis. [7]

This system allows a high and adjustable dilution ratio. The temperature of the dilution system and the temperature of the dilution air can be adjusted separately. It works well for particles below 1 µm; for larger particle losses due to deposition it causes high errors. The flow rate of the diluted gas is restricted to a few liters per minute.

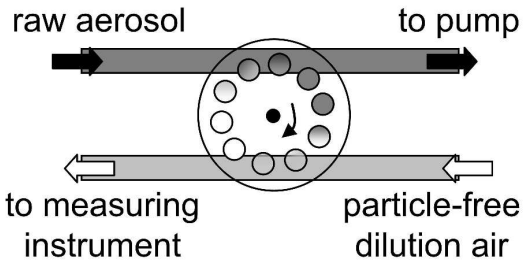


Figure 4: schematic diagram of a rotating disc diluter

Preventing nucleation and condensation

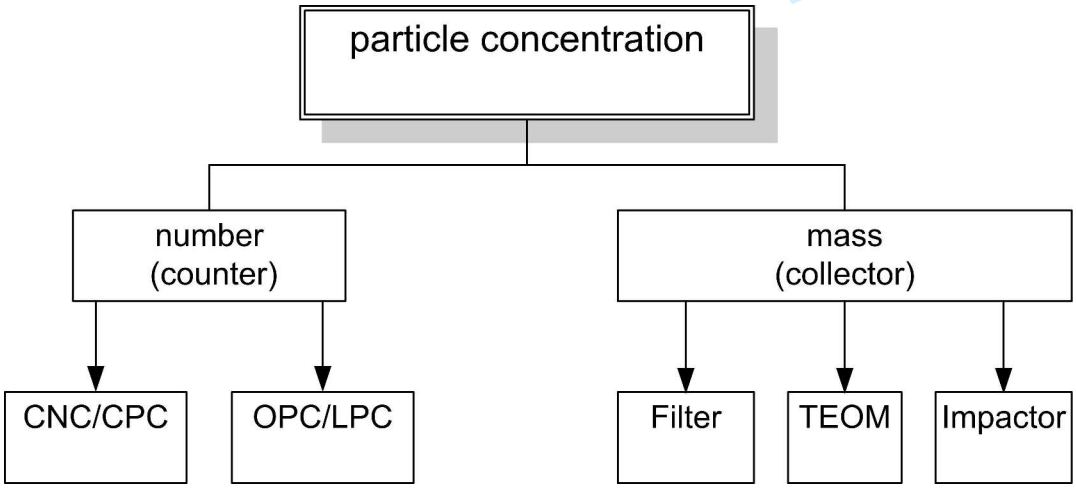
If hot sampling is necessary it is recommended to use a two-stage dilution system. The first stage has to be heated and diluted with hot air. This decreases the partial pressures of volatile components and so condensation and nucleation is prevented.

At the second stage it is possible to dilute cold air (e.g. room temperature) without condensation (at least water condensation). If needed, the secondary dilution is carried out with cold air to cool the sample. Therefore an adequate controller is recommended. Otherwise, some particles may be lost onto the transport lines by thermophoresis.

The dilution air for the first diluter and the first diluter itself should be heated approximately up to the temperature of the aerosol sample. Usually diluters are calibrated at normal conditions so during hot dilution the dilution ratio needs to be calibrated separately.

5.2 Concentration measurement

The most important property of particulate matter from (biomass) combustion is still the mass concentration. Thereby it is distinguished between total mass concentration and mass concentrations of special particulate matter fractions like PM10 or PM2.5 for example. In the following section, several useful techniques for concentration measurement are described in more detail.



CNC: condensation nuclei counter; CPC: condensation particle counter; OPC: Optical particle counter; LPC: Laser particle counter; TEOM: Tapered-element oscillating microbalance

Figure 5: overview of particle measurement techniques commonly used for concentration measurement on combustion analysis and presented in this article.

5.2.1 Gravimetrical mass concentration measurement

Gravimetrical mass concentration measurement is the most important method of particle measurement of combustion processes. It is a discontinuous measuring method and results give an average of the measuring period.

Measuring systems for determination particle mass concentration are impactors and filters. They are used either directly in the hot flue gas stream (in stack) or outside (out stack). In order to avoid condensation or nucleation out stack systems have to be heated (see section 5.1.4). For gravimetrical mass concentration measurement only a partial sample flow of the flue gas is investigated. It is directed through a filtering or deposition system where all particles or only particles of a defined size class are deposed. Finally the mass concentration is calculated from the aerosol volume that is led through the system and the deposited particle mass.

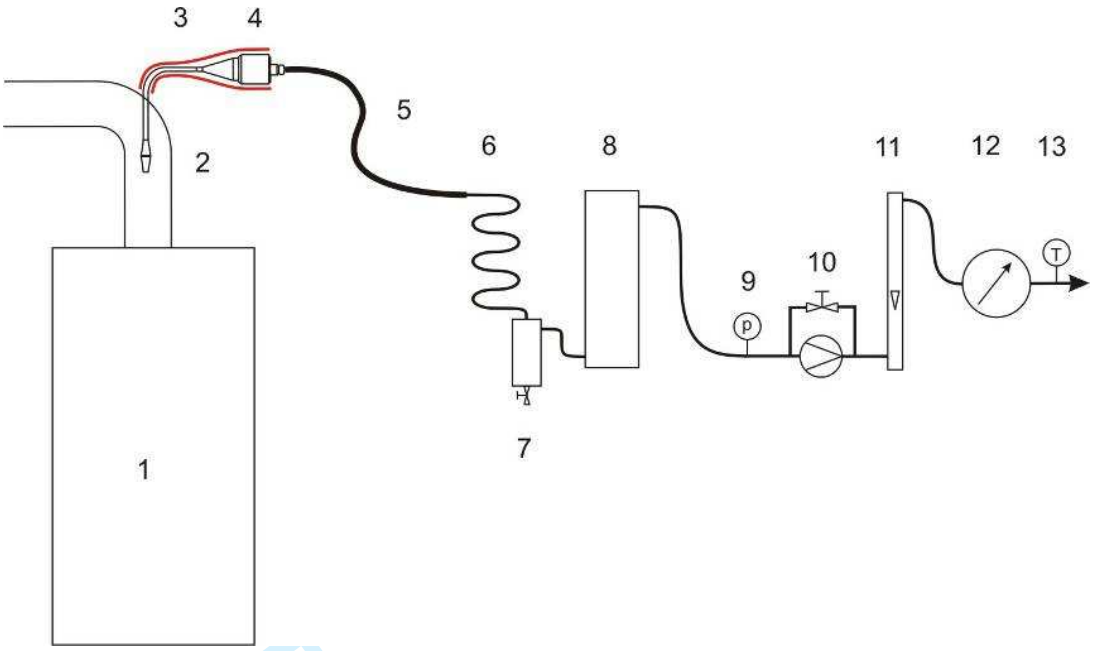
To determine the particle mass the filter or deposition system is weighted before and after being loaded with particles.

The advantage of these measuring methods is that particles can be analyzed microscopically, chemically or with any other method after the gravimetric measurement.

The mass alteration caused by deposited particles is small compared to the mass of the filters so pre- and post processing of the filters or deposition elements (drying, acclimating) is required and one possible source of error especially when using hygroscopic filter materials.

Filters or impactors can be used in stack as well as out stack. On small scale biomass combustions (typically up to 50 kW thermal energy) the diameter of the flue gas tube is usually between 100 and 200 mm. Filter holder or impactors are about 60 to 80 mm in outer diameter, so in stack is not reasonable at this flue gas tube diameter.

The typical setup for out stack operation of filters or impactors is described in detail in the German VDI guideline 2066 part 1 [5], Figure 6 shows the schematic diagram.



1 combustion, 2 sampling probe for isokinetic sampling, 3 electrically heated tube, 4 electrically heated filter / impactor holder, 5 flexible tube, 6 cooling, 7 condensation chamber, 8 drying (silica gel), 9 manometer, 10 vacuum pump with bypass valve,
11 variable area flow meter, 12 bellows-type gas flow meter, 13 thermometer

Figure 6: schematic diagram of out stack setup for gravimetric particulate matter measurement.

5.2.1.1 Filter

Several filtering techniques differing in the geometrical form of the filter are available. The operating principle of collecting particles is the same in all these techniques:

Before measuring the empty filter has to be conditioned and weighted at defined climatic states (temperature, humidity). Conditioning is typically baked out at temperatures higher than expected at the measurement so that there are no volatile components on the filter material that evaporate during the measurement. At the measurement the aerosol is directed through the filter while its volume is measured. Afterwards the filter is weighted again at the same climatic states as at the weighing at the beginning avoiding errors caused on temperature and humidity. Depending on the required result in some cases the filters are baked out again before weighing so that only non-volatile components of the dust are included. Good practice for good weighing results are given in section 5.2.1.3.

Planar filter

For planar filters typically glass or quartz fiber filters with diameters from 30 to 100 mm are used.

For example a schematic diagram of the filter holder for planar filters regarding to VDI guide line 2066 [5] is shown in Figure 7.

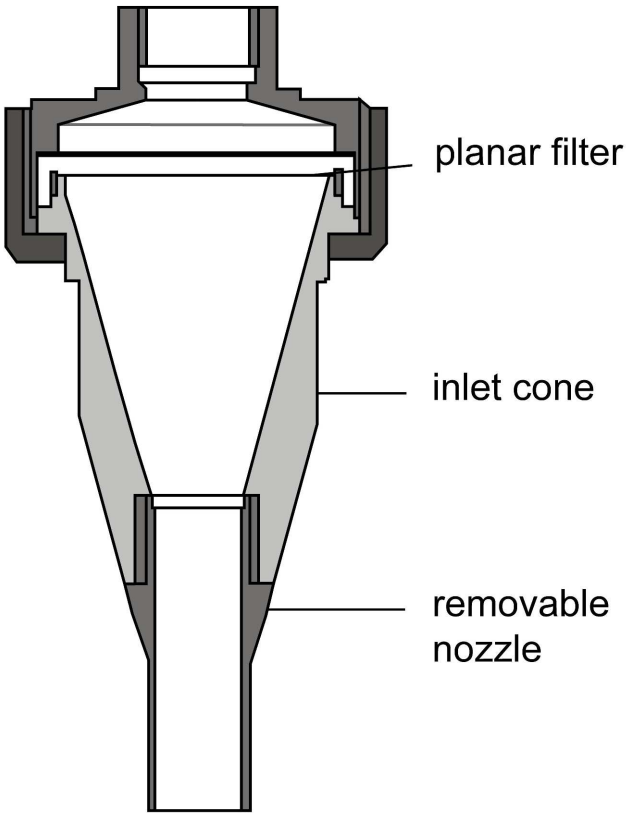


Figure 7: schematic diagram of a filter holder for planar filters regarding to VDI guideline 2066 [5].

Filter Cartridge

Instead of planar filters also filter cartridges are commonly used in appropriate filter holders.

A practical application in Germany for example is the recurring check of wood fired combustions by chimney sweepers.

A previously conditioned and weighted filter cartridge is loaded with particles during 15 minutes. Therefore 135 liter flue gas (STP) are extracted from the flue gas tube and piped through a filter cartridge. Afterwards the filter cartridge is back-weighted and hence the separated particle mass is calculated.

Simultaneously the mean flue gas composition is determined during the measurement period by collecting the sample flue gas within a plastic bag and afterwards by measuring the composition of this produced mean gas mixture.

This mean gas mixture is needed for the calculation of the residual oxygen content where the particle concentration is related on [6]. Filter conditioning and weighing is done central in one German chimney sweeper institute which leads to about four weeks between measurement and result.

Filter holder for fiber tamped casings (design Stroehlein)

Another filtering method is already used: fiber material (for example quartz fiber wool) is tamped in a casing the aerosol is conducted through and the particulate matter is deposited. The whole tamped casing has to be weighted before and after. Additionally a planar backup filter can be integrated downstream.

5.2.1.2 Impactor

Generally, impactors are instruments for collecting aerosol particles by utilizing the inertia. Thereby the aerosol is accelerated by deflection of the stream flow direction (Figure 8).

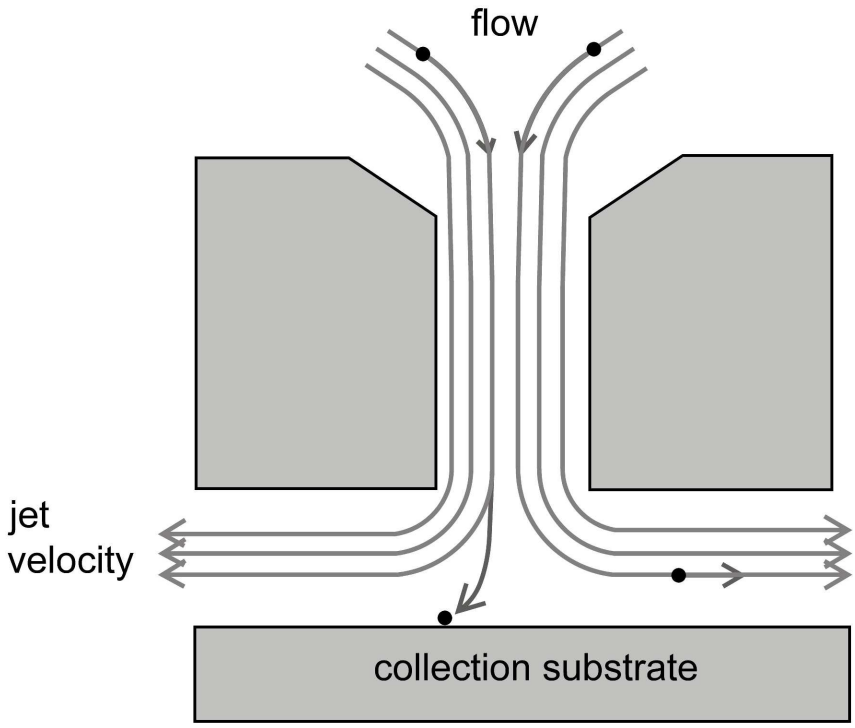


Figure 8: aerosol behavior due to deflection of the stream flow direction

The centrifugal force evolved from the deflection causes the particles to be unable to follow the stream flow and carry them out to the collecting area. There they deposit on a collection substrate. As in filtering systems the particle mass could be determined by weighing the collecting substrate.

The probability of such an inertia separation increases with the mass of the particle. So depending on the impactor geometry (deflection) and the flow velocity there is a typical mass respectively size of particles that can only just follow the flow.

Impactors classify particles into two fractions. Particles that are bigger than this typical size are deposited and smaller ones can follow the flow. For this reason impactors are used for measuring size distribution (see section 5.3.1).

The probability that one particle of a specific size deposits and stays in the impaction area is a statistic problem. It is described as the collection efficiency. Figure 9 gives an example of a collection efficiency curve depending on the aerodynamic particle diameter which can also be specified by the dimensionless Stokes number.

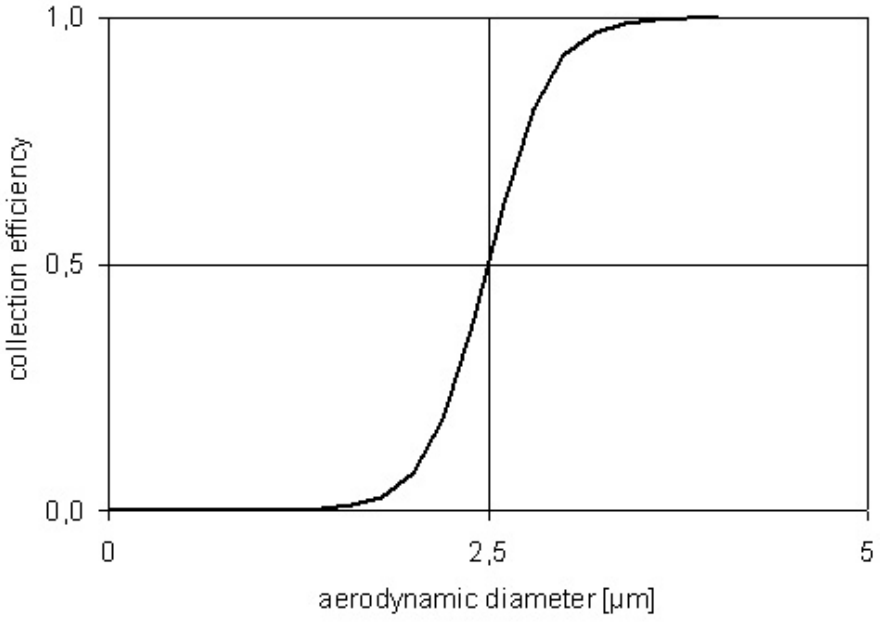


Figure 9: example of the collection efficiency of an impactor (d50 = 2.5 µm)

The function of the collection efficiency could be approximated as a saltus function. The diameter 50 % of the particles are separated on is called cut of diameter and is used as a border between deposited and non deposited particles.

Changes of the flow rate, temperature and pressure of the aerosol modify the flow conditions in the impactor and have an influence on the cut point. This should be avoided and therefore they have to be controlled during measurement. [15]

5.2.1.3 Conditioning, handling and interpretation of filters

The filter conditioning typically happens according to DIN EN 13284-1 T3 [10] paragraph 7.2 to 7.4. There should be a two hour baking out and drying at 180 °C within a drying oven.

Additionally a drying and cooling is done within a desiccator during a minimum of twelve hours. Baking out temperature should always be higher than its application temperature. Thereby all volatile components of the filter substance that evaporate lower than this temperature are removed before weighing. Otherwise some components could evaporate during the measuring and cause mass losses that falsify the measuring. Before weighing, filters have to be equilibrated under uniform conditions in the weighing room. Constant

temperature and humidity is recommended. The weighing of the filters is generally held with an adequate microbalance.

After sampling the particle-loaded filters can be kept within glass Petri dishes. Afterwards, the filters can be baked out as described in DIN EN 13284-1 T3 [10] or analyzed without any thermal post-processing, depending on the type of question. If volatile compounds from the particles are also of interest, baking should be avoided.

If necessary they can also be dried within an desiccator at room temperature.

Subsequently the filters have to be reweighted on the same microbalance under the same conditions as before. Another humidity of the filters would lead to a false mass determination. Thereby a minimum of three weightings is performed during initial weighing and reweighing and the arithmetic average is calculated.

For determination of the collected particle mass the basic weight has to be subtracted from the weight of the loaded filter.

5.2.2 In-situ mass concentration measurement with TEOM

In Tapered-Element Oscillating Microbalance (TEOM) devices aerosol mass is collected on an oscillating collection substrate. Mass changing of this substrate is determined by measuring the changing of its natural frequency.

The active element of a TEOM system is a specially tapered tube consisting of elastic material. So deposed particle mass during time is known so as mass stream of the filtered gas so particle mass concentration could be calculated during time.

Generally, the TEOM represents a continuous weighing. It offers a good time resolution, a sufficient sensitivity and is especially suitable for determination of mass concentration below 5 µg/m³ range. It is usually used for ambient air monitoring and with a suitable dilution system it is also going to be used on emission measurements of combustion processes.

The wide end of the tube is firmly mounted on a relatively massive base plate. The narrow end supports a replaceable collection medium, such as a filter or impaction plate. This tube combined with the collection material forms an oscillating system and it is oscillated during the measurement. Particle-loaded gas streams are drawn through the collection medium (filter), where its particles are deposited. The filtered gas is then drawn through the hollow, typically controlled by an automatic mass flow controller.

However, it is not always directly comparable with the classical gravimetric determination because the instrument has to be operated on a very continuous temperature – generally 40 °C. Despite improvements in gravimetric measurement methods the results are considerably below the values of in-situ measurement. Probably this is due to the relatively big sized nozzle (coming with gravimetric measurement methods) also acts like a separation area for the electrical high-loaded particles behind the separator and thus the measurement result is

influenced. [2], [11]. More detailed information on TEOM also can be found at Thermo Fisher Scientific (TEOM Series) [20].

5.2.3 In-situ number concentration measurements

Following common measurement instruments for in-situ determination of particle number concentration are presented.

5.2.3.1 Condensation nuclei (particle) counter (CNC / CPC)

At this measuring method particles are detected by light scattering or light extinction.

Therefore the aerosol is leaded through a monochromatic light beam that is detected by a photo sensor. Particles of the aerosol scatter respectively extinguish a part of the light and lead to a signal on the sensor. At this method optical properties of a particle collective are crucial for detection. Thereby the optical properties of the particles, the number concentration and the size distribution influence the scattering simultaneous and can not be distinguished.

For certain detection and for eliminating the influences of the particle size and different optical properties they are magnified by condensation. Figure 10 shows the operating principle of a CPC.

At a first step the aerosol is saturated with vapor. Therefore it is lead through a saturator tube where it is in contact with the working fluid. Typical liquids are alcohol (Butanol) or water. In the next step the aerosol saturated with vapor is cooled in the so called condenser tube which leads to a super saturation of the aerosol. Now particles function as nucleation agents and grow by condensation of the vapor onto the particle surface. They grow approximately to the same size (on the order of a few micrometers) with the same optical properties (properties of droplets). In this particle or droplet collective the scattering or light extinction is only influenced by the number concentration so hence it can be used for exclusive determination of the number concentration and is let through the optical detector.

Another advantage of the particle growing is that CPCs can detect particles down to a very small size range. At stable conditions even particles with a size of 1 to 3 nm are detectable. The Typical measuring range is up to 1.0E+8 particles per cm^3 [2]. CPCs are available e.g. from TSI Inc. [21], Grimm [22] or Kanomax [23].

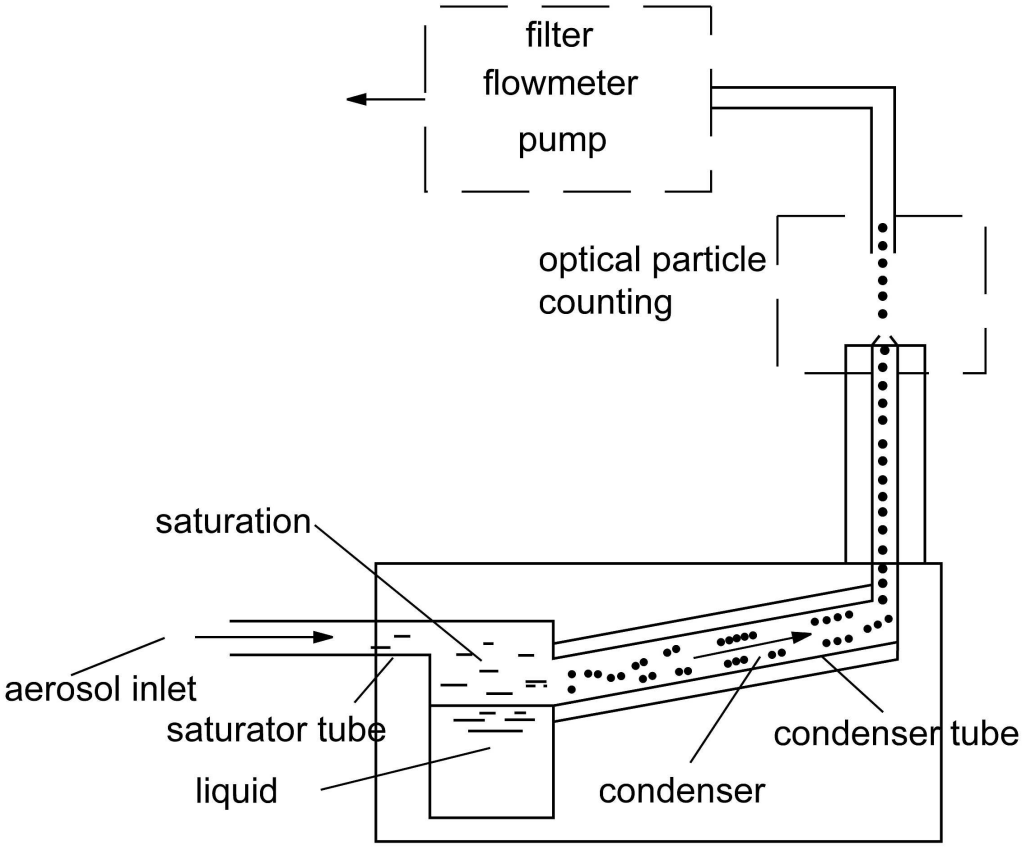


Figure 10: functional schematic of a condensation particle counter (CPC)

5.2.3.2 Optical or Laser particle counters (OPC / LPC)

Photoelectric optical particle counters (OPC) are single particle counters (SPC) based on the theory of light scattering from individual particles.

The OPC represents a quick and efficient sensor. An OPC measures the size and number concentration of aerosol particles in a limited size range by means of light scattering by single particles. Therefore, a stream of aerosol is drawn through a concentrated light beam which is either broadband (white light) or monochromatic (laser or light-emitting diode) source. Light flashes scattered from individual particles are received by a photo detector and converted into electrical pulses. From the count rate of the pulses, the number concentration and from the pulse height the size of the particles is derived. The light power that an individual particle scatters is a function of its size, refractive index and shape [2].

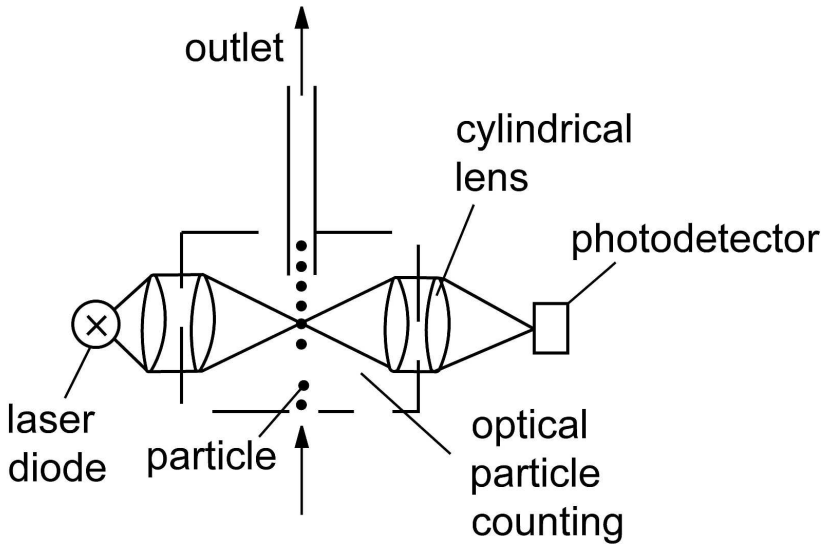


Figure 11: functional schematic of an optical particle counter (OPC)

Important characteristic features of an OPC are its permissible range of number concentration, its sampling flow rate, its sensitivity (lower detection limit) and its size measurement accuracy.

An OPC can be selected as stand-alone instrument with high-speed particle detection technique for obtaining information about individual particles or for determining total particle concentrations.

Using a laser particle counter (LPC) the light scattering of each particle is identified over a range of angles and converted to an electronic pulse that is a complex but principally increasing function of particle size. The light scattering has a complex dependence on the light source, the range of detection angles, the particle size, particle shape and the particle refractive index. As it is usually difficult to predict or compensate particle shape and particle refractive index in real-world situations the sizing capability of OPCs is generally only an approximation [2].

Particle detection by light scattering loses sensitivity in the small size range. Its lower limit is about 0.1 µm under optimum conditions. For detection of particles smaller than 1 µm a CPC is often used to aid by condensational growth of small particles.

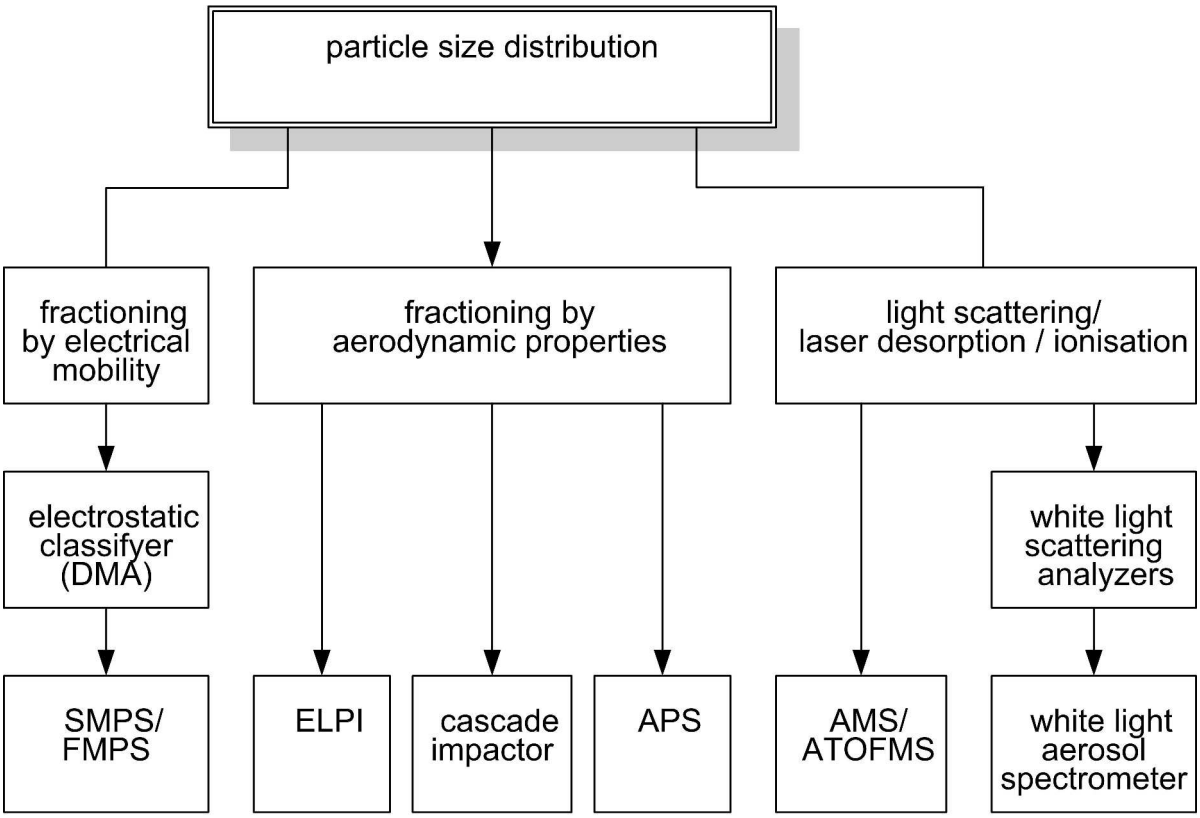
Trends in development are handheld, battery-operated counters with a laser diode as the light source. OPCs are manufactured for example by Climet [25] , Palas GmbH [18] or TOPAS GmbH [26] and are used to measure particles above 0.1 µm in diameter.

For other optical methods, such as soot characterization by laser-induced incandescence it is referred to volume 2, chapter B15 in this handbook. Further, chapter B20, volume 2, deals with ultrafast optical diagnostics of combustion generated nanoparticles.

5.3 Size distribution measurement

Regarding to their size particles show a different performance in flow and in electric fields. In a flow field particles move dependent on their aerodynamic diameter, in an electric field particles move dependent on their mobility diameter (see chapter 5.1.1).

So particles could be analyzed regarding to their aerodynamic properties or their electrical mobility.



DMA: differential mobility analyzer; SMPS: Scanning mobility particle sizer; FMPS: Fast mobility particle sizer; ELPI: electrical low pressure impactor; APS: aerodynamic particle sizer; AMS: aerodynamic mass spectrometer; ATOFMS: Aerosol-Time-of-Flight-mass spectrometer

Figure 12: overview of particle measurement techniques commonly used for size distribution measurement on combustion analysis and presented in this article.

5.3.1 Gravimetric size distribution measurement with cascade impactors

For the gravimetric measuring of size distribution aerodynamic properties of aerosol particles are used for separation into size classes. This is achieved by cascading several impactors with different cut points. Determination of the deposited particle mass on each step, as described in chapter 5.2.1, leads to a size depending mass concentration.

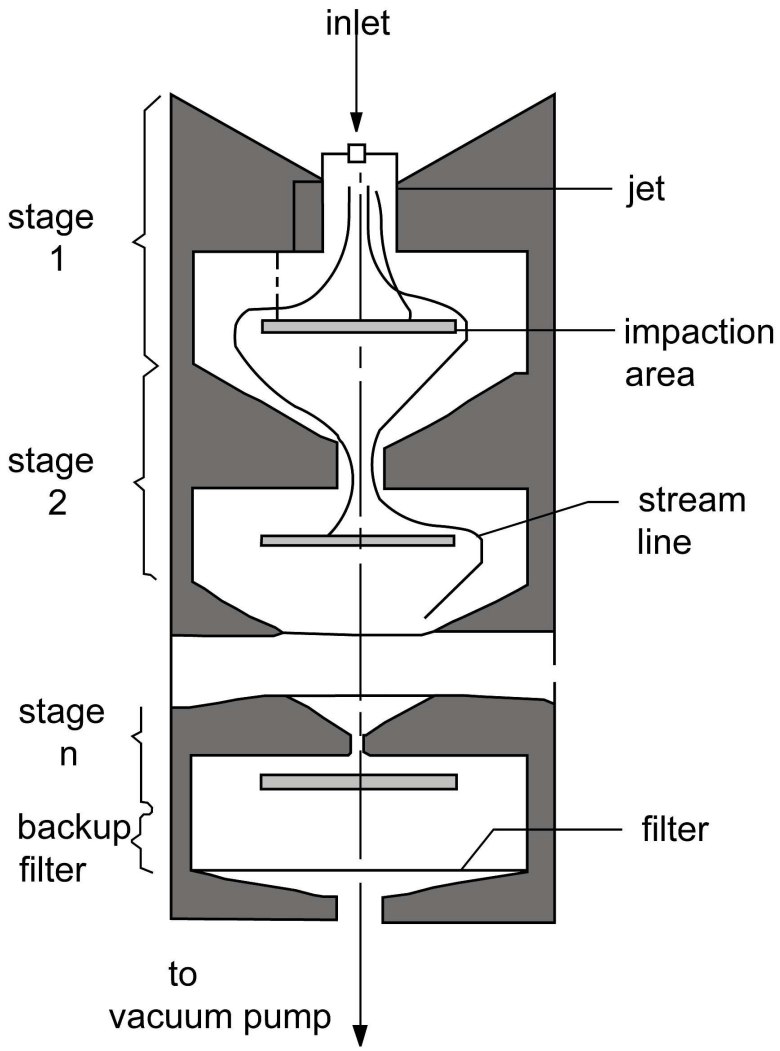


Figure 13: functional schematic of a cascade impactor

Each impactor step separates particles in the size range between the cut point of the previous stage and its own. The separation of more and more smaller particles is reached by increasing the stream flow velocity and the thereby increased inertial effects at the deflection. Flue gas density at atmospheric pressure and usual temperatures limit the separation of particles smaller than approximately 1 µm. Separation to the lower nanometer range is possible by decreasing the pressure in the range of 100 mbar.

The last step of a cascading impactor is performed as a filter that collects the residual particles (backup filter).

Table 2 : Overview on most commonly used cascade impactors

Common name	**Andersen**	**Berner (BLPI™)**	**Cascade impactor of ELPI™**	**JohnAS™**	**Kalman**	**MOUDI™**
References	Andersen Instruments Inc.	Hauke Aeras	Dekati Ltd.	Paul Gothe GmbH Bochum	KÁLMÁN SYSTEM LTD.	MSP Corporation
Number of stages	6, 8	up to 12	12	3	3 x 2	3, 8, 10, 13
Measurement principle and main components	Multi-stage, multi-orifice sampler	Low pressure impactor with critical ejector	Low pressure impactor	Impactor with back-up filter, modular construction	chamber system and circular orifice jet double stages	Many micro-orifice nozzles (up to 2000)
size range [µm]	0.41-17.4 Mark II, 2: 0.41 – 9	0,02 – 20	0.03–10 with filter stage 0.007-10	1.5 – 10	0.3 - 20	0.056 - 18
Max. Stack Temp. [°C]	850	90*/180	< 150	135	220	
Nominal flow rate [lpm]	3 – 30	2 -150 (typ. 25)	10 or 30	17 – 50 (typ. 30)	17 – 43 (typ. 25)	30
diameter impaction area [mm]	70	25	25	50	50	25

5.3.2 In-situ size distribution measurement

In the following section common measurement instruments for in-situ determination of particle size distribution are presented.

5.3.2.1 Electrical low pressure impactor (ELPI)

The ELPI-system of Dekati (electrical low pressure impactor ELPI ™ [17]) combines aerodynamic fractioning with a electrical detection of charged particles. Thus real-time measurement is possible with a reaction time of lower than five seconds within the particle size range between 7 nm and 10 µm.

The system consists of the three components low pressure cascade impactor (12-stage), corona charger and multichannel electrometer. The generally function of a cascade impactor is given in chapter 5.3.1.

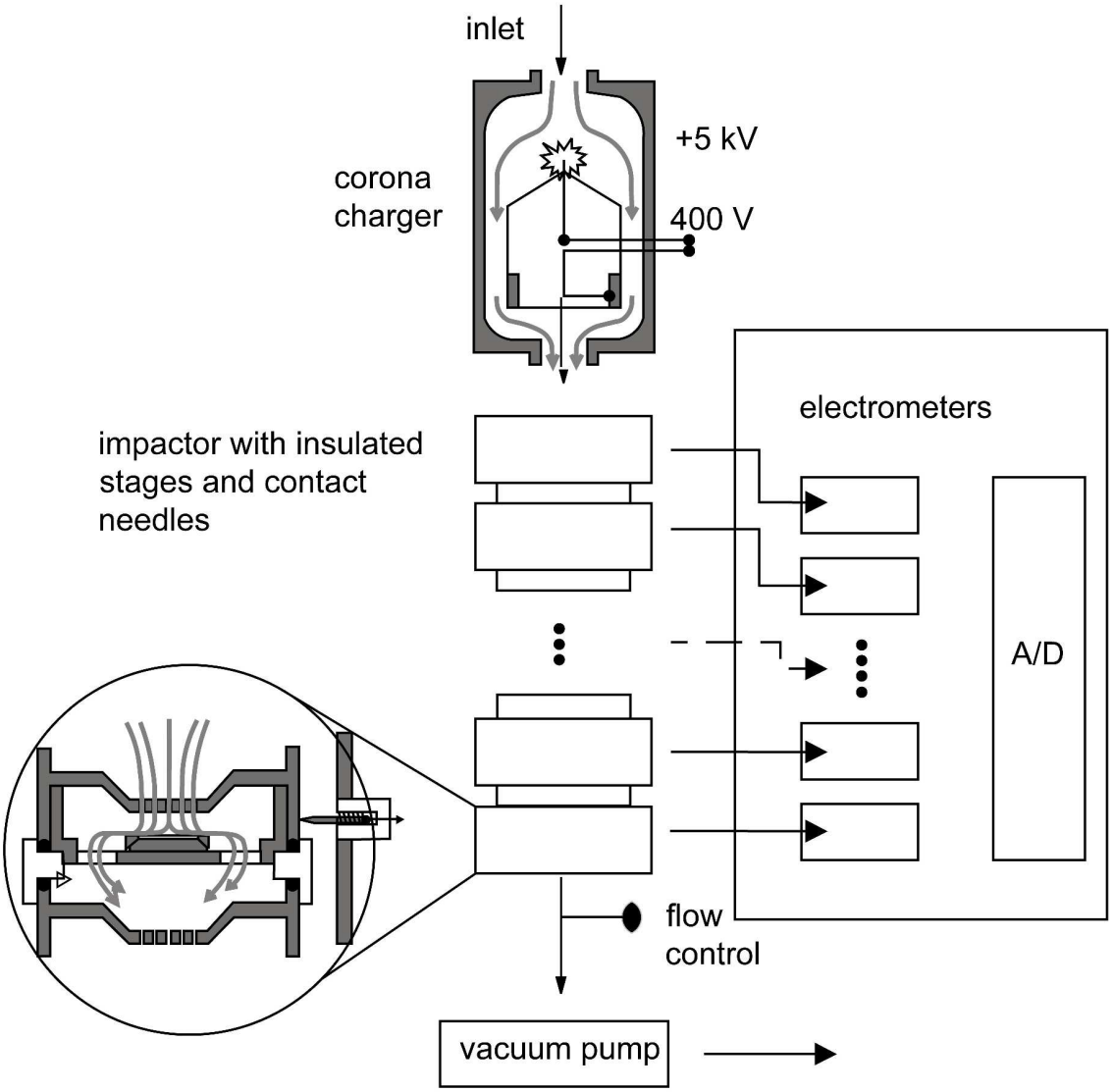


Figure 14: functional scheme of the electrical low pressure impactor (ELPI),adapted from [12]

Electrical detection of particles could be divided into two steps. First particles are charged by passing the corona charger and second deposited particles are detected by measuring their charging. The corona charger consists of a pin which is supplied with high voltage and it generates charge carriers by gas ionization processes. These processes accumulate at the particles and charge them. Charging efficiency depends, among other things, on the particle diameter and is known as a function [12].

At the following cascade impactor the charged particles are deposited on impaction plates. They release their charge at these plates and hence cause an electric current. It is possible to calculate the current into a particle number time series by measuring this current and using the size range of the impactor stage together with the charging efficiency function.

The current value of each impactor step (12 size classes) is proportional to the number of particles collected, and thus to the particle concentration in the particular size range. The current values are converted to a (aerodynamic) size distribution using particle size dependent

relations describing the properties of the charger and the impactor stages. The ELPI ™ is manufactured by DEKATI Ltd., for specifications it is referred to [12] and [17].

5.3.2.2 Scanning mobility particle sizer (SMPS)

A SMPS system consists of an electrical classifier and downstream a particle counter.
Usually, a particle neutralizer is the first device the polydisperse aerosol flow passes. Ongoing the aerosol is classified in a differential mobility analyzer (DMA). At the outlet of the DMA a monodisperse aerosol is available with different particle sizes at different times. So the downstream particle counter first gets small particles, later on larger ones and at least the largest particles, that may pass the DMA.

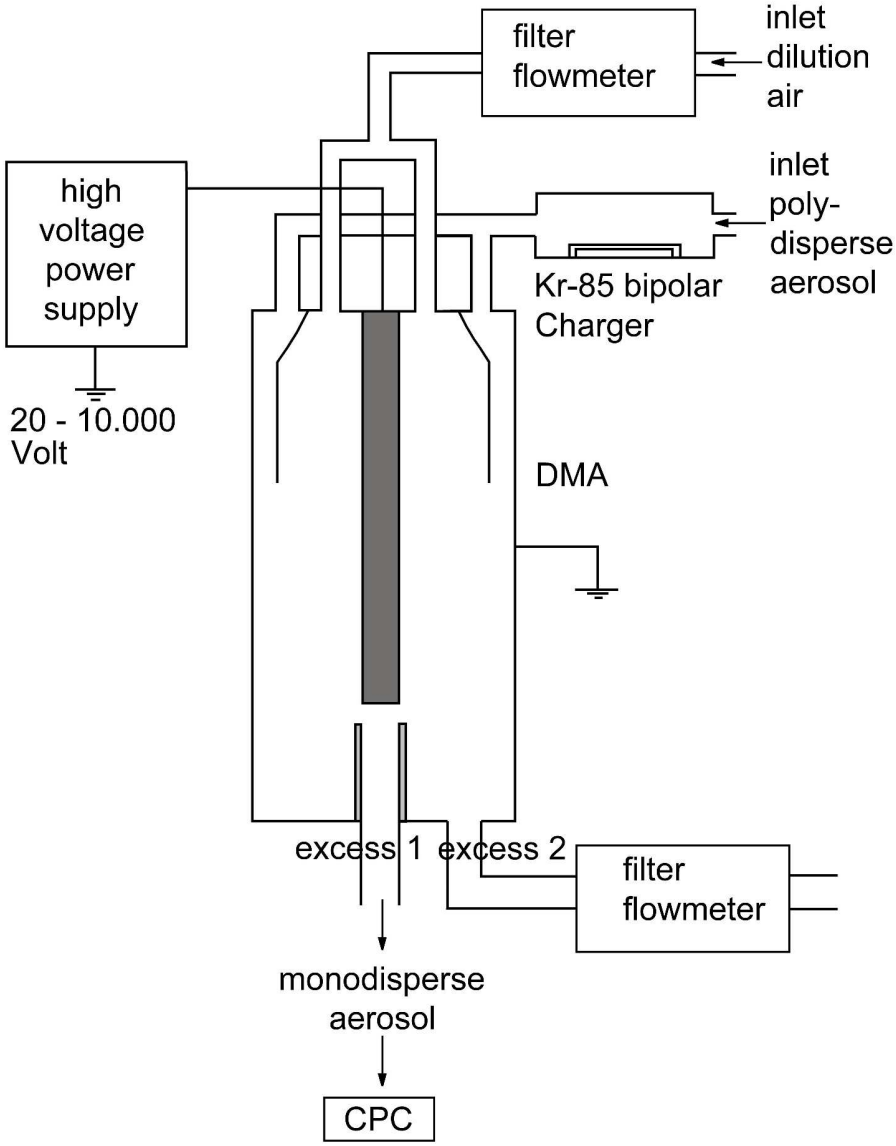


Figure 15: functional scheme of a SMPS, *adapted from* [21]

To avoid failures due to multi-charging particles don't have to enter the charger over the measurement area. Generally, larger particles are separated via an impactor before entering the DMA. During operation the voltage is stepwise increased at the DMA.

Thereby defined loaded particles enter the DMA after a Kr-85 bipolar charger (neutralizer) through an annular gap. When flowing through the tube they drift towards the central electrode within the electrical field.

Only a defined size fraction dependant on the voltage reaches the outlet and it is thereby selected. The number concentration of these monodisperse aerosols is measured by a downstream CPC in a scanning mode which leads to a particle size distribution according to the mobility equivalent diameter.

The SMPS measures the total particle distribution in the particle size range from 0.01 µm to 3 µm within 360 seconds. The functionality of a CPC is described within chapter 5.2.3.1.

More detailed information on SMPS instruments including those with electrometers can be found at [21] and [22].

5.3.2.3 Aerodynamic particle sizer (APS)

The direct-reading measurement instrument APS sizes particles by measuring their velocity relative to the air velocity within an acceleration nozzle. This velocity is compared with a calibration curve established using monodisperse spheres. The APS can be applied within the particle size range of 0.5 – 20 µm. Several commercial instruments have been developed by TSI [21] so far.

The APS allows the rapid, precise measurement of aerodynamic size of most particles whereby various factors bias that measurement.

The bias is caused by particle density, particle shape factor, gas viscosity, and gas density. It is sufficiently well understood that corrections to measured size can be made. The size of these biases is often on the order of 25% or less. Thus for many purposes, an estimated value of the particle density can yield sufficient accuracy in the corrected aerodynamic size.

5.3.2.4 Fast mobility particle sizer (FMPS)

A combination of a differential mobility analyzer (DMA, section 5.3.2.2) and an electrical multi-stage detection as in the ELPI (section 5.3.2.1) is constructed for example by TSI Inc. [21]. This is the so called fast mobility particle sizer (FMPS).

The particles are charged in a corona charger, classified in an electrical field like in an DMA but not only a specific particle size is analyzed after exhaust. On their way to the negative electrode the particles impact on circular electrometers. The number of electrometers gives the number of classification stages. The electrometers have to be cleaned periodically depending on their fouling in effect of particle penetration.

The FMPS measures particles in the size range from 5.6 to 560 nm and totally offers 32 size channels (16 channels per decade).

It can be configured for continuous measurement (up to 12 hours) of single or several ways.

5.3.2.5 Diffusion Size Classifier (DiSC)

The Diffusion Size Classifier (DiSC) is an instrument to measure number concentration and average diameter of nanometer sized particles in the size range 10 – 200 nm. It is small, easily portable and battery operated and therefore well suited for field measurements. The measurement range is applicable for ambient air concentrations (1.000 – 500.000 particles/cm³); adding a diluter it is also suitable for emission measurements.

The number concentrations measured with DiSC agree well with those measured with a condensation particle counter. The response time (one second) is short enough to measure transient engine operation.

DiSC is based on the diffusion charger (DC). In a diffusion charger, aerosol is charged with unipolar ions, and the current acquired by the particles is measured in an insulated particle filter. This type of measurement gives no information on the particle size. The diffusion size classifier has a second measurement stage in addition to the filter stage: A stack of stainless steel grids captures particles with high diffusivity in front of the filter, i.e. small particles are deposited preferentially in the diffusion stage while large particles are deposited preferentially in the filter stage. The ratio of the diffusion and filter current is a measure for the average particle size; the aerosol concentration is then determined via the total current deposited.

The measurement uncertainty is typically +-30%, which is sufficient for many aerosol measurements, since aerosol concentrations can vary over many orders of magnitude. [13]

Further information about the DiSC are held by the Institute for Aerosol and Sensor Technology, University of Applied Sciences Brugg, North-western Switzerland.

5.3.2.6 White-Light-Scattering Analyzers

Within white-light-scattering analyzers white-light illumination is chosen to maximize monotonicity of the scattering intensity versus diameter response curve and to reduce (though not eliminate) index of refraction effects.

These white-light systems are well suited for filter efficiency testing, especially at high pressures or temperatures. The velocity operating range is typically from 0.1 to 10 m/s, although particle velocities are not measured. [2]

The particle size can be analyzed in the range of approximately 180 nm to 40 µm. With the welas® series from Palas and a CNC module also the measurement of ultra-fine particles is possible.

White-light-scattering analyzers are manufactured e.g. by Palas GmbH [18] offering an white light aerosol spectrometer.

5.3.2.7 Aerosol mass spectrometer (AMS) and Aerosol-Time-of-Flight-mass spectrometer (ATOFMS)

The aerosol mass spectrometer (AMS) is an online method for classifying aerosol particles according to specific mass. The AMS quantitatively measures the size and chemical composition of volatile/semi-volatile submicron aerosols.

The principle of the aerosol mass spectrometer is based on the separation of aerosols and the surrounding gas phase by combining a aerodynamic lens (hence focussing of particles with a single lens) with a differential pumped vacuum system.

Afterwards the mass composition of the particles is determined with a magnetic mass spectrometer.

Figure 16 shows the basic concept of an aerosol mass spectrometer manufactured by Aerodyne [28].

Figure 16: principal steps of an aerosol mass spectrometer from Aerodyne [28]

The AMS combines standard vacuum and mass spectrometric techniques with recently developed aerosol sampling techniques.

The Aerosol-Time-of-Flight-mass spectrometer (ATOFMS) uses an aerodynamic size-determining technique to perform real-time measurements of ambient individual particles. It is suitable for analysis of single particle size and the chemical composition.

Aerosols are size-classified via a photoelectric barrier technique and analyzed in terms of the chemical composition with laser desorption / ionization. Previous investigations with this technique revealed valuable insights into aerosol transformation processes in both field studies and laboratory studies as well as useful findings about the composition of aerosol particles. Thereby it was focussed on the inorganic core composition so far.

Pulsed UV laser radiation desorbs and ionizes the particle for chemical analysis in a bipolar, time-of-flight mass spectrometer.

Due to characteristic mass peaks it can be concluded to the chemical nature and hence to possible sources.

The UF-ATOFMS from Prather Group is configured with an aerodynamic lens for detection of ultrafine particles from 50-300 nm. The third generation ATOFMS (“Laverne”) is field

transportable and dual-polarity and was the prototype for TSI's commercial ATOFMS instrument, Model 3800^{TM} [27].

The TSI ATOFMS instruments with Aerodynamic Focusing Lens Technology (e.g. Series 3800) provide single particle size and composition measurements in the size range from 30 to 3000 nanometers. They also use an aerodynamic sizing technique that provides results similar to those obtained from a TSI Aerodynamic Particle Sizer® spectrometer.

More detailed information in terms of available AMS and ATOFMS as well as their specifications can be obtained by Aerodyne [28], TSI Inc. [21], Grimm Aerosol [22] and by the Prather Research Group [27].

6 Particles from Biomass combustion

All kind of biomass (including wood) consist of some inorganic components (minerals) which are incombustible. This fraction is called ash. One part of this ash is emitted as particulate matter (fine and ultrafine particles) by the flue gas into the ambient air. Also a lot of different kinds of organic particles may be emitted from a biomass combustion depending on the completeness of the oxidation.

The technical ongoing of biomass combustions has lead to a significant decrease of fine particle emissions from these kind of combustions.

6.1 Formation

Aerosol forming by combustion processes depends directly on the fuel composition. So the formation of particles from biomass combustion is subjected to a lot of different mechanisms with a lot of different particle types as consequence. It depends on volatile compounds formed by incomplete burnout and inorganic compounds (potassium, sodium, sulfur, chlorine) as well as volatile heavy metals as zinc, lead and cadmium) [29]. A small overview is presented as a scheme in Figure 17.

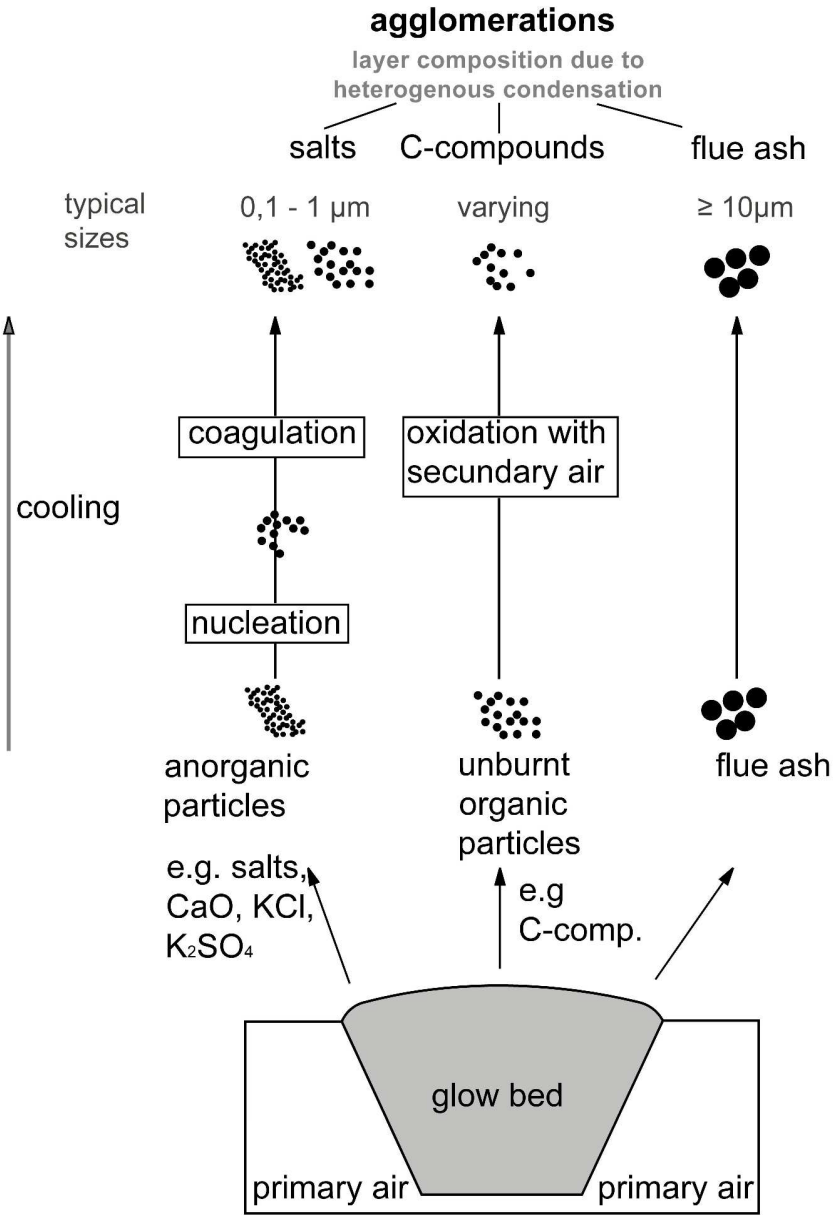


Figure 17: formation of particles from biomass combustion: particle formation factors are condensation, coagulation and nucleation, adapted from [30]

Particles from a combustion process consist of a solid nucleus (unburned carbon or inorganic ash) with adsorbed organic or inorganic compounds [9].

The solid-particle-path means former existing particles (from the wood or formed in the glow) which are carried out from the firebed by the flue gas stream without being transformed into the gas phase [31]. Those particles usually are about 1 µm or larger in diameter (coarse mode). Second there is the so called solid-vapor-particle-path [31]: components are vaporizing from the glow, carried with the flue gas stream and particles were formed by cooling (condensation). These particles usually are in the size range of about 100 nm in diameter (fine mode).

On cooling of the flue gas from wood combustion always a heterogeneous nuclei formation takes place: condensation nuclei (carbon and ionic compounds, metals and their oxides) are present and an oversaturation occurs by cooling [30].

If the vapor pressure of one component overrides the saturation pressure particles were built by nucleation. Particles of this nucleation mode are only a few nanometers in diameter. Those particles grow by agglomeration on their way through the combustion with the flue gas by collisions. Additional, they grow on by condensing of ash building vapors on their surface if they reach a critical number. Those two things, agglomeration and condensation, lead to the typical particle size distribution of the aerosols in the flue gas.

In bark there are usually more aerosol forming components than in hard wood or soft wood.

Organic carbon compounds originate from incomplete combustion during incomplete gas phase burnout by condensation of gaseous carbon compounds. They also form particles (soot) by condensation and agglomeration.

Soot forming depends on the burnout conditions in the combustion process itself and can be directly influenced by combustion and control technology.

For further information on formation processes, especially the chemistry of combustion processes, it is referred to chapter A2 (volume 1).

6.2 Typical size distribution on biomass combustion

Biomass combustion mainly leads to particulate emissions smaller than 10 µm, the main fraction of the particulate matter in the flue gas is even smaller than 1 µm. So this fraction of aerosols is the most interesting. Typical size distributions of particles in the flue gas of a 25 kW wood pellet boiler are shown in the following figures. The left one (Figure 18) is measured with an ELPI ^{TM} and describes the size distribution regarding to the aerodynamic diameter assuming the unit density (1 g/cm³). The right figure (Figure 19) is determined with a SMPS and presents the size distribution regarding to the electrical mobility diameter, also assuming the unit density.

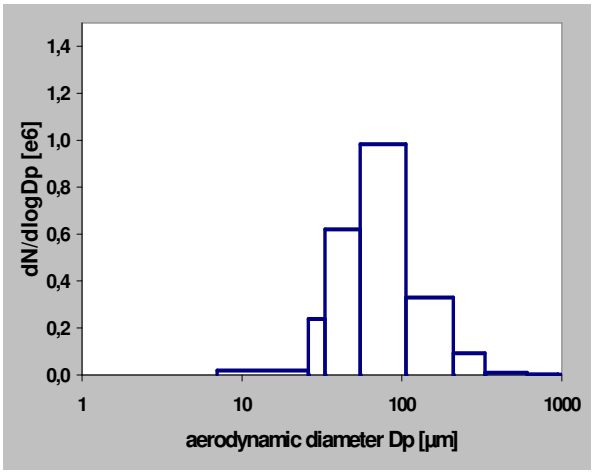


Figure 18: typical size distribution related to aerodynamic diameter, particles in the flue gas from wood pellet boiler, measured by ELPI

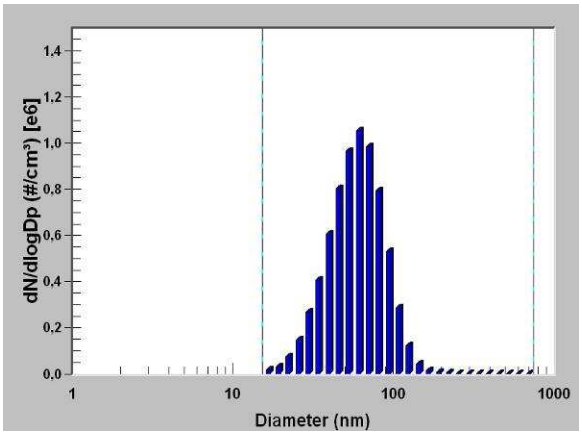


Figure 19: typical size distribution related to mobility diameter, particles in the flue gas from wood pellet boiler, measured by SMPS

Comparing the results is not as easy because of the two different diameter definitions the results are related to. Both diagrams were recorded under same conditions on a parallel measurement. The flue gas analyzed here was diluted by a cascade of two ejector diluters with a resulting dilution ratio of 100. So the absolute number of particles (y-axis) shown in the diagrams has to be multiplied with factor 100. This leads to a maximum particle number in the rage of 1.0E8 dN/dlogDp in the flue gas of this 25 kW wood pellet boiler investigated.

6.3 Particle density

To draw conclusions from the size and the number of particles to mass relating values the density of the particles is an important information.

6.3.1 Definition of density

A variety of definitions of particle density are available, which differ in terms of whether pores are included in the particle volume, and whether voids are included. Therefore it is necessary to define the density that is talked about in this section:

The **bulk density** (effective density) is defined as the mass of many particles of the material divided by the total volume they occupy. The total volume includes particle volume, inter-particle void volume and internal pore volume.

The bulk density is especially dependent on the size of the particles. It decreases if the diameter gets smaller because the fraction of cavities in the bulk increases.

It may not mistaken to the **absolute density**, which is defined as the ratio of particle mass to the volume of the particle exclusively the pore volume [33] .

6.3.2 Calculation theory

Due to the coherence between mobility diameter and aerodynamic diameter there is the possibility to determine the effective density of particles.

Mathematically there is the following relation between these two diameters:

$$d_a^2 \cdot C(d_a) \cdot \rho_0 = d_b^2 \cdot C(d_b) \cdot \rho_e$$

$C(d_a)$, $C(d_b)$	[-]	Cunningham correction factor
ρ_0	1 [g/cm³]	unit density with 1 [g/cm³]
ρ_e	[g/cm³]	effective density (Formula 2)

The calculation of particle density is based on the well-known mechanism of measuring particles with the ELPI ™ (see section 5.3.2.1). The charging of the particles in the corona charger of the ELPI ™ can be calculated as well as their separation by impaction in the impactor. To determine the density of the particles the charging and the impaction in the ELPI ™ are simulated with the number distribution given by the SMPS (see section 5.3.2.2), which is a function of mobility diameter.

The result is a distribution which is shifted versus the measured ELPI ™ distribution in the diameter axis. By changing the density, the density with the best analogy of the two distributions shape is found. The effective particle diameter results iteratively from the best overlay of the both size distributions as possible with as low deviations as possible [33].

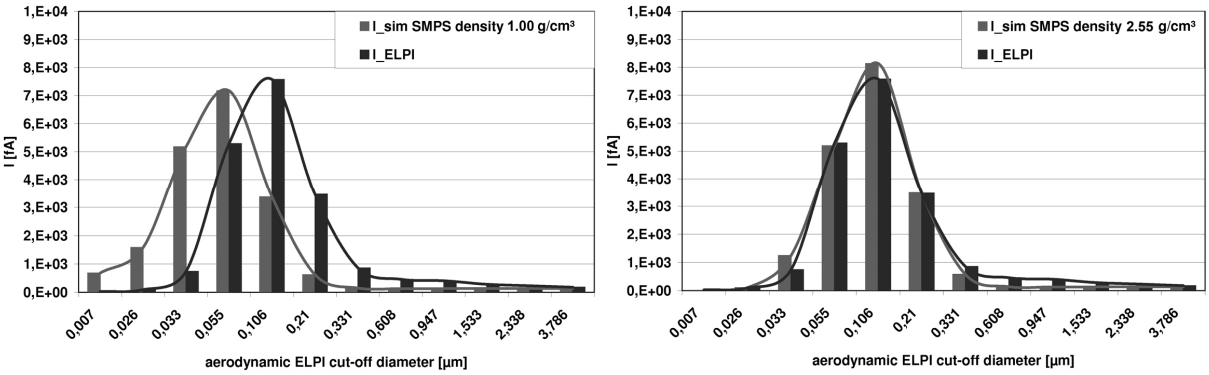


Figure 20: shift of distributions, left: shifted distributions; right: fitting distributions.

Figure 20 shows the shift of the distribution. In the left diagram the measured ELPI distribution and the calculated SMPS distribution do not match, because the density of the particle differs from the unit density of 1 g/cm³.

The right diagram shows the two distributions with the SMPS distribution calculated with a density of 2.55 g/cm³, which shows the best analogy.

This density is the average density of all particles in the considered diameter range from 15 nm to about 1 µm (measuring range of SMPS) [33].

Another method for measuring effective density and fractal dimension of aerosol agglomerates is described by Virtanen [34].

6.3.3 Calculation experience and results

In the following, the calculation of particle density of aerosol from wood combustion is described based on measurements by ZAE Bayern.

Therefore a scanning mobility particle sizer (SMPS, see chapter 5.3.2.2) and an electrical low pressure impactor (ELPI, see chapter 5.3.2.1) were used. The SMPS system provides the number distribution of particles as a function of mobility diameter. ELPI gives the number distribution as a function of aerodynamic diameter.

By means of data from on-site measurements at small scale wood and oil firing systems particle densities were calculated. The results of the density calculations are shown in Table 3.

Table 3: results of density calculations

Firing system	Density [g/cm³]
Wood pellets	2.0 – 3.5 *
Light fuel oil	1.5

* depending on burnout conditions

The average calculated particle density of all observed wood pellet boilers was 2.9 g/cm³. [33]

The density of the particles from the oil firing system is clearly lower than the results from the wood firing system. Published values of the density of particles from diesel engines, which are using the same fuel, are in the range of 1.0 to 1.5 g/cm³. These values are in line with the calculations carried out in this study. The higher density of particles from wood combustion is caused by the mineral constituents in the ash of wood firing system.

Obernberger [35] presented bulk density values between 2.3 g/cm³ and 3.0 g/cm³ of the particles from wood combustion with a Helium pyknometer. Hence these values are significantly higher than those values from oil combustion (1.55 g/cm³). This is because there are mainly soot particles emitted from oil combustion which are more lightweight than particles with mineral parts as they increased occur with wood combustion.

Similar densities like those for oil combustion result from soot particles within diesel waste gas.

7 References

[1] Katsouyanni, K. et al.: Confounding and Effect Modification in the Short-Term effects of Ambient Particles on Total Mortality: Results from 29 European Cities within the APHEA 2 Project. Epidemiology September 2001; Vol. 12 No. 5

[2] Baron, P.A. and Willeke, K., Aerosol Measurement, John Wiley & Sons, New York, 2nd ed. (2001)

[3] American National Standards Institute, Inc., Guide to Sampling Airborne Radioactive Materials in Nuclear Facilities, ANSI N13.1-1969, New York, 1969

[4] Commission of Prevention of Air Pollution at VDI (Association of German Engineers) and DIN (German Institute for Standardization) - Standardization Committee KRdL, VDI guideline 3491 part 1: "Messen von Partikeln; Kennzeichnung von Partikeldispersionen in Gasen; Begriffe und Definitionen" (Particulate matter measurement; characteristics of suspended particulate matter in gases; terms and definitions) 1980-09 (checked 2005-04)

[5] Commission of prevention of air pollution at VDI (Association of German Engineers) and DIN (German Institute for Standardization) - standardization committee KRdL, VDI guideline 2066: "Messen von Partikeln - Staubmessungen in strömenden Gasen - Gravimetrische Bestimmung der Staubbeladung" (Particulate matter measurement - Dust measurement in flowing gases - Gravimetric determination of dust load) several parts available; 1994 – 2006

[6] German Federal Government, "1. Bundesimmissionsschutzverordnung" (1st Ordinance for the Implementation of the Federal Immission Control Act -Ordinance on small and medium sized combustion facilities) 1. BImSchV, 1988

[7] Hüglin, Ch., Scherrer, L., and Burtscher, H. (1997): An Accurate, Continuously Adjustable Dilution System (1:10 to 104) for Submicron Aerosols, J. Aerosols Sci., 28 , No. 6, pp.1049-1055

[8] Burtscher, H.: Physical characterization of particulate emissions from diesel engines: a review, J. Aerosol Sci. 36, 896-932 (2005)

[9] Nussbaumer, T. (Ed.): Aerosols from Biomass Combustion, International Seminar at 27 June 2001 in Zurich by IEA Bioenergy Task 32 and Swiss Federal Office of Energy, Verenum, Zurich 2001

[10] Commission of prevention of air pollution at VDI (Association of German Engineers) and DIN (German Institute for Standardization) - standardization committee KRdL, DIN EN 13284-1: "Emissionen aus stationären Quellen - Ermittlung der Staubmassenkonzentration bei geringen Staubkonzentrationen – Teil 1: Manuelles gravimetrisches Verfahren" (Stationary source emissions - Determination of low range mass concentration of dust - Part 1: Manual gravimetric method), 2002-04

[11] Griffin T., Burtscher H., Beispiel zur Messung der Wirksamkeit eines Partikelabscheiders für kleine Holzfeuerungen. Federal Office for the Environment (Bundesamt für Umwelt) and Swiss Federal Office of Energy (Bundesamt für Energie), Switzerland, 2008-02

[12] Marjamäki, M. et al.: (2000). Performance Evaluation of the Electrical Low-Pressure Impactor (ELPI). J. Aerosol Sci. Vol. 31, No. 2, pp. 249-261, 2000

[13] Fierz M. et al.: Field measurement of particle size and number concentration with the Diffusion Size Classifier (DiSC), SAE Paper 2008-01-1197 (2008)

[14] GSM Neuss: "STE 4 Staubsammelgerät zur Staubprobenahme in strömenden Gasen - Filterkopfgerät VDI 2066-2" (STE 4 Dust collector device for dust sampling from gas flows – filter head device VDI 2066-2). GSM Gesellschaft für Schadstoffmesstechnik GmbH, Neuss-Norf, Germany, http://www.gsm-neuss.de/html/TISTE4G-D.pdf, date 2009-03-23

[15] Hinds W.C., Aerosol Technology, Properties, behaviour, and measurement of airborne particles, second edition, John Wiley and Sons, New York, 1999

[16] Office for Official Publications of the European Communities, Council Directive 88/436/EEC of 16 June 1988 amending Directive 70/220/EEC on the approximation of the laws of the Member States relating to measures to be taken against air pollution by gases from engines of motor vehicles (Restriction of particulate pollutant emissions from diesel engines), Official Journal L 214, 06/08/1988 P. 0001 - 0017

[17] Dekati Ltd, Tampere, Finland, http://www.dekati.com/

[18] PALAS® GmbH, Karlsruhe, Germany, http://www.palas.de/

[19] Matter Engineering, Wohlen, Switzerland, http://www.matter-engineering.com/

[20] ThermoFisher SCIENTIFIC, Waltham, MA, USA, http://www.thermofisher.com/

[21] TSI Incorporated, Shoreview, MN, USA, http://www.tsiinc.de/

[22] Grimm Aerosol Technik GmbH & Co. KG, Ainring, Germany, http://www.grimm-aerosol.com

[23] Kanomax, Andover, NJ, USA, http://www.kanomax-usa.com/

[24] Cambustion, Cambridge, UK, www.cambustion.co.uk

[25] Climet Instruments company, Redlands, CA, USA, http://www.climet.com/

[26] Topas GmbH, Dresden, Germany, http://www.topas-gmbh.de/

[27] Prather Research Group, UC San Diego, CA, USA, http://atofms.ucsd.edu/

[28] Aerodyne Research Inc., Billerica, MA, USA, http://www.aerodyne.com/

[29] Obernberger, I., Brunner, T., Bärnthaler, G.: Aktuelle Erkenntnisse im Bereich der Feinstaubemissionen bei Pelletsfeuerungen; 5. Industrieforum Holzenergie vom 12.-13. 10. 2005; Stuttgart, 2005

[30] Oser, M. et al., Bundesamt für Energie; Bundesamt für Umwelt, Wald und Landschaft (publ.), Grundlagen der Aerosolbildung in Holzfeuerungen - Beeinflussung der Partikelemissionen durch Primärmassnahmen und Konzept für eine partikelarme automatische Holzfeuerung (Low-Particle-Feuerung); Schlussbericht April 2003

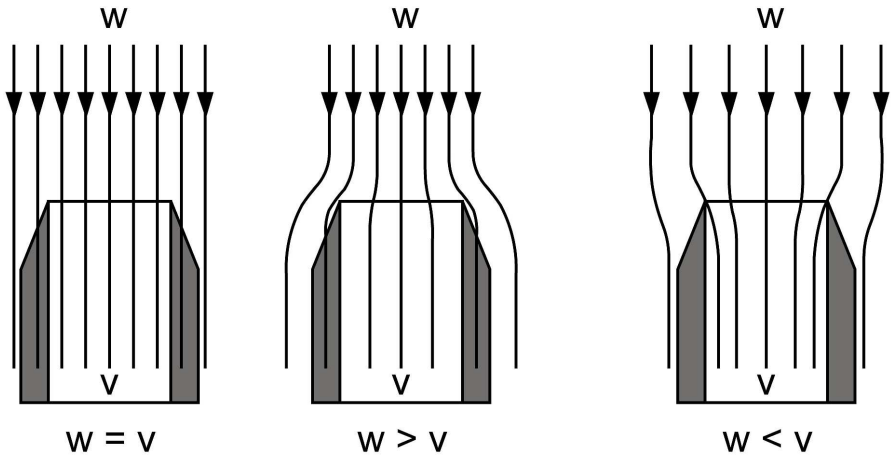
[31] Livbjerg, H., Aerosol Formation from Straw Combustion – Danish Experiments; Aerosols from Biomass Combustion – Seminar on IEA BioenergyTask 32: Biomass Combustion and Cofiring, June 2001, Zurich, Switzerland

[32] Nussbaumer, T., Czasch, C., Klippel, N., Johansson, L., Tullin, C., Particulate Emissions from Biomass Combustion in IEA Countries. Survey on Measurements and Emission Factors on behalf of the International Energy Agency (IEA) Bioenergy Task 32, Swiss Federal Office of Energy (SFOE), Zürich, 2008

[33] Lautenbach, M., Kunde, R., Gaderer, M. (2007): Calculation of Particle Density of Aerosol from Wood Combustion; European Aerosol Conference, Salzburg/Austria, September 2007

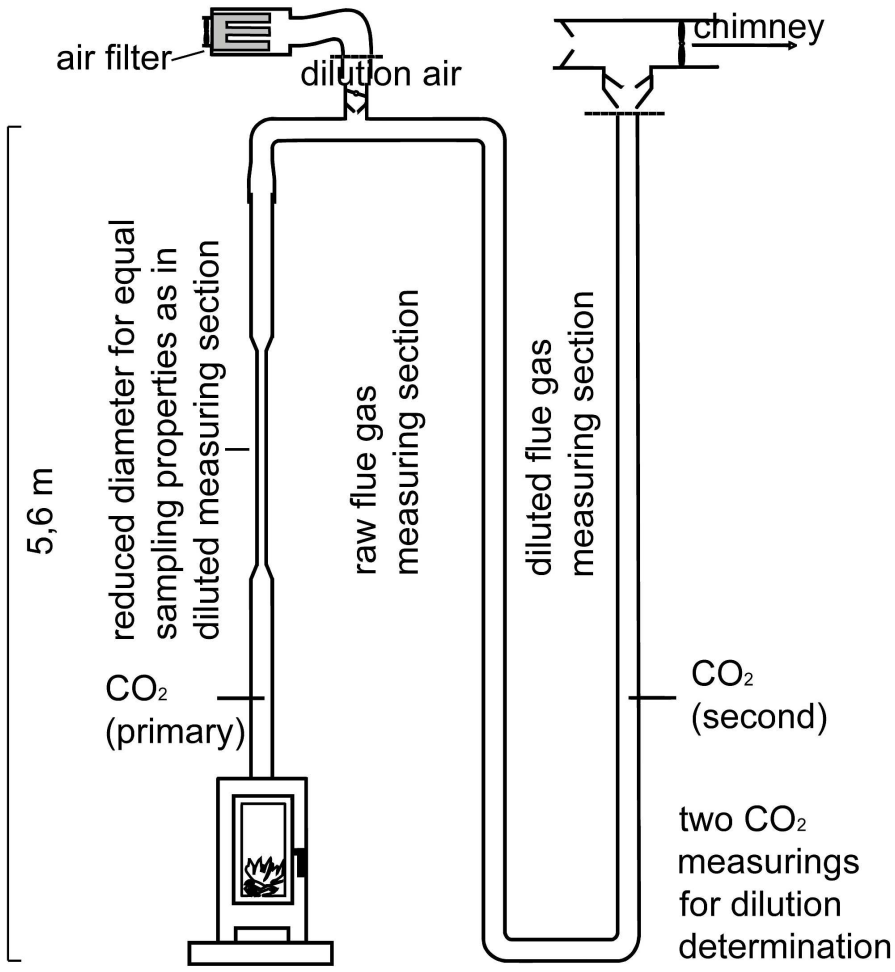
[34] Virtanen, A. et al. (2004): Method for Measuring Effective Density and Fractal Dimension of Aerosol Agglomerates, Aerosol Science and Technology, 38:5, 437 — 446

[35] Obernberger, I.; Nutzung fester Biomasse in Verbrennungsanlagen - Band 1, dbv-Verlag TU Graz, ISBN 3-7041-0241-5, 1997

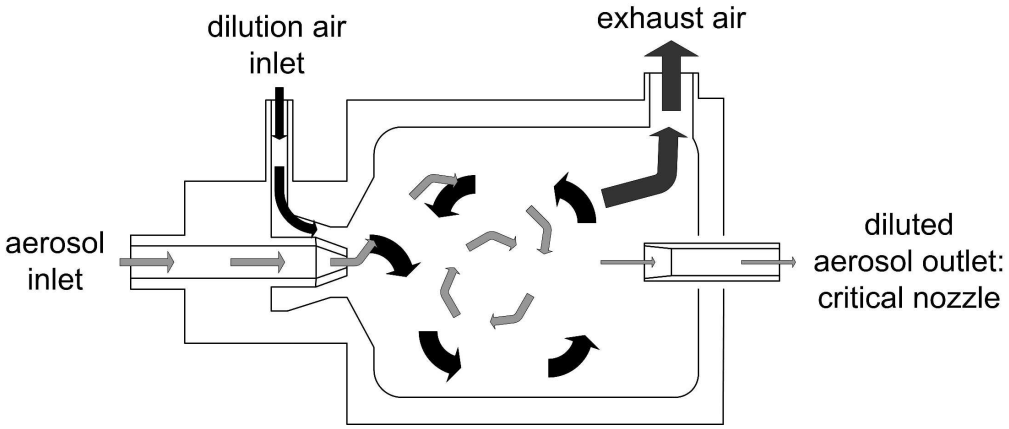


isokinetic (left), sub- (middle) and super-isokinetic sampling (right), with w = flow velocity and v = extraction velocity

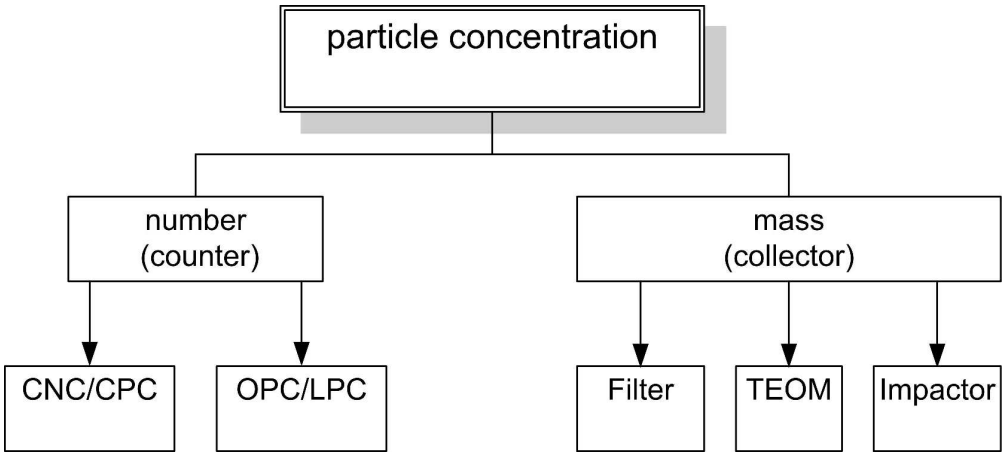
175x99mm (600 x 600 DPI)



schematic diagram of a dilution tunnel with solid fuel single room firing, dilution air T-fitting and top down sampling line at the laboratory of the TFZ (technology and advancement center) Straubing, Germany
189x197mm (600 x 600 DPI)

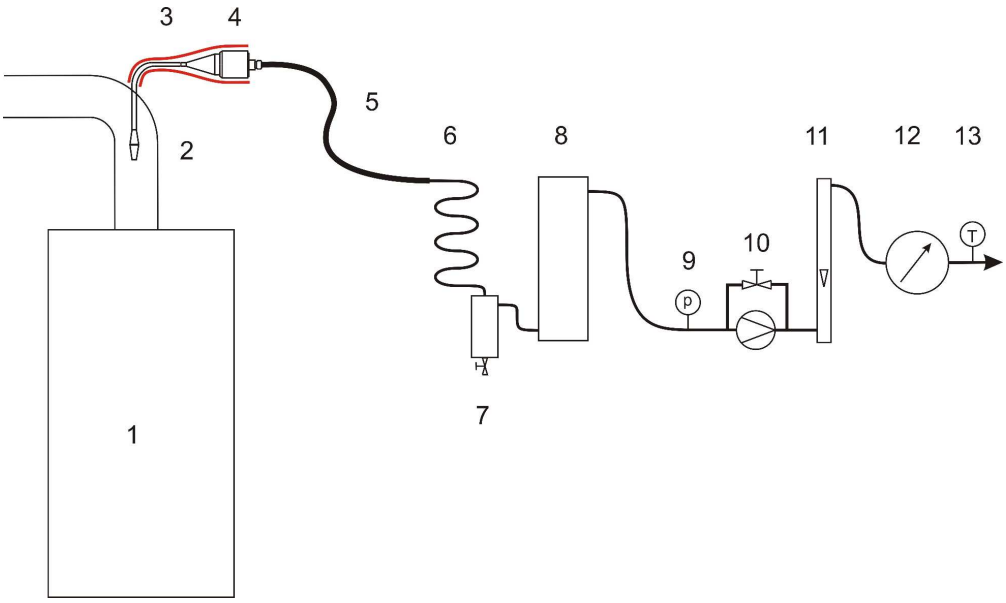


function chart of an ejector diluter
184x79mm (600 x 600 DPI)

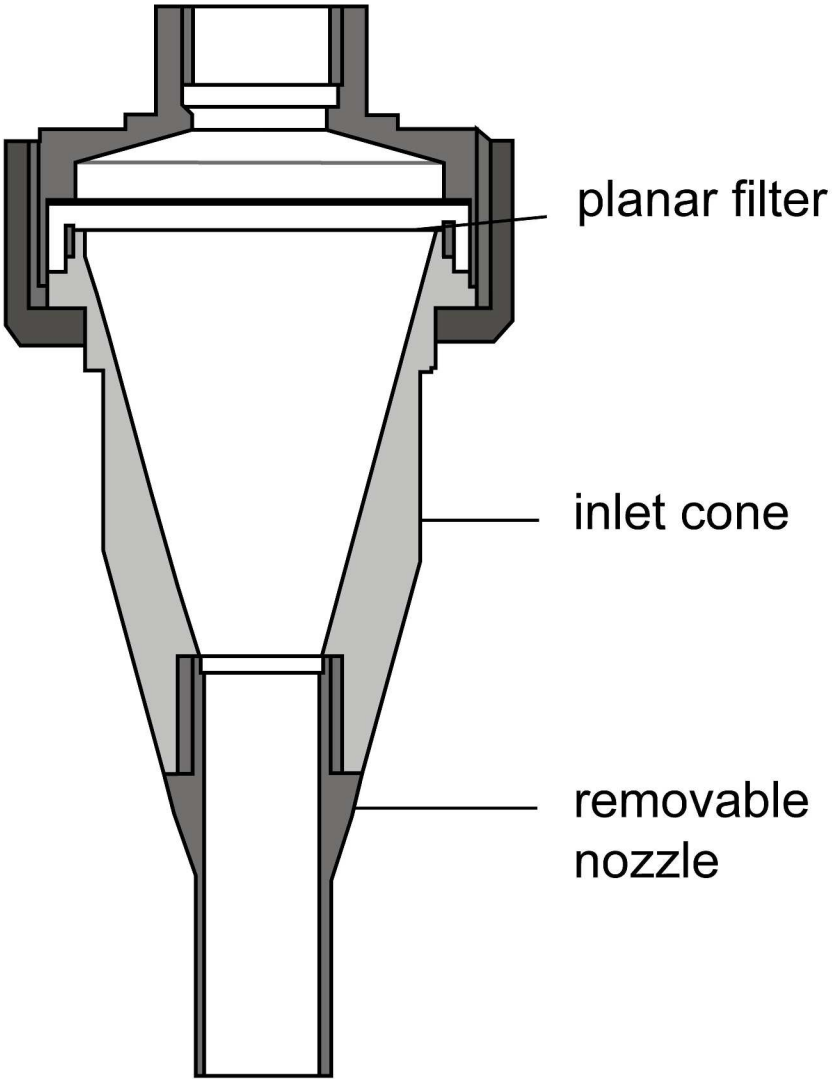


overview of particle measurement techniques commonly used for concentration measurement on combustion analysis and presented in this article.

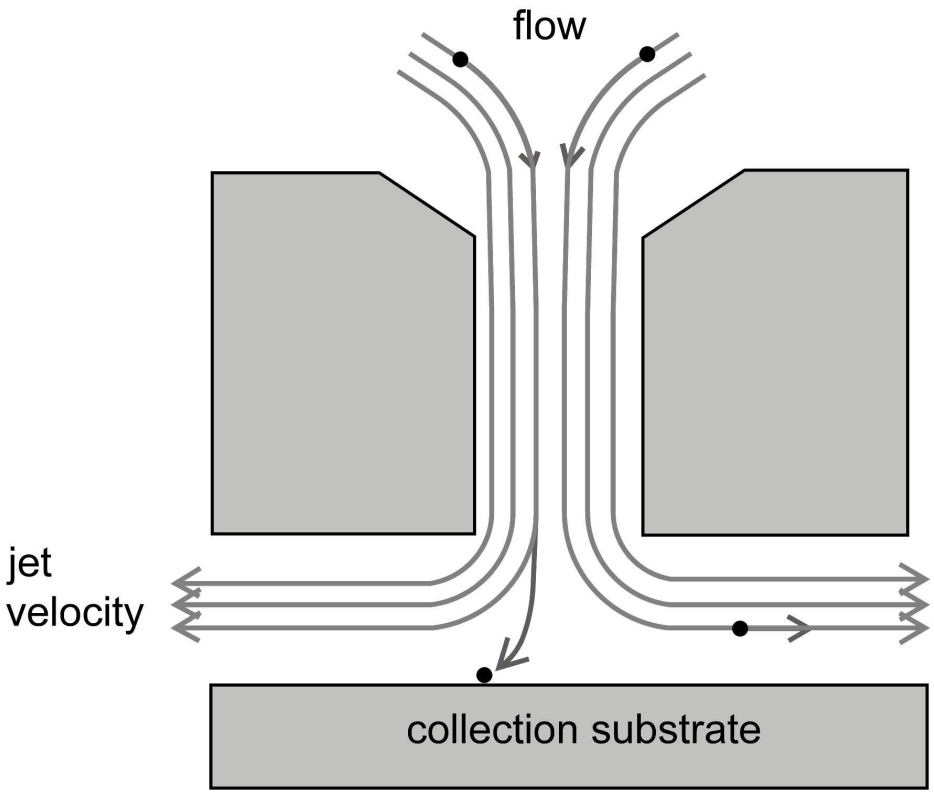
141x63mm (600 x 600 DPI)



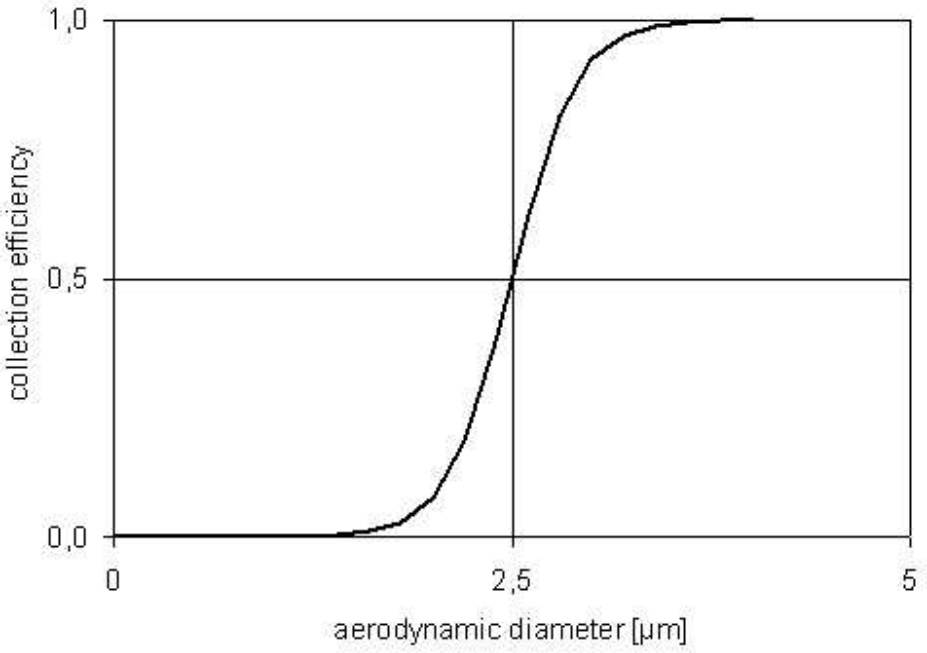
schematic diagram of out stack setup for gravimetric particulate matter measurement.
1 combustion, 2 sampling probe for isokinetic sampling, 3 electrically heated tube, 4 electrically heated filter / impactor holder, 5 flexible tube, 6 cooling, 7 condensation chamber, 8 drying (silica gel), 9 manometer, 10 vacuum pump with bypass valve, 11 variable area flow meter, 12 bellows-type gas flow meter, 13 thermometer
249x147mm (600 x 600 DPI)



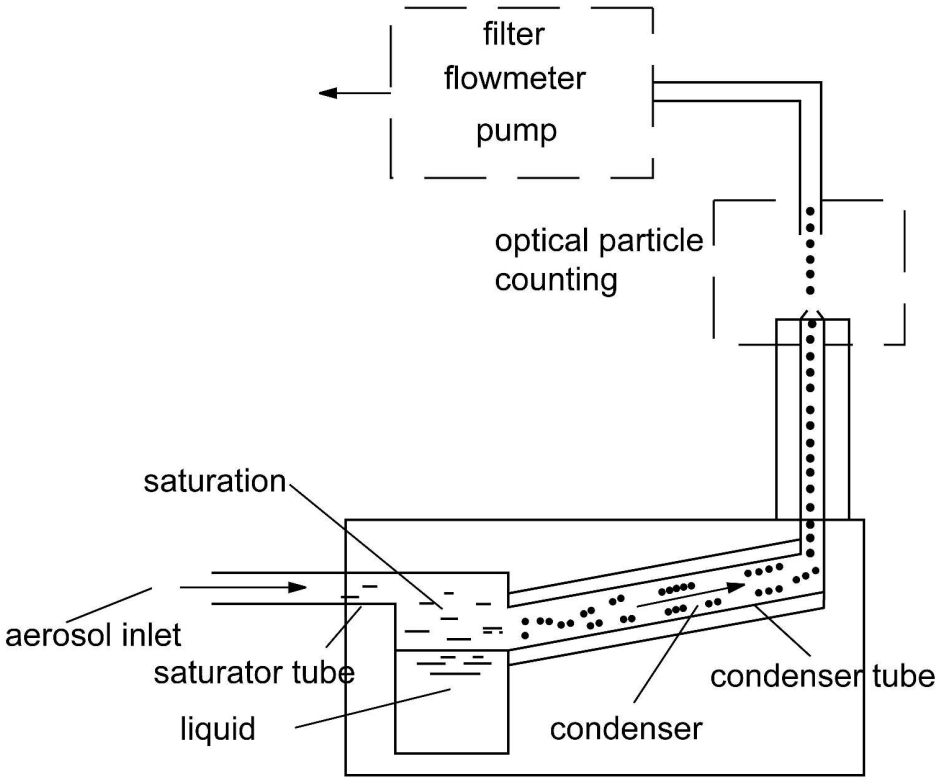
schematic diagram of a filter holder for planar filters regarding to VDI guideline 2066 [5].
122x159mm (600 x 600 DPI)



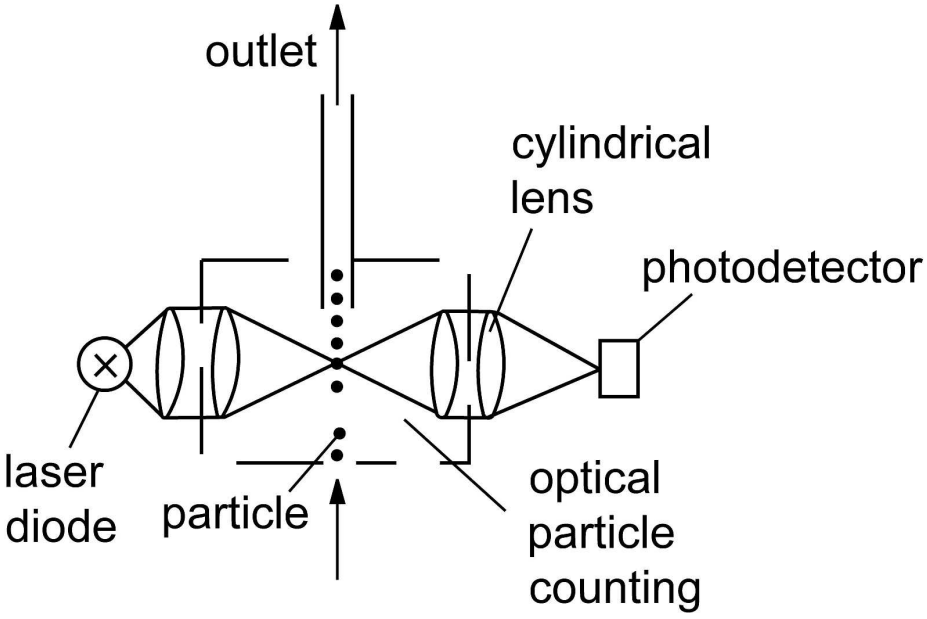
aerosol behavior due to deflection of the stream flow direction.
161x143mm (600 x 600 DPI)



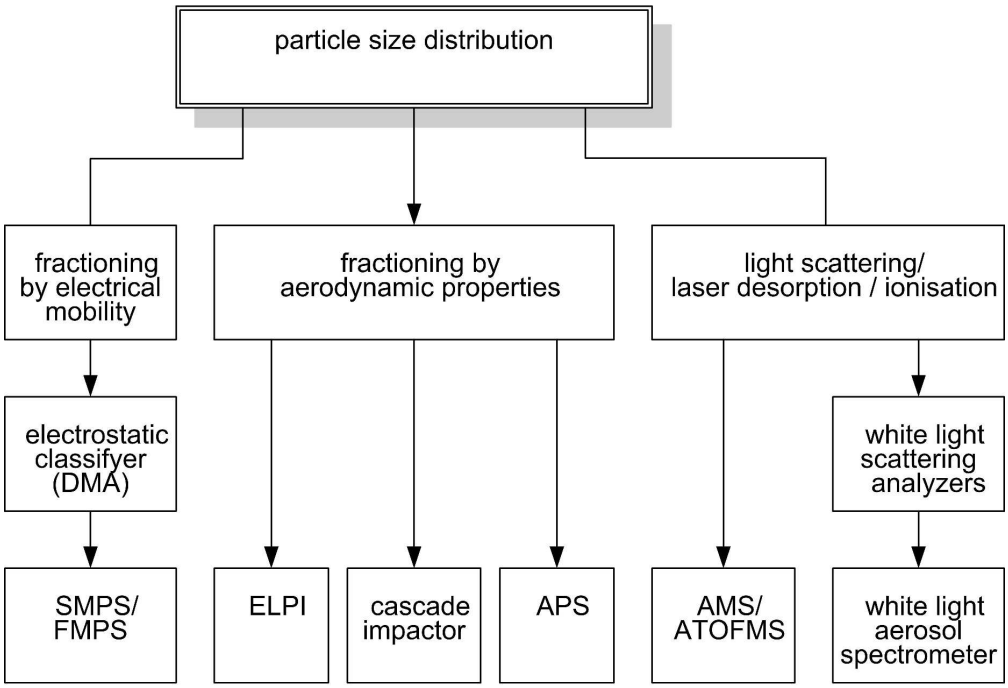
example of the collection efficiency of an impactor (d50 = 2.5 µm)
43x31mm (300 x 300 DPI)



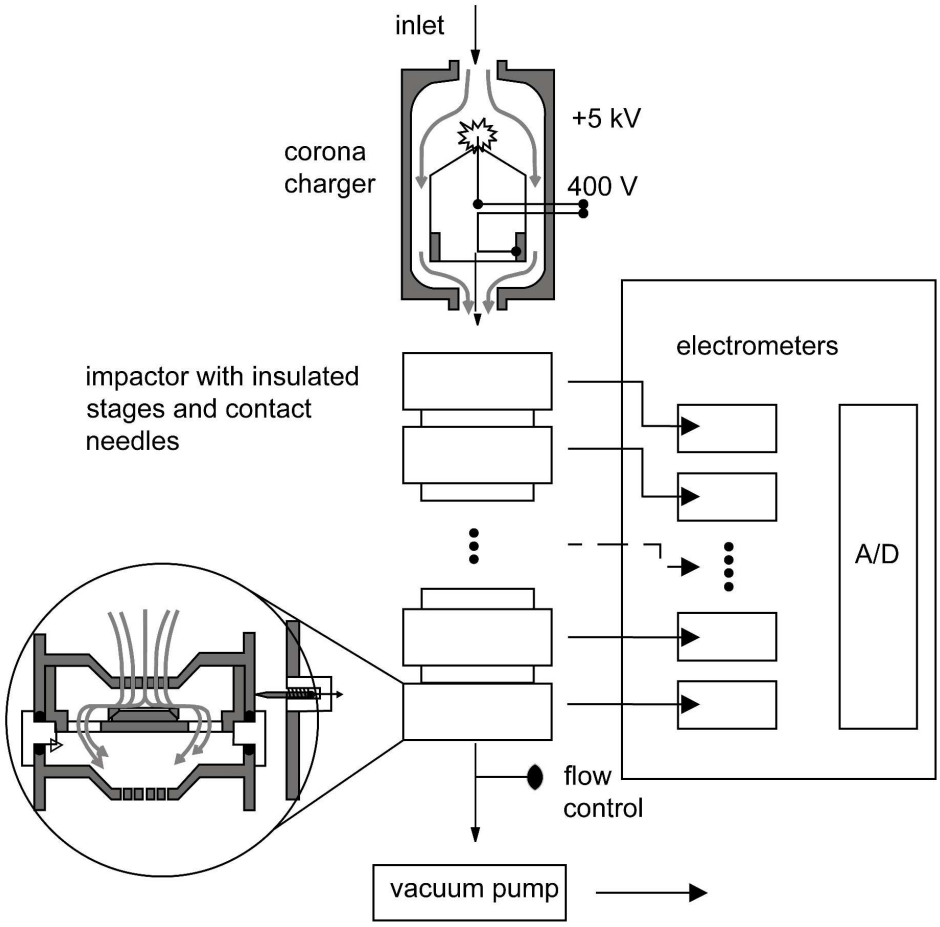
functional schematic of a condensation particle counter (CPC)
204x176mm (600 x 600 DPI)



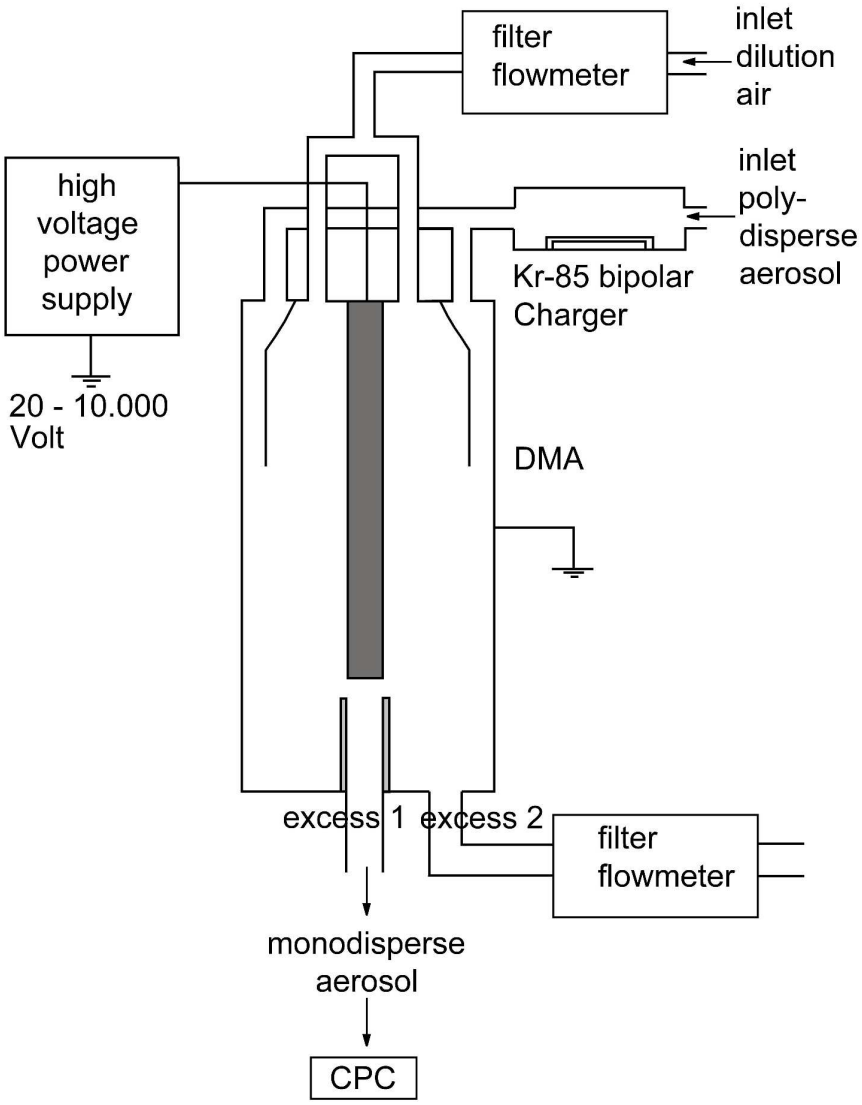
functional schematic of an optical particle counter (OPC)
145x101mm (600 x 600 DPI)



overview of particle measurement techniques commonly used for size distribution measurement on combustion analysis and presented in this article.
DMA: differential mobility analyzer; SMPS: Scanning mobility particle sizer; FMPS: Fast mobility particle sizer; ELPI: electrical low pressure impactor; APS: aerodynamic particle sizer; AMS: aerodynamic mass spectrometer; ATOFMS: Aerosol-Time-of-Flight-mass spectrometer
157x108mm (600 x 600 DPI)

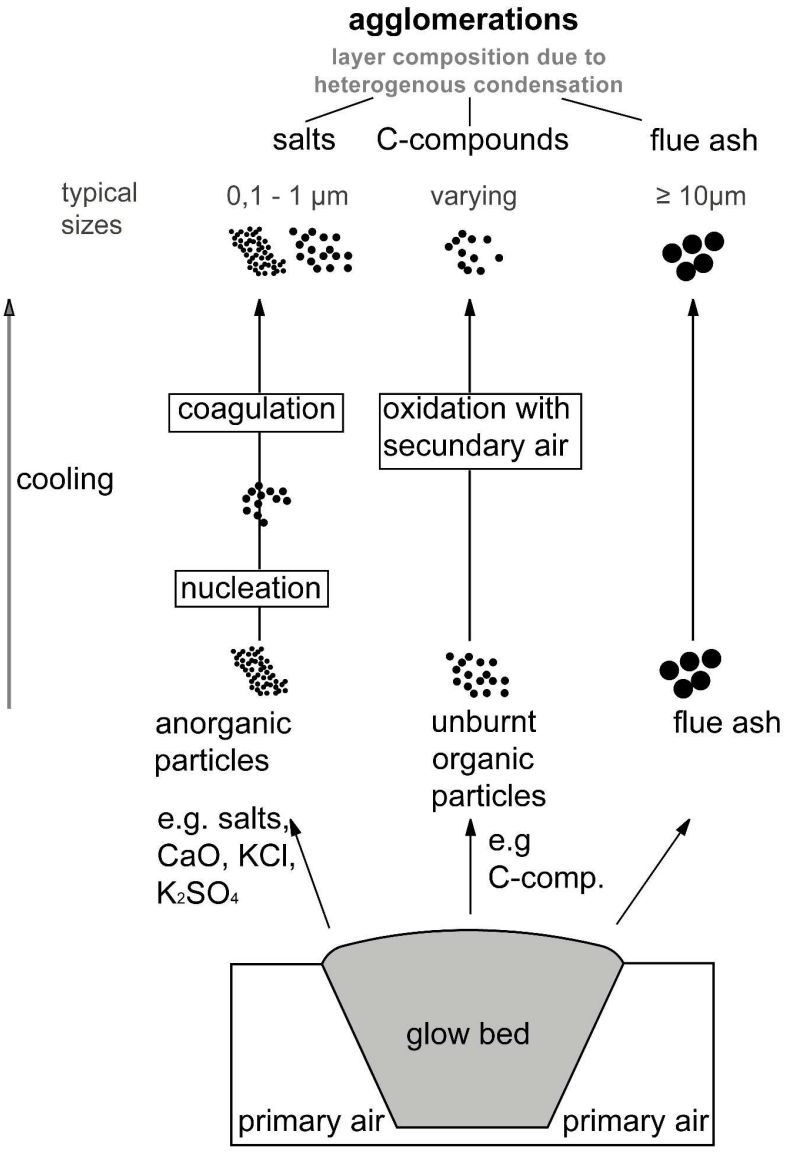


functional scheme of the electrical low pressure impactor (ELPI),adapted from [12]
248x248mm (600 x 600 DPI)

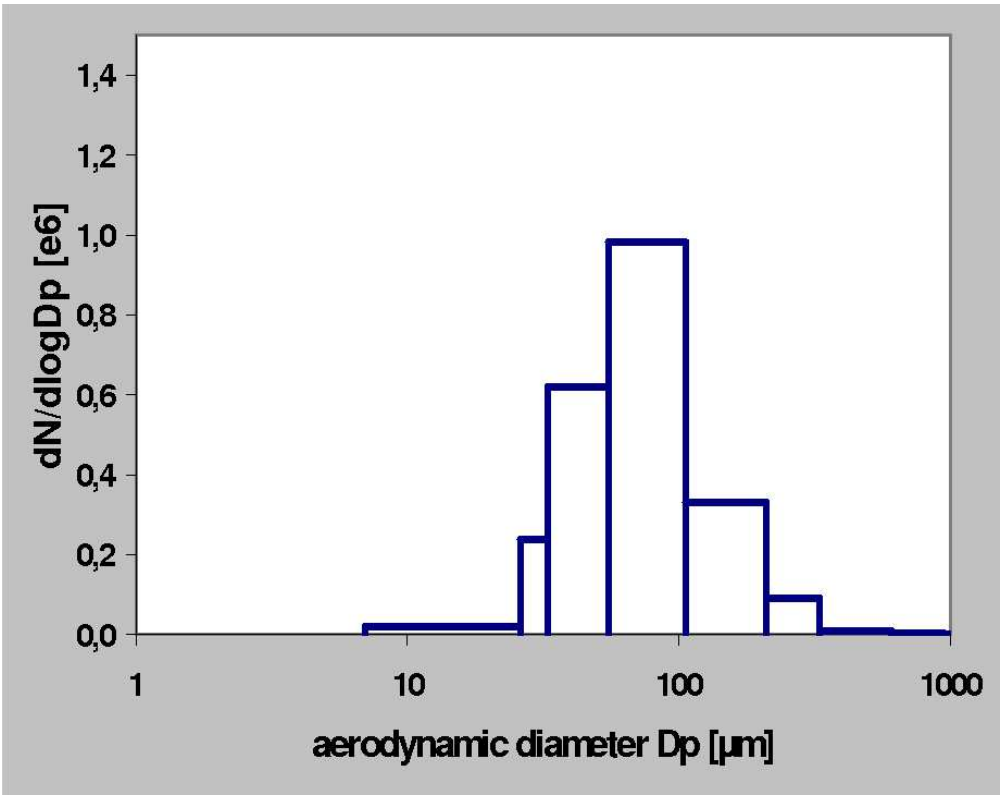


functional scheme of a SMPS, adapted from [21]
208x254mm (600 x 600 DPI)

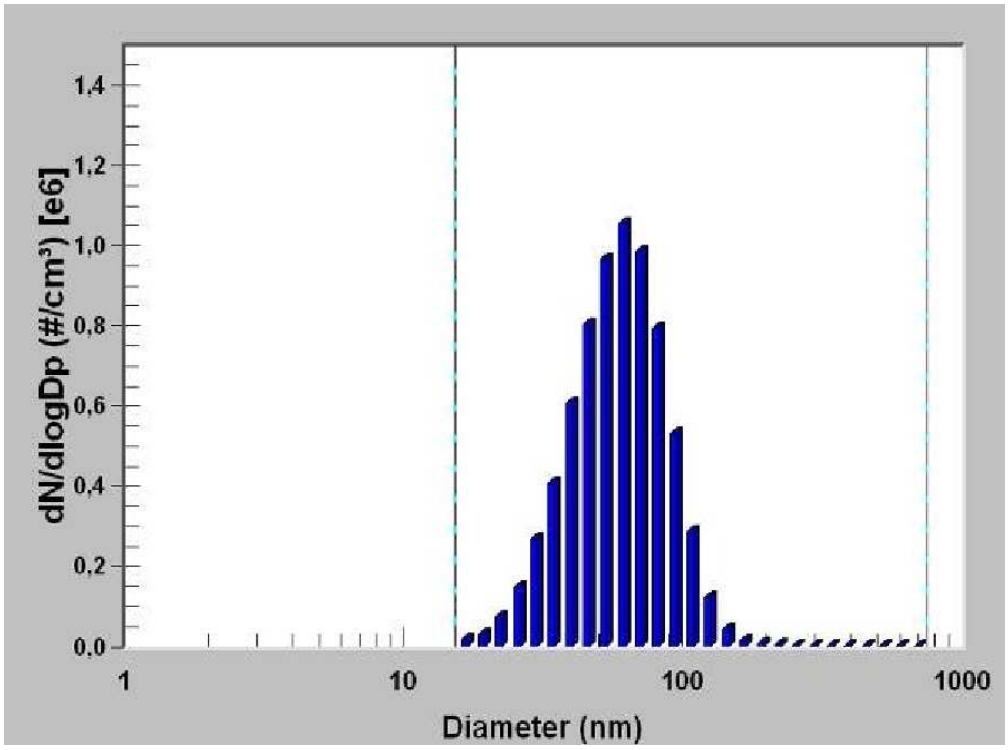
principal steps of an aerosol mass spectrometer from Aerodyne [28]
197x20mm (600 x 600 DPI)



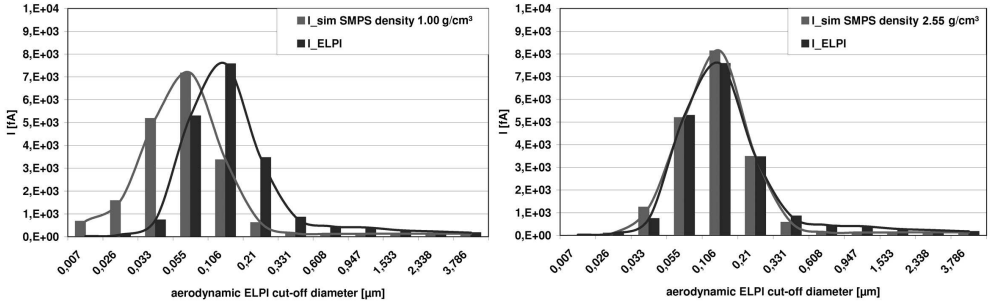
formation of particles from biomass combustion: particle formation factors are condensation, coagulation and nucleation, adapted from [30]
183x258mm (600 x 600 DPI)



typical size distribution related to aerodynamic diameter, particles in the flue gas from wood pellet boiler, measured by ELPI
77x61mm (300 x 300 DPI)



typical size distribution related to mobility diameter, particles in the flue gas from wood pellet boiler, measured by SMPS
76x56mm (300 x 300 DPI)



shift of distributions, left: shifted distributions; right: fitting distributions
199x62mm (300 x 300 DPI)

Table 2 : Overview on most commonly used cascade impactors

Common name	Andersen	Berner (BLPI™)	Cascade impactor of ELPI™	JohnAS™	Kalman	MOUDI™
References	Andersen Instruments Inc.	Hauke Aeras	Dekati Ltd.	Paul Gothe GmbH Bochum	KÁLMÁN SYSTEM LTD.	MSP Corporation
Number of stages	6, 8	up to 12	12	3	3 x 2	3, 8, 10, 13
Measurement principle and main components	Multi-stage, multi-orifice sampler	Low pressure impactor with critical ejector	Low pressure impactor	Impactor with back-up filter, modular construction	chamber system and circular orifice jet double stages	Many micro-orifice nozzles (up to 2000)
size range [µm]	0.41-17.4 Mark II, 2: 0.41 – 9	0,02 – 20	0.03–10 with filter stage 0.007-10	1.5 – 10	0.3 - 20	0.056 - 18
Max. Stack Temp. [°C]	850	90*/180	< 150	135	220	
Nominal flow rate [lpm]	3 – 30	2 -150 (typ. 25)	10 or 30	17 – 50 (typ. 30)	17 – 43 (typ. 25)	30
diameter impaction area [mm]	70	25	25	50	50	25

Overview on most commonly used cascade impactors
189x181mm (300 x 300 DPI)

HANDBOOK ON COMBUSTION

Chapter B2: Measurement of particles properties: concentration, size distribution, density

Dr.-Ing. M. Gaderer, Dipl.-Ing. R. Kunde, Dipl.-Ing. Ch. Brandt

Glossary

Term	Acronym	Explanation
Aerodynamic diameter	D_a	Relation diameter of a spherical particle density 1 g/cm³ that has the same gravitational settling velocity as the particle of interest.
Aerodynamic particle sizer	APS	In an APS, the particle size is determined by the particle speed in an accelerating gas flow.
Aerosol		Dispersion of fluid / solid particles in a gaseous material.
Condensation particle counter	CPC	Optical counter for detecting particle number concentration of an aerosol using condensation of vapor around particles to magnify them.
Condensation nuclei counter	CNC	Optical detector to count droplets condensed around particles. Droplets are made by leading particles through a saturated vapor.
Cunningham correction factor		Correction factor of Stokes law for particles in the scale of the mean free path length λ (70 nm for air).
Dew point	Td	Temperature where condensation starts for a given specific load of water in air/aerosol.
Differential Mobility Analyser	DMA	Particle size screening device that makes use of the deflection of homogeneously charged particles in an electrical field. Depending on the field strength, only the fraction with matching mobility diameter reaches the detector.
Diffusion equivalent diameter		Diameter of spherical particles density 1 g/cm³ with the same diffusion rate (Brownian motion) as the particle of interest. Applies for particles < 0.5 µm.
Dilution tunnel		Device for dilution the whole or a sample flow of an exhaust stream. It is used to image conditions like at the exhaustion at the end of a chimney.
Dimensionless Stokes number		Ratio of stopping distance of a particle in a fluid to a characteristic dimension.
Electrical low pressure impactor	ELPI	Continuous measuring method for particle size distribution and number concentration by a cascade impactor with electrical detection.
Ejector diluter		Diluter that uses venturi effect of dilution air in a converging nozzle to draw sample gas.
Equivalent diameter		Diameter of a spherical particle with the same key attribute as the particle of interest.
Form factor		Measure for the deviation of a particle shape from sphericity, often as the quotient of two equivalent diameters for different key attributes of the same particle.
Isokinetic sampling		Taking a sample probe at the same flow velocity and direction in the probe inlet as in the examined gas flow.
Impactor		Device to deposit particles above a critical diameter on a sampling target by inertial forces caused on deflection.
Laser particle counter	LPC	Single particle counter measuring the size and number concentration of aerosol particles by the deflection and scattering properties of the particles in laser light.
Mobility diameter	Db	Relation diameter of a spherical particle density 1 g/cm³ moving with the same velocity in an electric field as the particle of interest
Normal cubic meter		Amount of gas that takes the Volume of one cubic meter at STP.
Optic equivalent diameter		Relation diameter of a particle with the same optical scattering characteristics to light as the particle of interest.

Optical particle counter	OPC	Single particle counter measuring the size and number concentration of aerosol particles in a limited size range by means of light scattering by single particles.
Particulate matter	PM	Disperse solid particles smaller than 10 µm.
Particle neutralizer		Device to create an overall neutral ionized aerosol with a well defined charge distribution. Typically weak beta ray emittents are used, e.g. Kr-85.
Porous tube diluter		Sample dilution system. Sample is leaded through a porous tube. Dilution air is added through the porous material (holes).
Rotating disc diluter		Dilution system using a rotating disc with cavities to carry rotationally portions oft undiluted sample flow into a continuous dilution air flow.
Respirable fraction	PM2.5	Collective of particles smaller than or equal 2.5µm in an aerosol.
Settling velocity		Equilibrium sinking speed of a particle under gravity in a fluid.
Standard conditions for temperature and pressure	STP	Reference conditions (temperature and pressure) for specification of properties of gasses. Various definitions exist. Present IUPAC definition T=0℃ p=1000 hPa, DIN 1343 T=0℃ p=1013 hPa.
Stokes' law		The Stokes law describes the frictional force (also drag force) on a spherical particle in a fluid dependent on radius, dynamic fluid viscosity and particle velocity.
Stroehlein design		Design of a filtering system by Stroehlein. At this system a shell is padded with quartz fibre wool and is used for deposition of particulate emissions.
Sub-isokinetic sampling		Taking sample probe at a lower flow velocity in the probe inlet than in the examined gas flow.
Super-isokinetic sampling		Taking sample probe at a higher flow velocity in the probe inlet than in the examined gas flow.
Tapered element oscillation microbalance	TEOM	Device for in situ particle mass concentration measurement by determination mass changing of a colleting substrate using its resonance frequency.
Thermophoresis		Particle movement induced by a temperature gradient, particles move from hot to cold.
Thoracic fraction	PM10	Collective of particles smaller than or equal to 10µm in an aerosol.
Total suspended particulate matter	TSP	Collective of all particles in an aerosol.
Alveolar fraction	PM1	Collective of particles smaller than or equal 1µm in an aerosol.
Venturi nozzle		Nozzle to decrease static pressure by accelerating the fluid. It is used to generate negative pressure. At particle measurement it is used to exhaust a sample flow with simultaneous dilution.