

## DUST - PARTICLE FORMATION AND CHARACTERISTICS

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## Summary

Dust is a very complex subject. Its origin may be natural, or a consequence of human activity. Primary particles are as they were formed, secondary particles originate in atmospheric conversion processes.

Aitken particles are the largest in number, but represent little in mass units. They are important in cloud formation. Aerosols create haze and are relatively stable.

Total Suspended Particles represent the bulk of atmospheric dust and mass is still the basis of dust emission codes. From a health point of view, however, it is important to know whether dust is inhalable and how deeply it penetrates into the lungs. Today, there is a shifting concern, from particulates smaller than 10  $\mu\text{m}$  ( $\text{PM}_{10}$ ) to  $\text{PM}_{2.5}$  and even much smaller.

The diameter of a particle may be defined in numerous ways, depending on the property considered. Sieving addresses cross-sectional area, sedimentation, centrifugation and elutriation an aerodynamic diameter. Particles can be examined using a microscope, Coulter counter, laser diffraction, and cascade inertial impaction. Sampling and dust monitoring methods are discussed.

## 1. Survey

Particulate matter (PM) is very variable in origin, nature, concentration, and size distribution. Natural particulate arises from erosion, sand storms, and surf, from forest fires and volcanic activity. Bio-aerosols comprehend pollen, a seasonal allergen, as well as transformation products of natural semi-volatiles, such as terpenes and isoprene.

Anthropogenic particles originate from combustion, metallurgy, bulk and filter dust handling, and are a carrier of adsorbed chemicals, bio-contaminants or condensed gases, which can trigger various health effects.

Primary particles are introduced into the air in solid or liquid form, while secondary particles are formed in the air by gas-to-particle conversion of oxidation products of emitted precursors.

Atmospheric particles are evaluated very differently, depending on whether mass or number is handled as a main criterion.

The amount of Total Suspended Particles (TSP) in the atmosphere is expressed in mass units. Strong winds will enhance TSP, by remobilizing settled dust.

Inhalable particles, presented as PM<sub>10</sub>, are considered more important from a health viewpoint. Size strongly influences in which part of the respiratory tract the particles are deposited. Larger particles are deposited in the nasal area and in the upper parts of the respiratory tract. Smaller particles follow the airflow to the deeper parts and have a high probability of depositing by diffusion.

Aitken particles, smaller than 0.1  $\mu\text{m}$  in diameter, represent by far the largest number of particles and play a role in atmospheric processes, such as cloud formation, rainout and washout.

Aerosols are defined differently in various disciplines. They are relatively stable suspensions of particles, and may also be termed mist, fog, fumes, and smoke.

The size of particles determines dynamic properties, behavior and fate during transport. Large particles are mainly of crystal origin, and from natural sources. The highest level of concentration of trace elements and toxins from anthropogenic sources and radioactivity from natural sources is related to the very small particles.

Particle physical and chemical properties bear a relation to the sources generating the particles. This helps to identify the parameters or their ranges that should be specifically targeted for various types of emission sources operating in the environment under investigation.

Atmospheric aerosol concentrations range from:

- 2  $\mu\text{g m}^{-3}$  in polar regions;
- 10  $\mu\text{g m}^{-3}$  as background value;

- 30  $\mu\text{g m}^{-3}$  for remote and rural locations;
- 170  $\mu\text{g m}^{-3}$  for polluted urban areas up to
- 100 000  $\mu\text{g m}^{-3}$  in sand storms!

## 2. Sources

Coarse particles are mainly from mechanical processes, including grinding, breaking and wear of material, transport, and dust re-suspension, and contain largely earth crust compounds.

Fine particles are mainly from combustion, photochemical processes, and gas to particle conversion. Typically they contain soot, organic compounds, and acid condensates, i.e. sulfates and nitrates, as well as trace metals and other toxins.

Some processes generate particles with broad size distributions, covering both fine and coarse ranges, e.g. in forest fires there are airborne combustion products, as well as large diameter particles that are entrained into the smoke column as a result of the turbulence and buoyancy generated by the fire. In most cases, however, fine and large particles result from totally different generation processes. Thus fine and coarse airborne particles, or particle number and mass are not necessarily correlated. It is evident that from the measurement of total particle mass only limited information can be obtained.

Primary biological aerosol particles are discussed in *Indoor Air Quality Monitoring and Control*.

- Condensed water aerosols comprise haze, fog, and clouds.
- Raindrops, snow and hail are very short-lived.
- Hydrometeors are atmospheric particles with water as a dominant component.
- Clouds can be subdivided into:
  - *cumulus*, clouds with considerable vertical development;
  - *stratus*: layer clouds;
  - *nimbus*: rain clouds and
  - *cirrus*: fibrous ice clouds.

These are further combined to subgroups, e.g. *strato-cumulus*.

In haze horizontal visibility is between 1 and 10 km; in fog it descends below 1 km.

Particle properties strongly depend on both particle formation and post formation processes. Fine and coarse mode particles have different chemical composition and origins, are transported and removed by different mechanisms, and require different detection techniques. Many efforts have been made to correlate emission sources and immission of particulate, on a basis of composition, elemental and isotopic ratio, and other characteristics, termed source markers.

### 3. Physical Characteristics

Some important physical properties of particles (individually, or as a group) include:

- Number and number size distribution;
- Mass and mass size distribution;
- Specific surface area;
- Shape;
- Volatility;
- Hygroscopicity;
- Electrical charge.

There are no instruments that can measure the entire particle size range, from nanometers to tens of micrometers and usually there is a size range selected for investigations that depends on the objectives of the investigations. Various classifications and terminologies have been used to define particle size ranges.

#### 3.1. Number and Number Distribution

Large numbers (up to millions per cubic meter) are associated with Aitken particles and Cloud Condensation Nuclei. A second mode (i.e. a maximum in the distribution curves) is generally generated by fine or coarser aerosol particles, caused by emissions and by atmospheric chemical reactions often involving ammonia and sulfuric acid.

Coarse particles are generally blown up by the wind and are of crystal origin.

#### 3.2. Particle Sizes and Size Distribution

Size is characterized by particle diameter, or for irregular shapes - equivalent particle diameter, i.e. the diameter of a sphere having the same value of a physical property as the particle being measured. Equivalent diameter relates to any property, e.g. inertia, electrical or magnetic mobility, light scattering, radioactivity, Brownian motion, or to chemical or elemental concentration, cross-sectional area, and volume to surface ratio.

Particles from most atmospheric sources have a lognormal size distribution: a particle concentration versus particle size curve is normal (bell shaped), when the particles are plotted on a logarithmic scale. Particle size distributions often contain several distinct peaks, called modes.

A wide-ranging aerosol collector (WRAC) provides an estimate of the full coarse mode distribution. Inlet restrictions of the high volume sampler for TSP, the PM<sub>10</sub> sampler, and the PM<sub>2.5</sub> sampler reduce the total mass reaching the sampling filter.

#### 3.3. Droplet Size

Droplets are approximately spherical in shape, although elongation occurs under industrial flow conditions. Depending on the application at hand the representative droplet size is selected differently.

Droplet size is frequently denoted by a mean or median diameter. Each nomenclature for describing droplet sizes leads to different numerical values. Mass Volume Median Diameter is the largest of all and number median diameter is the smallest. The differences between the various mean and median diameters provide a way of conveniently specifying the spread of droplet sizes produced. If all droplets had been uniform in size, the mean and median diameters would have been identical with the uniform size. Droplet size has been measured with a PDPA (Phase Doppler Particle Analyzer) system.

| Mean Value               | Definition   |
|--------------------------|--|
| Arithmetic               | Weighted average of the diameters of all individual droplets in the spray sample   |
| Surface                  | Diameter of a droplet whose surface area, if multiplied by the total number of droplets, will equal the total surface area of all droplets in the spray sample |
| Volume Surface or Sauter | Diameter of a droplet whose ratio of volume to surface area is equal to that of the entire spray sample  |

[Source: Dr. Alan Rawle, “Basic Principles of Particle Size Analysis”, Technical Paper, Malvern Instruments Ltd.]

Table 1: Usual Methods of Describing Droplet Size

Mass (Volume) Median Diameter: the diameter, which divides the mass (volume) of spray into two equal halves.

$$V_m = V_g + V_p \quad \text{volume of mixture} \quad (1)$$

$$\alpha = V_g/V_m = 1 - V_p/V_m \quad \text{void fraction} \quad (2)$$

where

- $N$  = number of particles
- $V_g$  = volume of gas phase
- $V_p$  = volume of particulate phase

### 3.4. Number Frequency Distribution

$$\text{AREA} = F_N(D) \Delta D = \text{Fraction of particles between } D \text{ and } D + \Delta D \quad (3)$$

$$\text{Number mean } \mu_N = \int_0^\infty D F_N(D) dD \quad (4)$$

$$\text{Number variance } \sigma_N^2 = \int_0^\infty (D - \mu_N)^2 F_N(D) dD \quad (5)$$

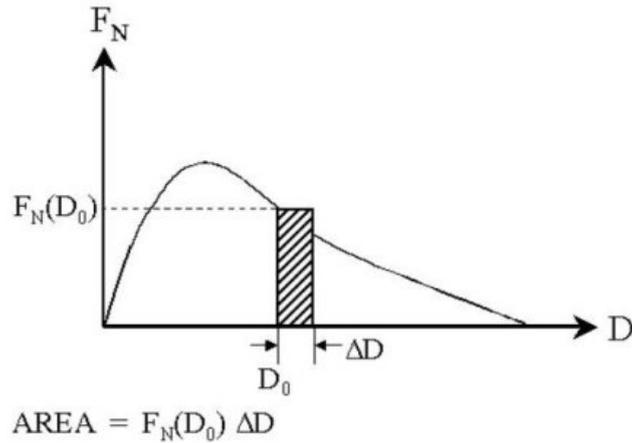


Figure 1: Number Frequency Distribution

### 3.5. Mass Frequency Distribution

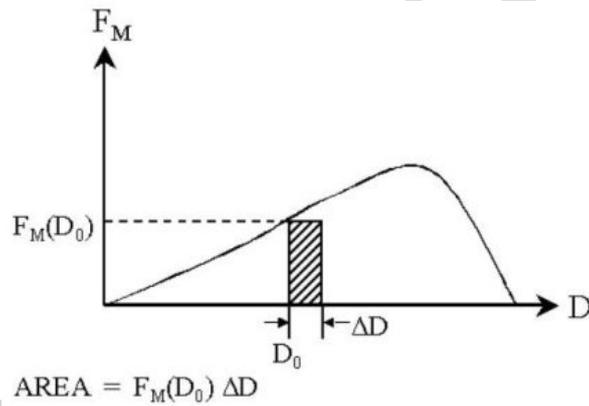


Figure 2: Mass Frequency Distribution

$$\text{AREA} = F_M(D) \Delta D \quad (6)$$

= Fraction of particulate mass associated with particles between  $D$  and  $D + \Delta D$

$$\text{Mass mean } \mu_M = \int_0^{\infty} D F_M(D) dD \quad (7)$$

$$\text{Mass variance } \sigma_M^2 = \int_0^{\infty} (D - \mu_M)^2 F_M(D) dD \quad (8)$$

## 4. Chemical Characteristics

Important chemical properties are:

- Elemental composition, including mineral dust and water.
- Secondary inorganic ions, mainly sulfate, nitrate and ammonium.
- Carbonaceous compounds (organic and elemental carbon).

- Organic composition.

#### 4.1. Elemental Composition

Combustion results in emissions of a cluster of different trace elements, present in the fuel or the lubricants used (motor vehicles). Since most trace elements are associated with ultra fine particles and are less prone to chemical transformations, they undergo long-range atmospheric transport.

Mechanical processes, such as mining, mineral processing, quarrying, breaking, grinding, dust re-suspension, etc, generate particles predominantly containing crustal elements. Table 2 relates common outdoor particle sources to common suites of elements.

| Emission Source  | Characteristic Elements Emitted  |
|--|--|
| Road transport<br>Motor vehicle emissions<br>Engine wear<br>Catalytic converters<br>Tyre wear<br>Road side dusts   | Br, Pb, Ba, Mn, Cl, Zn, V, Ni, Se, Sb, As<br>Fe, Al<br>Rare earths, Pt<br>ZnO, carbon black<br>EC, Al, Si, K, Ca, Ti, Fe, Zn |
| Industrial facilities<br>Oil fired power plants<br>Coal combustion<br>Oil Refineries<br>Nonferrous metal smelters<br>Iron and steel mills<br>Copper refinery | V, Ni<br>Se, As, Cr, Co, Cu Al, S, P, Ga<br>V<br>As, Sb, Cu, Zn, Pb, Cd, Hg<br>Zn, Pb<br>Cu, Zn                              |
| Refuse incineration  | Zn, Pb, Cu, Cd, Hg, K  |
| Mineral and material processing  | Si, Al, Ca, Mg, K, Sc, Fe, Mn.   |
| Sea spray  | Na, Cl, S, K   |
| Resuspended soil   | Si, Al, Ca, Mg, Fe, Ti, Sr, Mn, Sc   |

[Source: Adapted from “Guidelines for concentration and exposure-response measurement of fine and ultra fine particulate matter for use in epidemiological studies”, Ed. D. Schwela et al. World Health Organization, 2002.]

Table 2: Elements emitted from various particle sources (according to WHO), EC = Earth Crust

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## Biographical Sketch

**Alfons Buekens** was born in Aalst, Belgium; he obtained his M.Sc. (1964) and his Ph.D (1967) at Ghent University (RUG) and received the K.V.I.V.-Award (1965), the Robert De Keyser Award (Belgian Shell Co., 1968), the Körber Foundation Award (1988) and the Coca Cola Foundation Award (1989). Dr. Buekens was full professor at the Vrije Universiteit Brussel (VUB), since 2002 emeritus. He lectured in Ankara, Cochabamba, Delft, Essen, Sofia, Surabaya, and was in 2002 and 2003 Invited Professor at the Tohoku University of Sendai.

Since 1976 he acted as an Environmental Consultant for the European Union, for UNIDO and WHO and as an Advisor to Forschungszentrum Karlsruhe, T.N.O. and VITO. For 25 years, he advised the major industrial Belgian Bank and conducted more than 600 audits of enterprise.

Main activities are in thermal and catalytic processes, waste management, and flue gas cleaning, with emphasis on heavy metals, dioxins, and other semi-volatiles. He coordinated diverse national and international research projects (Acronyms Cycleplast, Upcycle, and Minidip). Dr. Buekens is author of one book, edited several books and a Technical Encyclopedia and authored more than 90 scientific publications in refereed journals and more than 150 presentations at international congresses. He is a member of Editorial Boards for different journals and book series.

He played a role in the foundation of the Flemish Waste Management Authority O.V.A.M., of a hazardous waste enterprise INDAVER, and the Environmental Protection Agency B.I.M./I.B.G.E. He was principal ministerial advisor in Brussels for matters regarding Environment, Housing, and Classified Enterprise (1989). Since 1970 he has been a Member of the Board of the Belgian Consumer Association and of Conseur, grouping more than a million members in Belgium, Italy, Portugal, and Spain.

He is licensed expert for conducting Environmental Impact Assessments (Air, Water, Soil) and Safety Studies regarding large accidents (Seveso Directive).

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