Aerosol Measurement Techniques

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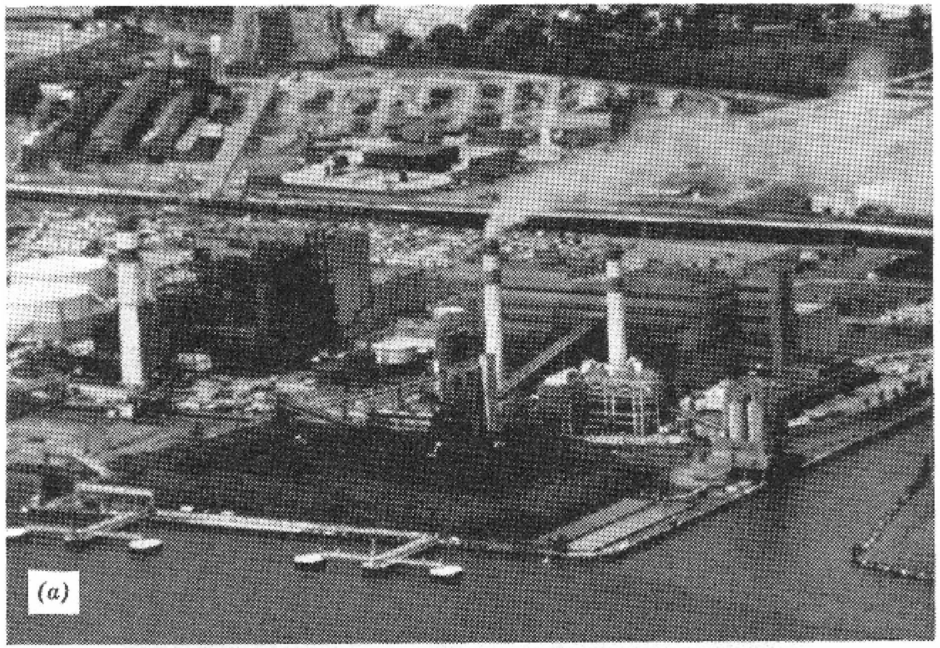
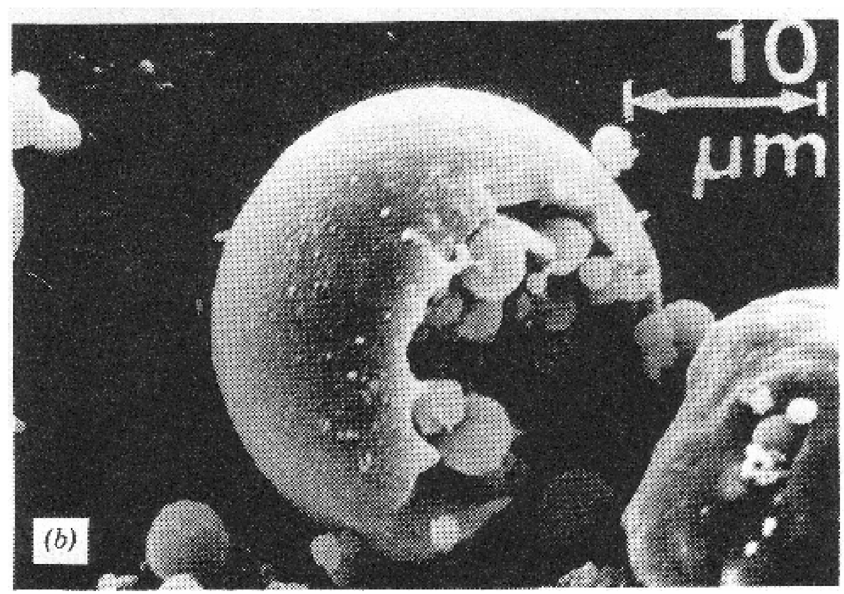
Aerosol

- Aerosol is a collection of liquid or solid particles suspended in air
  - Typical particle sizes – 1 nm to 100 μm
  - Examples of aerosol particles
    - Resuspended soil particles
    - Smoke from power generation
    - Primary and secondary particles from automobile exhaust
    - Photochemically formed particles
    - Salt particles
    - Water droplets
    - Ice particles

Atmospheric aerosol

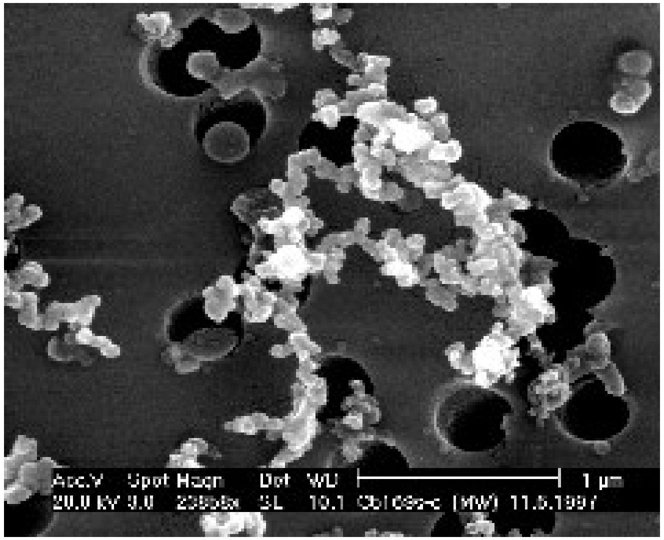


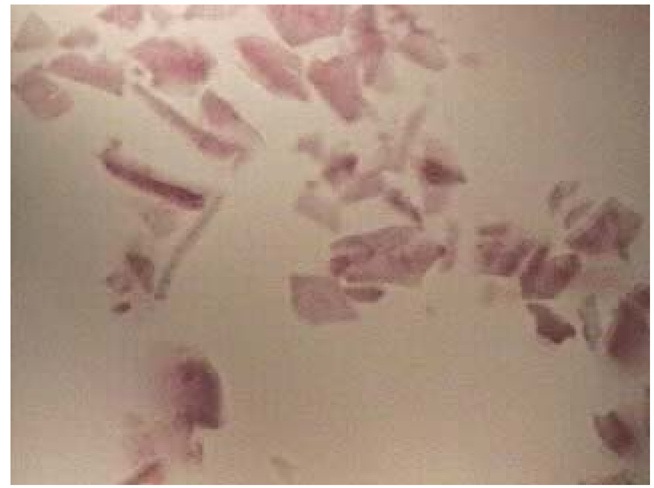
Aerosol emission from coal plants

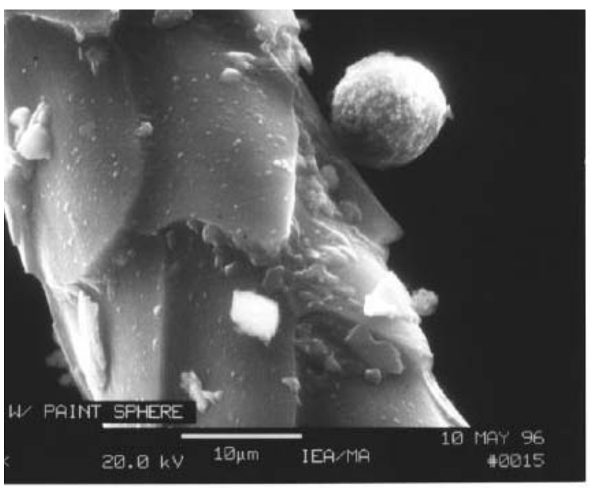


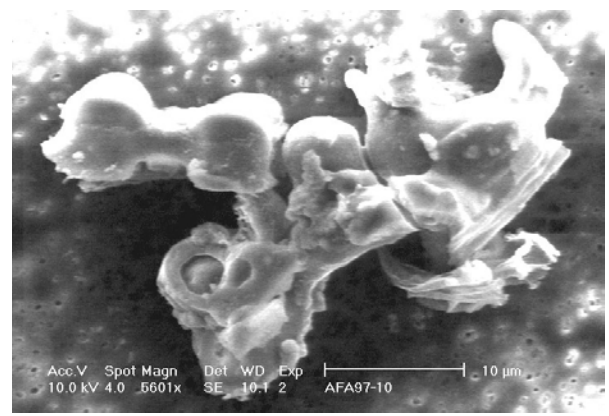
Typical coal fly ash particle

SEM of some particles









Aerosol role

- Wide range of roles
  - Atmospheric pollution
    - Influence production and transport of pollutants
    - Cause visibility problems
    - Smog
  - Health effects
    - Respiratory problems
    - Studies have shown correlation of nano-particle concentration in the urban environment to morbidity and mortality rates
  - Global warming
    - Aerosols contribute to the earth's radiation budget
  - Ozone loss
    - Polar stratospheric clouds provide the surface area for heterogeneous reactions that enable polar ozone loss

Industrial applications of aerosols

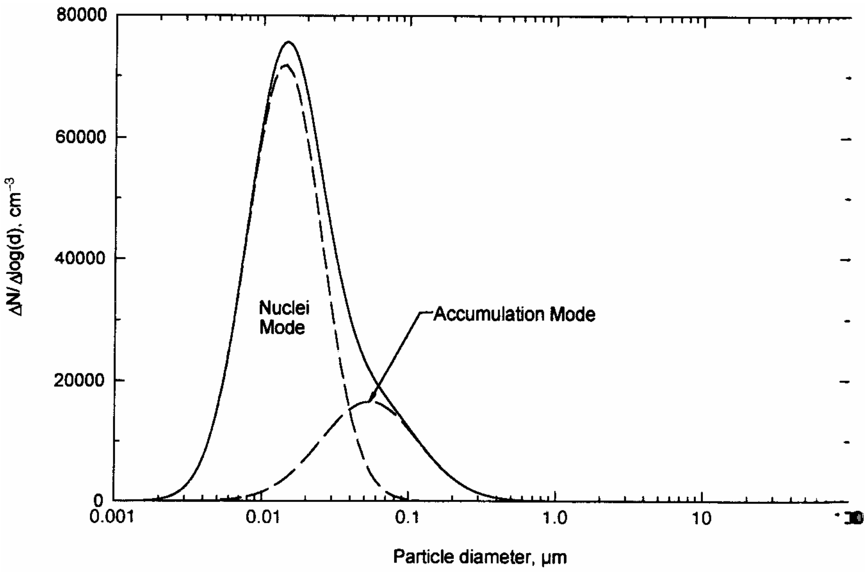
- Aerosol technology
  - Manufacture of spray-dried products
  - Fiber optics
  - Production of pigments
  - Application of pesticides
  - Nanomaterials and nanotechnology

Aerosol properties

- Different aerosol properties to be measured
  - Particle size
  - Number
  - Shape of particles
  - Mass
  - Composition
- Particle size is the most important matter to characterize aerosol behavior
  - Usually there is a distribution of particle sizes in the ambient

Atmospheric aerosol

Number distribution



Mass distribution

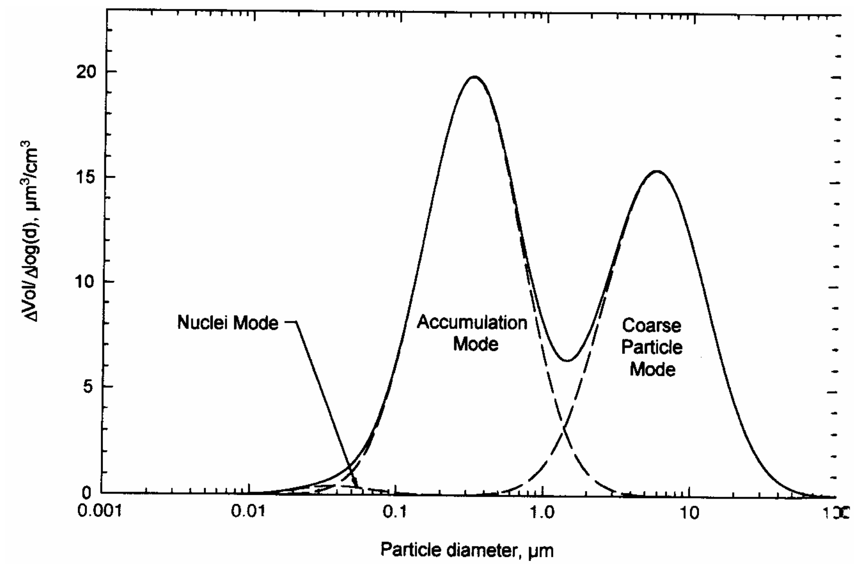


TABLE 14.3 Modal parameters for average urban aerosol.[a]

Mode	CMD (μm)	GSD	C_N (cm^{-3})	C_{vol} ($\mu m^3/cm^3$)
Nuclei	0.014	1.80	106,000	0.63
Accumulation	0.054	2.16	32,000	38.4
Coarse Particle	0.86	2.21	5.4	30.8

[a]Data from Whitby (1978).

Sampling artifacts

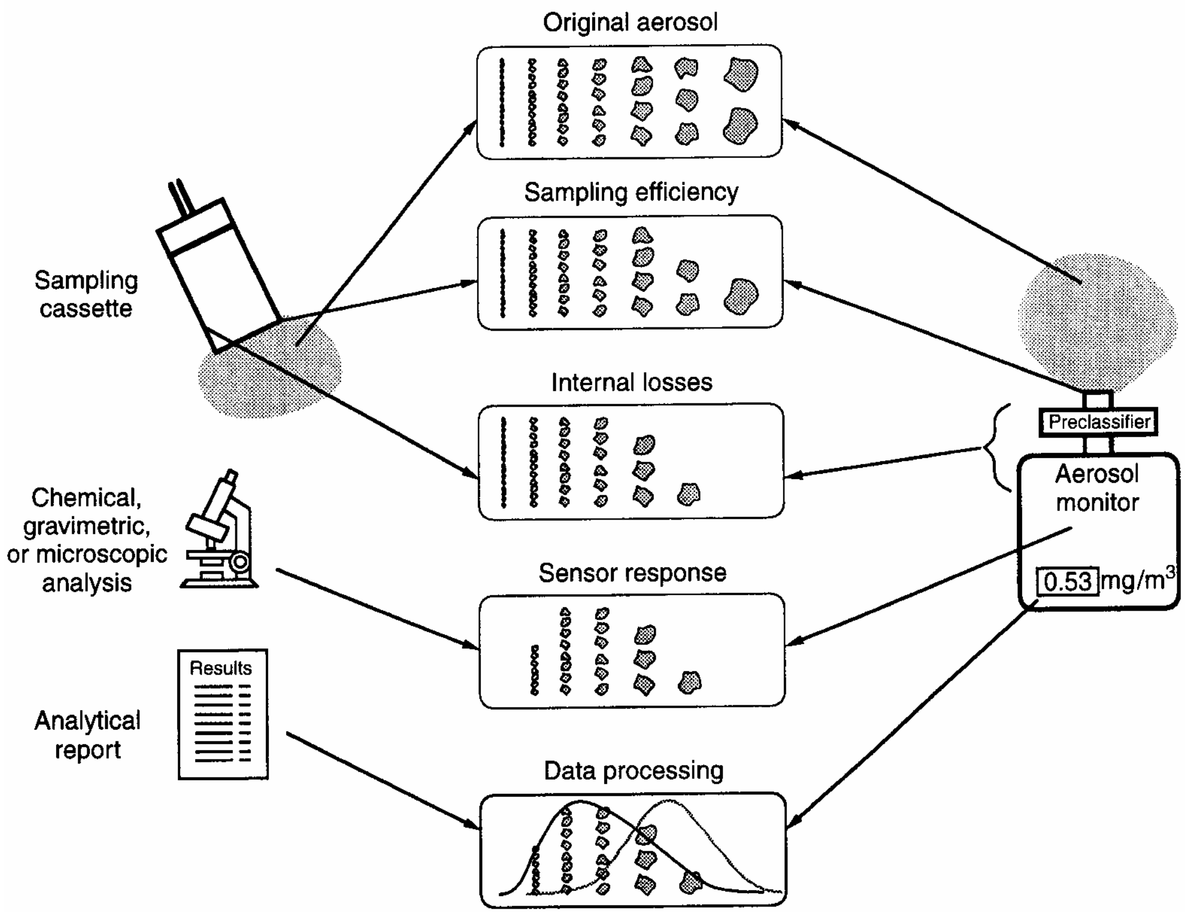


Fig. 7–3. Schematic representation of some important biases in aerosol monitoring. (Adapted from Willeke and Baron, 1990.)

Particle size characterization

From Hinds (1998)

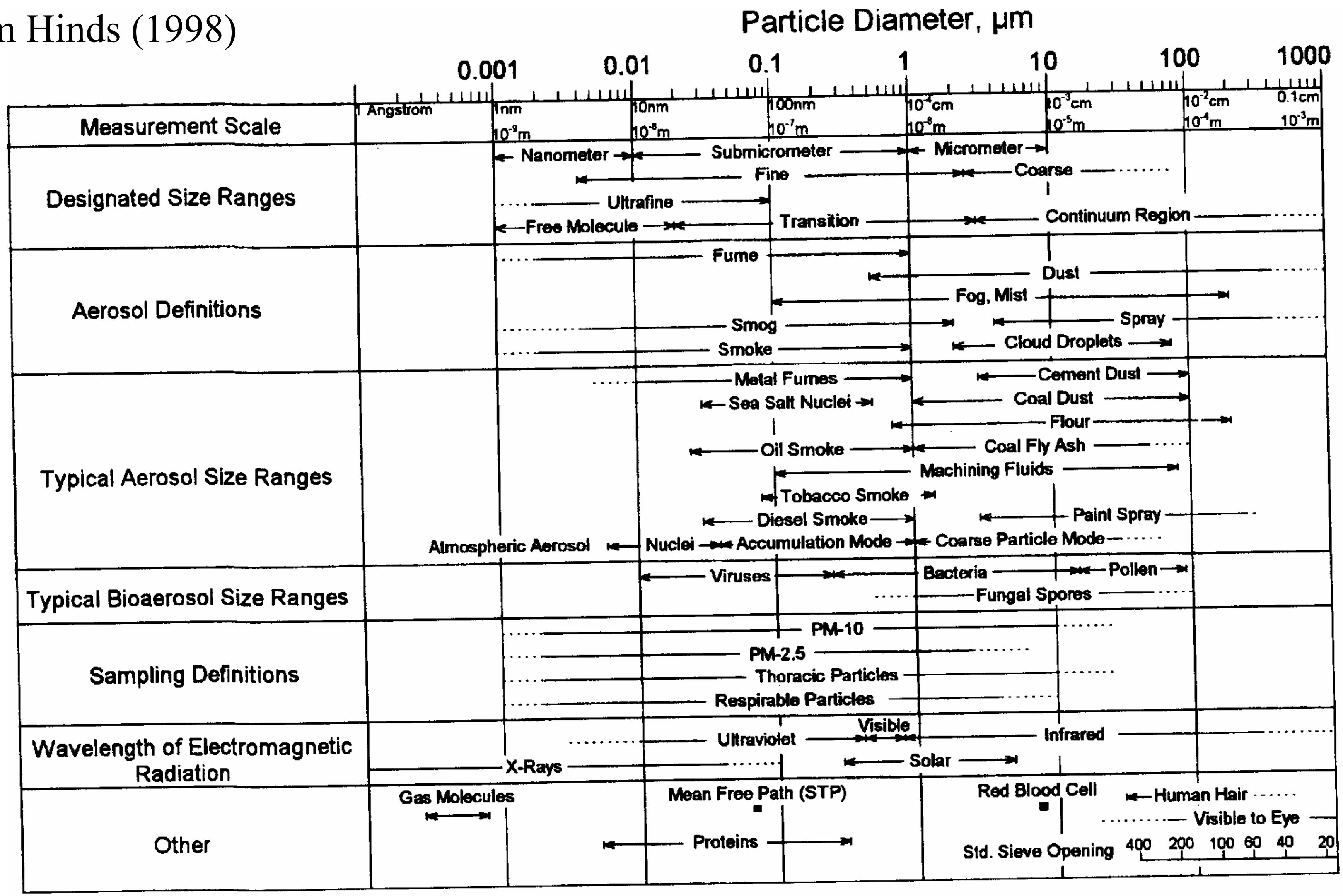


FIGURE 1.6 Particle size ranges and definitions for aerosols.

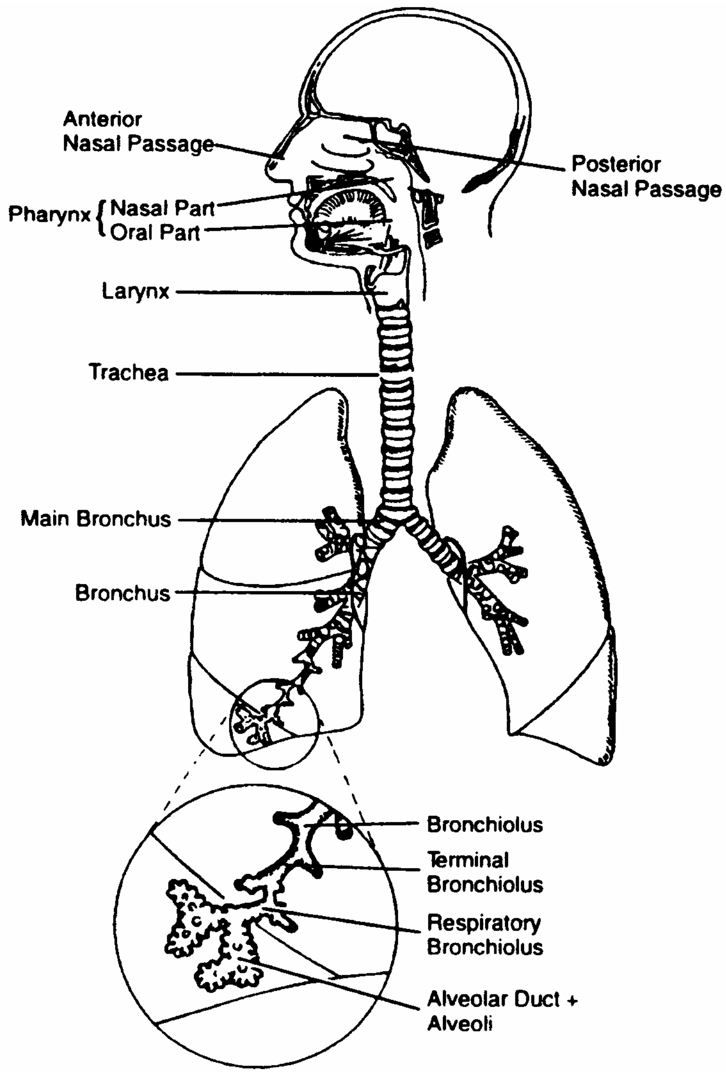
Atmospheric sampling

- Measures used by EPA to quantify aerosols in the atmosphere with respect to air quality and health effects.
  - TSP (Total Suspended Particulate)
    - Measure of all aerosol particles suspended in the air.
    - Dominated by dust and other particles that may not have any serious health effects
    - Old measure by EPA to measure air pollution
  - PM10
    - Particulate mass of particles smaller than 10μm.
    - Particles smaller than 10μm are respirable, i.e., they can be inhaled below the nasopharynx area (nose and mouth)
    - This measure was in vogue till very recently and still applicable

Atmospheric sampling

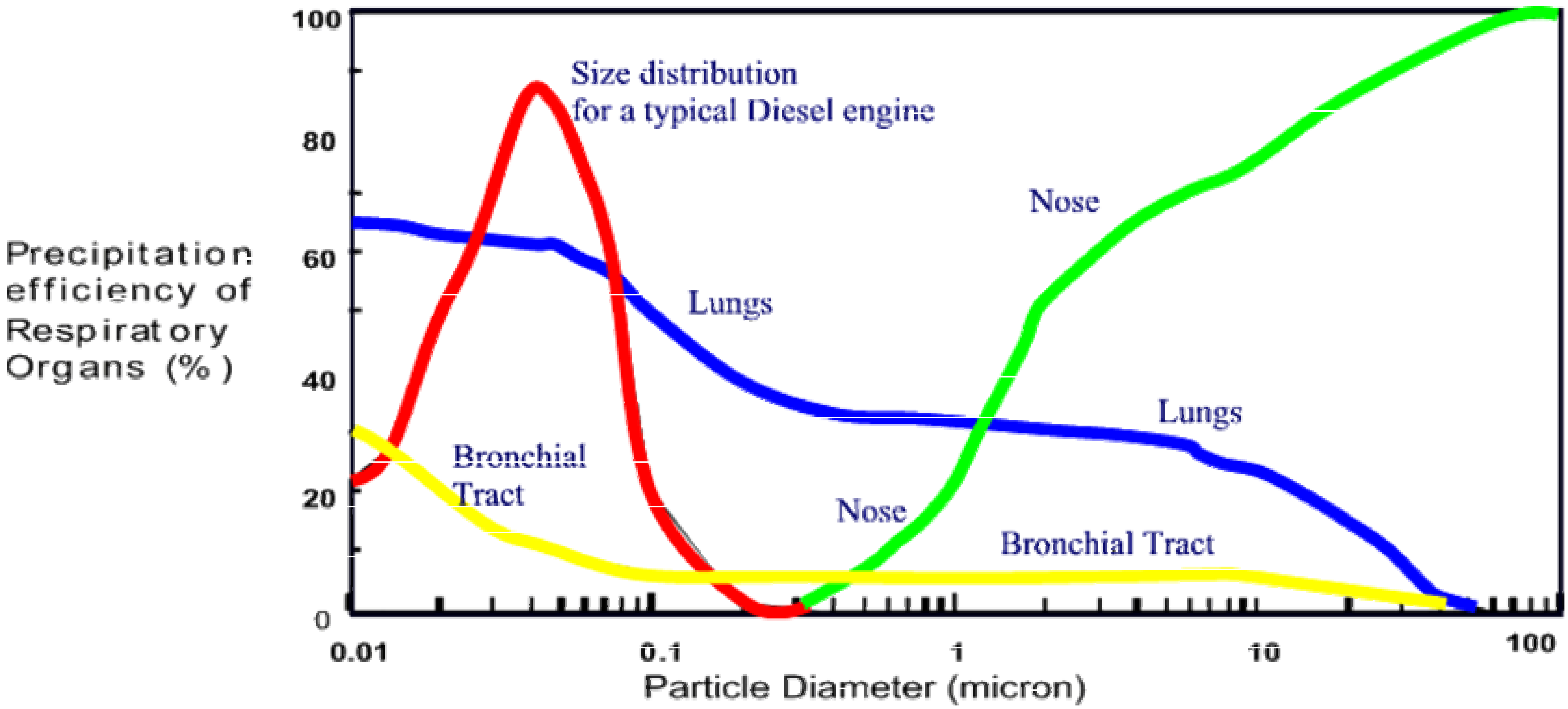
- PM2.5
  - Particulate mass of particles smaller than 2.5μm.
  - These particles travel down below the tracheobronchial region (i.e., into the lungs)
  - Also, significant fraction of anthropogenic aerosol (from human activities) are in this size range.
  - EPA currently uses this measure to determine if the atmospheric aerosol concentrations are acceptable
- PM1.0
  - Maybe in the future
- Ultrafine particles
  - Usually corresponds to particles with aerodynamic diameter less than 0.1μm.
  - These particles have shown to contribute significantly to respiratory problems
  - No regulation yet for these particles

Human Airways



The respiratory system

Particle deposition in the human respiratory system



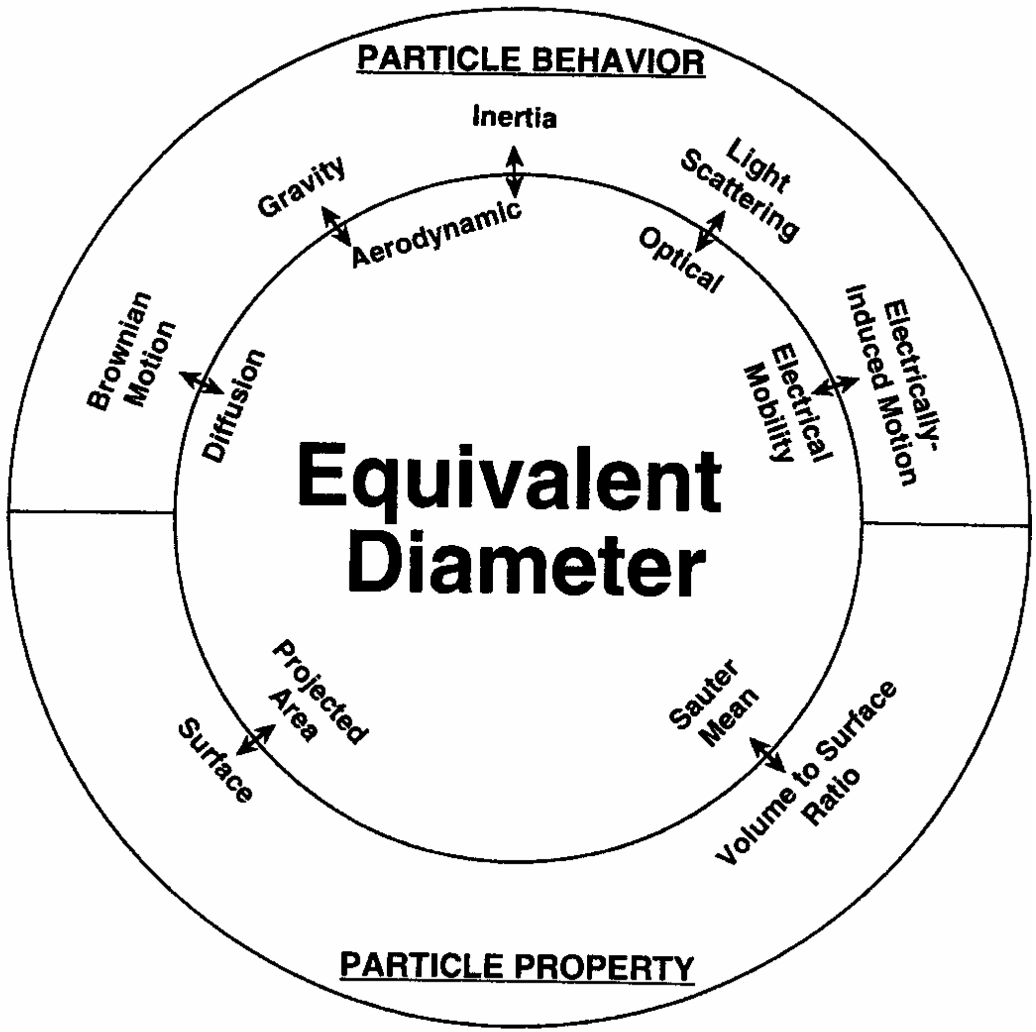
Particle sizing

- Microscope analysis
  - Slow and difficult
    - Only possible for a small sample
  - Sizing is based on particle property
    - Particle projected surface
    - Particle volume to surface ratio
- Real-time sizing
  - Particle size obtained based on behavior
  - Real-time, in-situ information can be obtained
  - Easy to obtain information on a large dataset
  - Analysis is complicated
  - Subject to interpretation errors
  - Laboratory calibration is often required

Particle sizing instruments

- No single instrument can measure particle sizes over the entire range (1nm to 100μm)
- A combination of techniques are required for aerosol measurement
- Different measurements yield different information about the particle
  - Therefore, multiple instruments are commonly used for aerosol characterization

Particle sizing



Inertial samplers

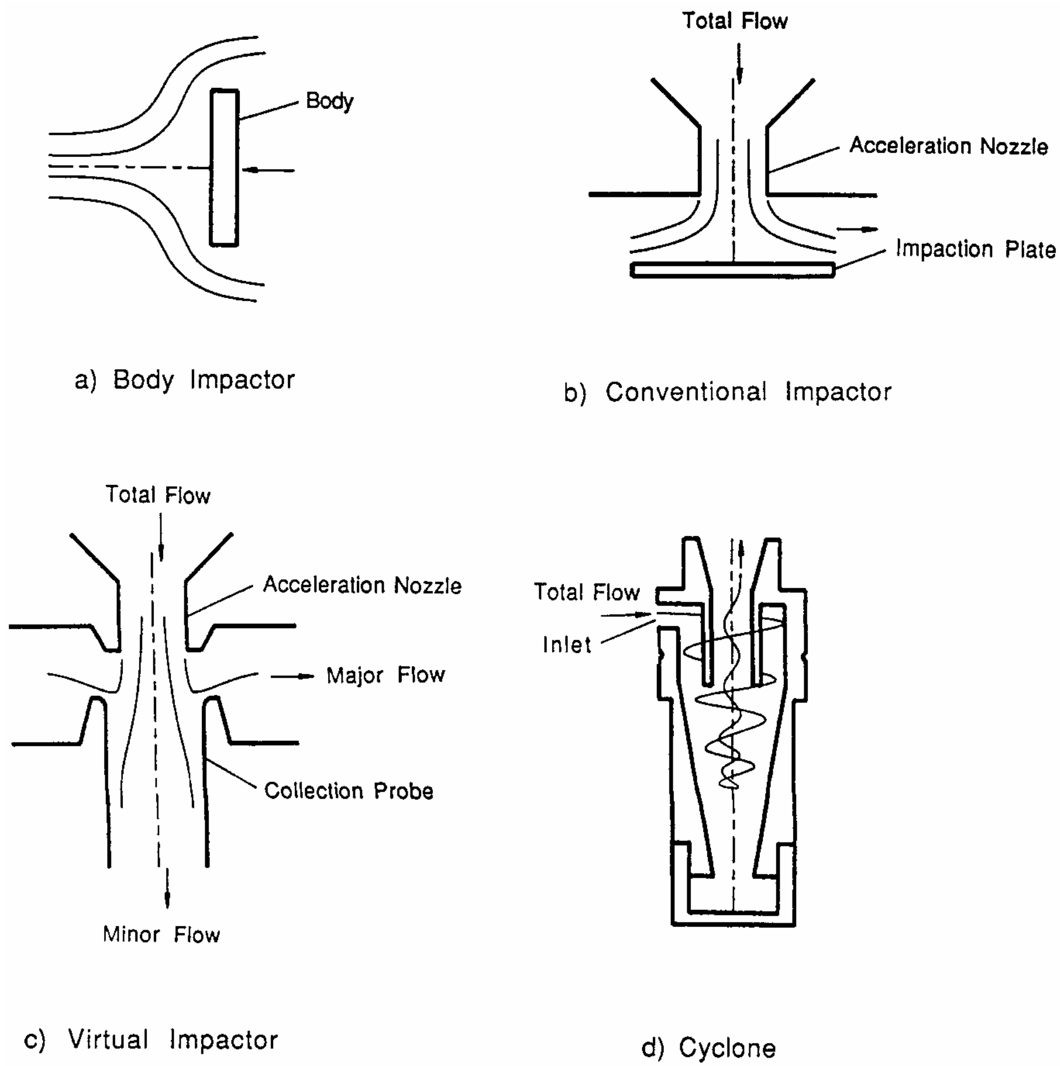


Fig. 10–1. Four types of inertial classifiers.

Inertial sampling

- Particles have a finite inertia and hence can deviate from the gas streamlines if a curvilinear motion is induced
  - The curvilinear particle motion is characterized by Stokes number
    - Stokes number is the ratio of the time it takes a particle to adjust to flow changes (i.e.,particle relaxation time) to the time available for adjustment

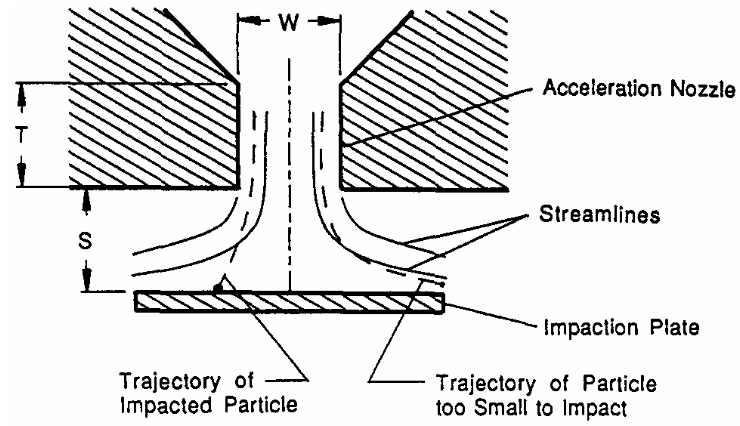
$$Stk = \frac{\tau}{d_c / U_0} = \frac{\tau U_0}{d_c}$$

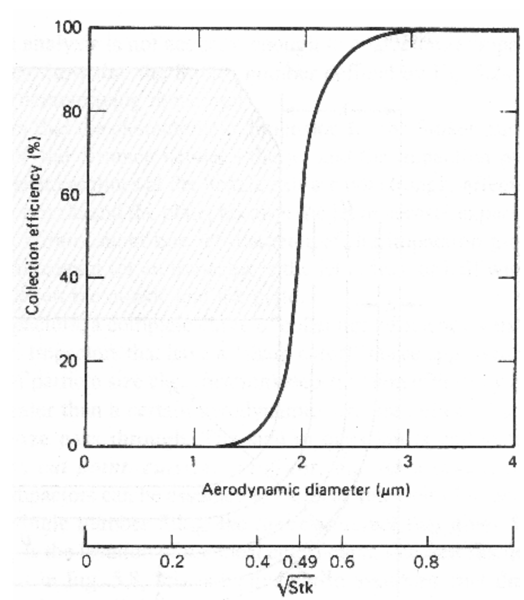
    - As Stk → 0, particles track the flow exactly
    - As Stk → ∞, particles resist any change in their direction

Inertial Impaction

$$Stk == \frac{\rho_p d_p^2 U C_c}{9 \eta D_j}$$

- Where ρ_p is particle density, d_p is particle diameter, U is gas velocity, C_c is the Cunningham slip correction factor, η is the gas viscosity, and D_j is the jet diameter

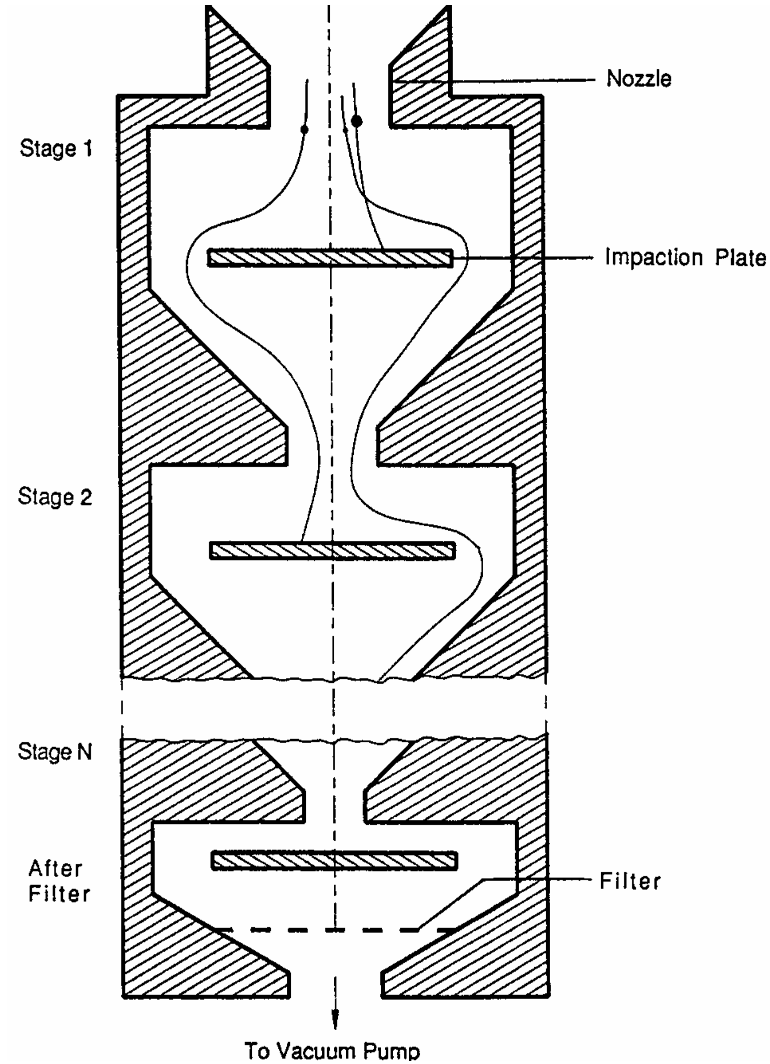




Typical impactor efficiency curve

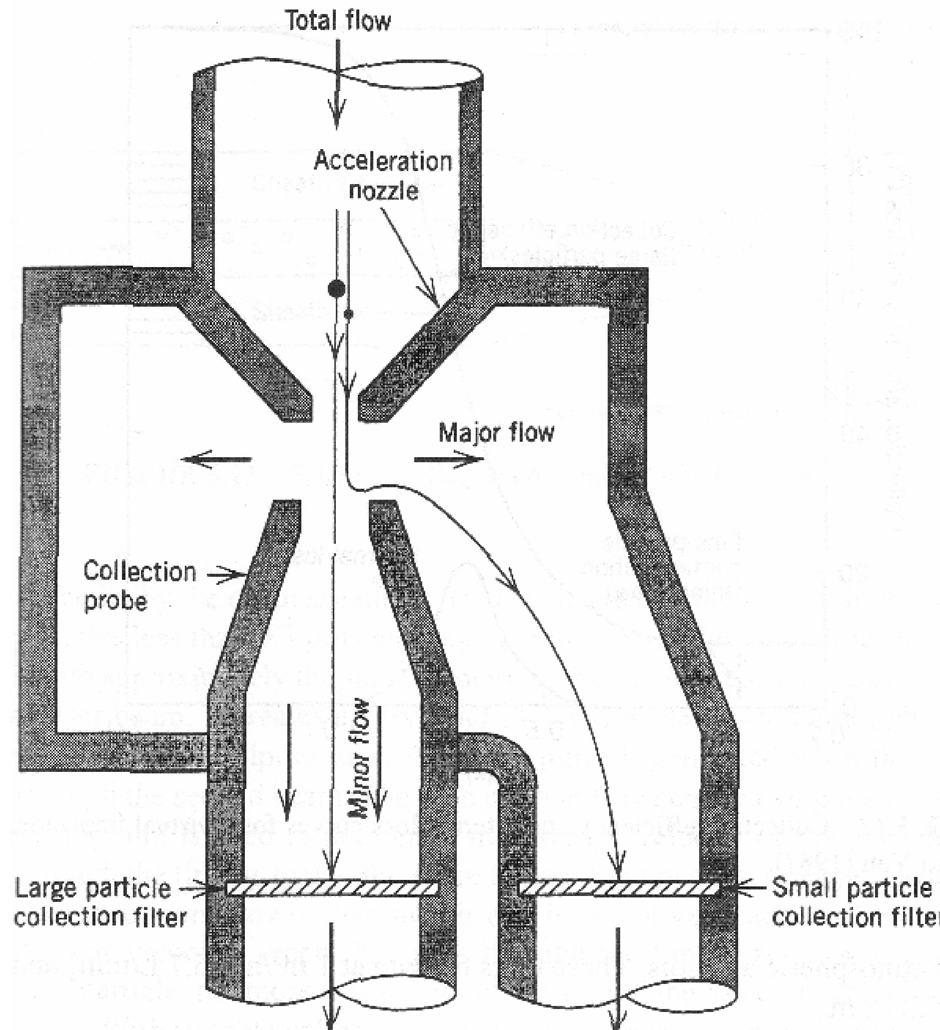
Inertial samplers

- With a series of impactors, particle mass as a function of size can be obtained
  - There are several commercially sold cascade impactors
  - One of the most popular methods to obtain particle mass distributions



Impactor

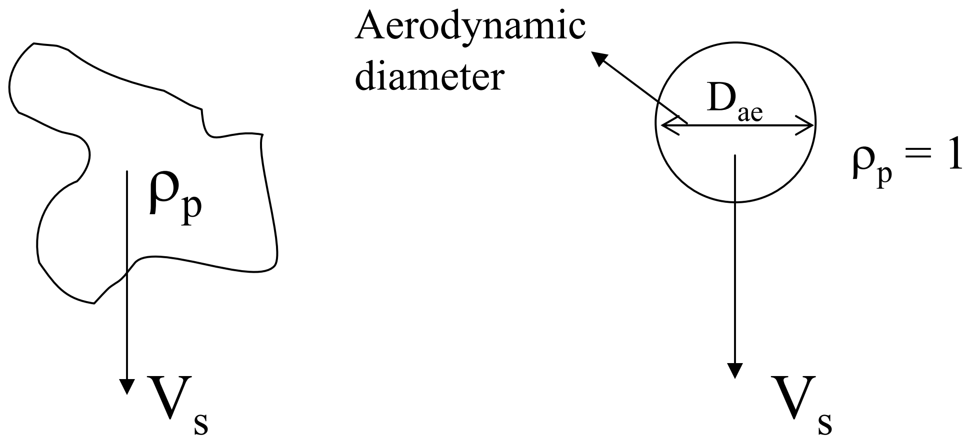
- Virtual impactor
  - Flow is split into two channels
    - Major flow carries most of the flow and small particles
    - Minor flow into which large particles from the total flow impact



Schematic diagram of a virtual impactor.

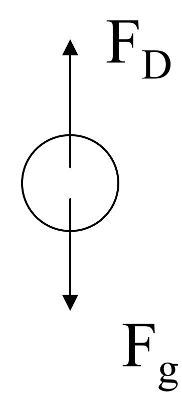
Aerodynamic sizing

- Aerodynamic diameter
  - Diameter of a unit density sphere (i.e., ρ_p=1, similar to a water droplet) with the same settling velocity as the particle in question



  - Settling velocity of a spherical particle

$$V_s = \frac{D_p^2 \rho_p C_c g}{18\eta}$$

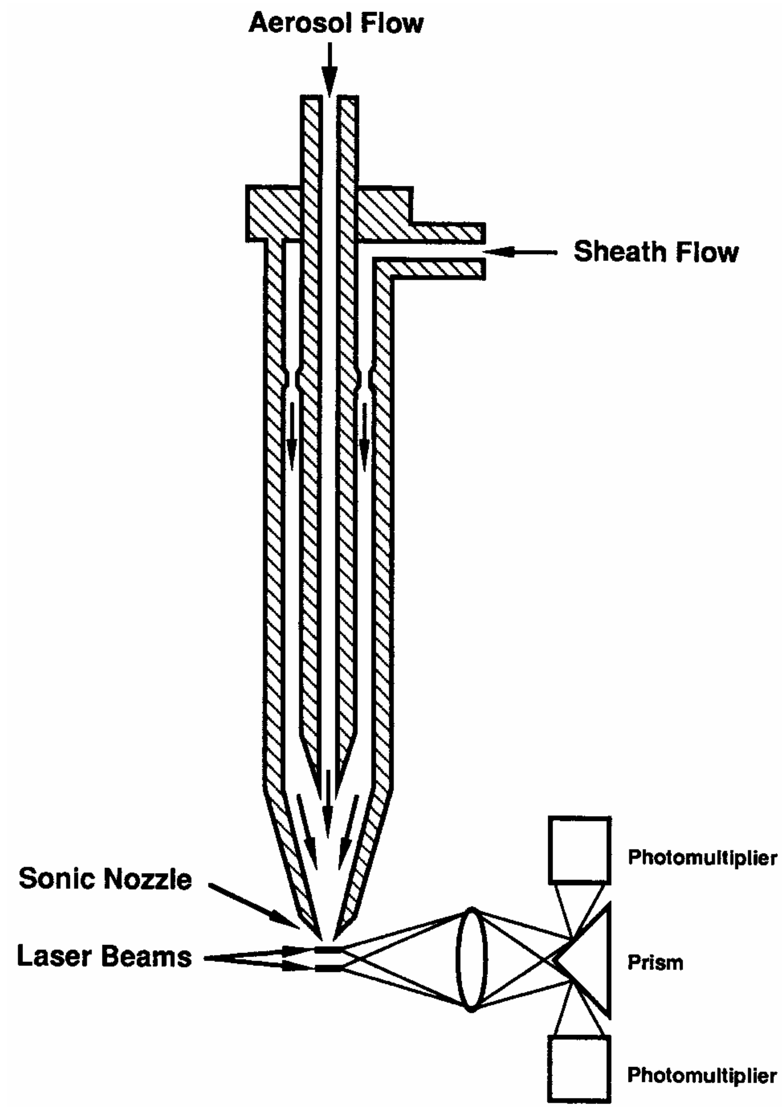


  - Aerodynamic size characterizes particle deposition in human lungs and filtration.

Aerodynamic sizer

- Time-of-flight instruments can provide real-time, high resolution measurement of aerodynamic particle size.

- Flow is accelerated through a nozzle, and small particles (< 0.3 μm) keep up with the acceleration while larger particles accelerate more slowly.
  - Particle size is obtained from measuring the transit time for particles between two laser beams.



Light Scattering

Mie Scattering

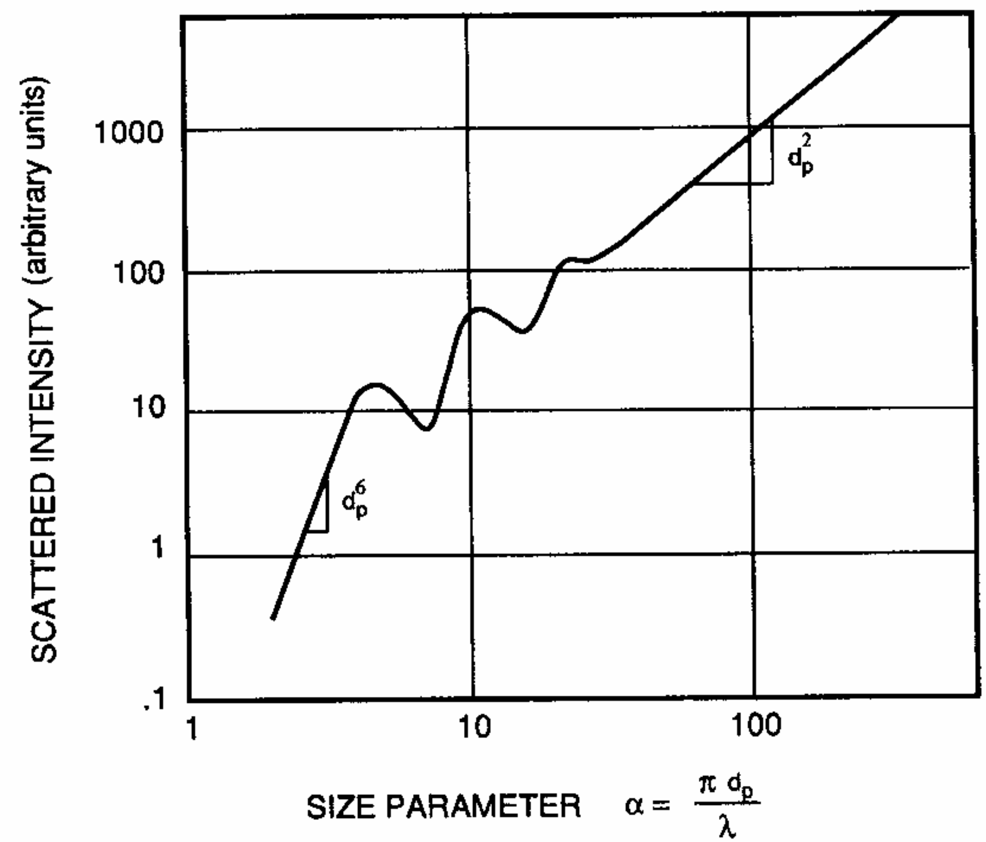
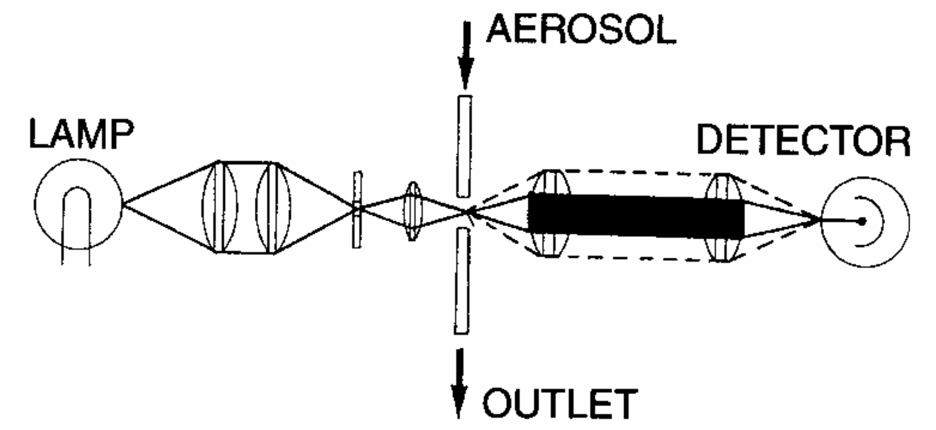
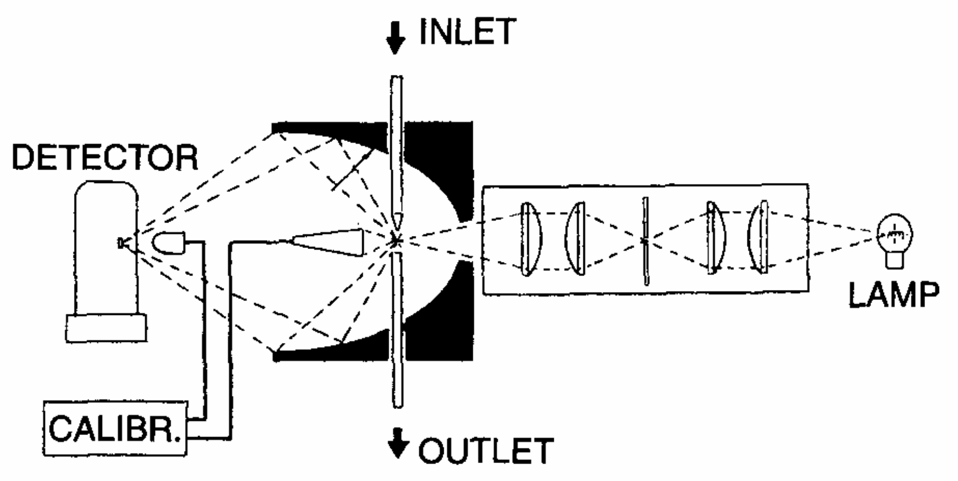


Fig. 16–2. Lorenz-Mie scattering response curve.

Light scattering instruments

- Schematic of a simple light scattering instrument
  - small collection angle





- Schematic of a CLIMET light scattering instrument
  - larger collection angle
  - Greater signal strength for the same aerosol size

Electrical mobility sizing

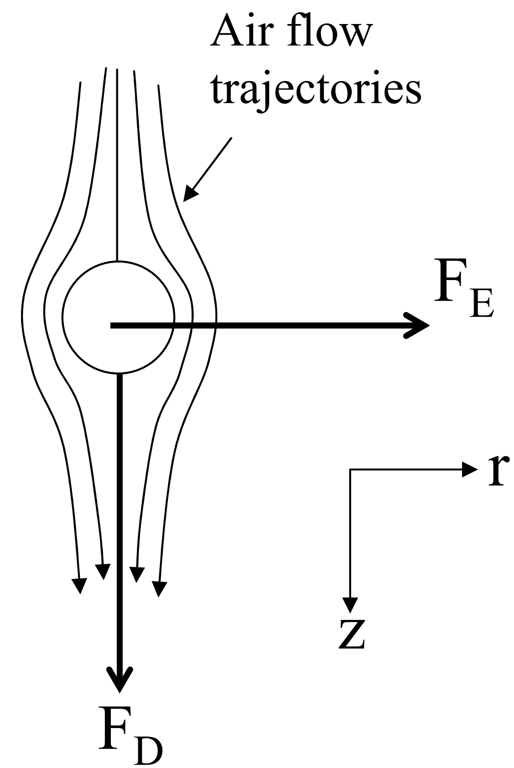
- Particles injected into the region with an applied electric field experience force in the r and z directions
  - z-direction force
    - Stokes drag due to flow around the particle

$$F_D = 3\pi\eta V d_p$$

      - Where η is the gas viscosity, V is the gas velocity and d_p is the particle diameter.
  - r-direction force
    - Due to the applied electric field

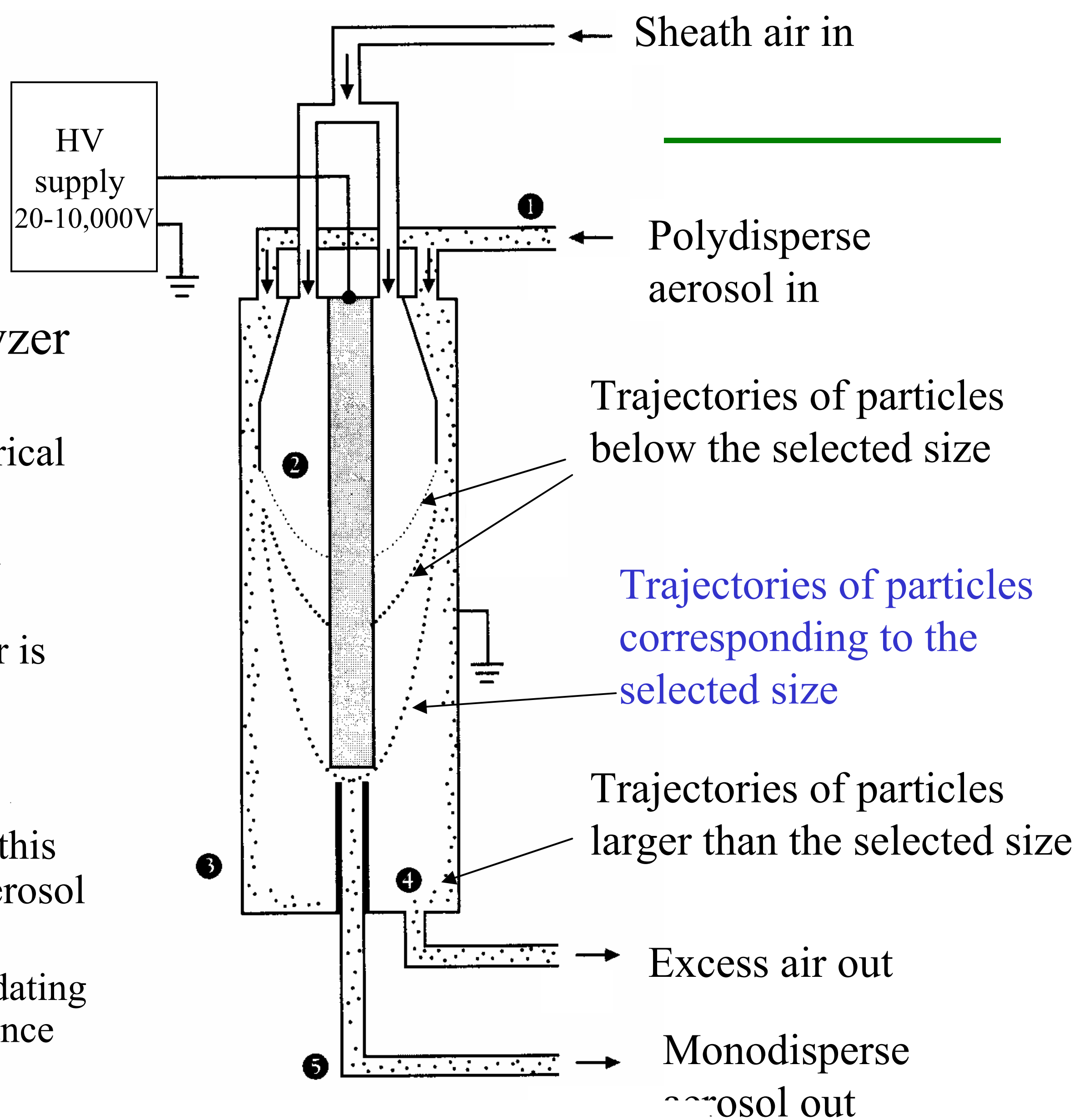
$$F_E = neE$$

      - Where n is the number of charges on a particle, e is the charge on an electron, E is the applied electric field



DMA

- Differential Mobility analyzer (DMA)
  - Sizes particles by their electrical mobility
  - Usually very high resolution measurements are possible
  - Downstream particle counter is required for particle size distribution measurements
    - Usually a CNC
  - Due to the high accuracy of this instrument it is a standard aerosol instrument
    - Used for testing and validating new instrument performance

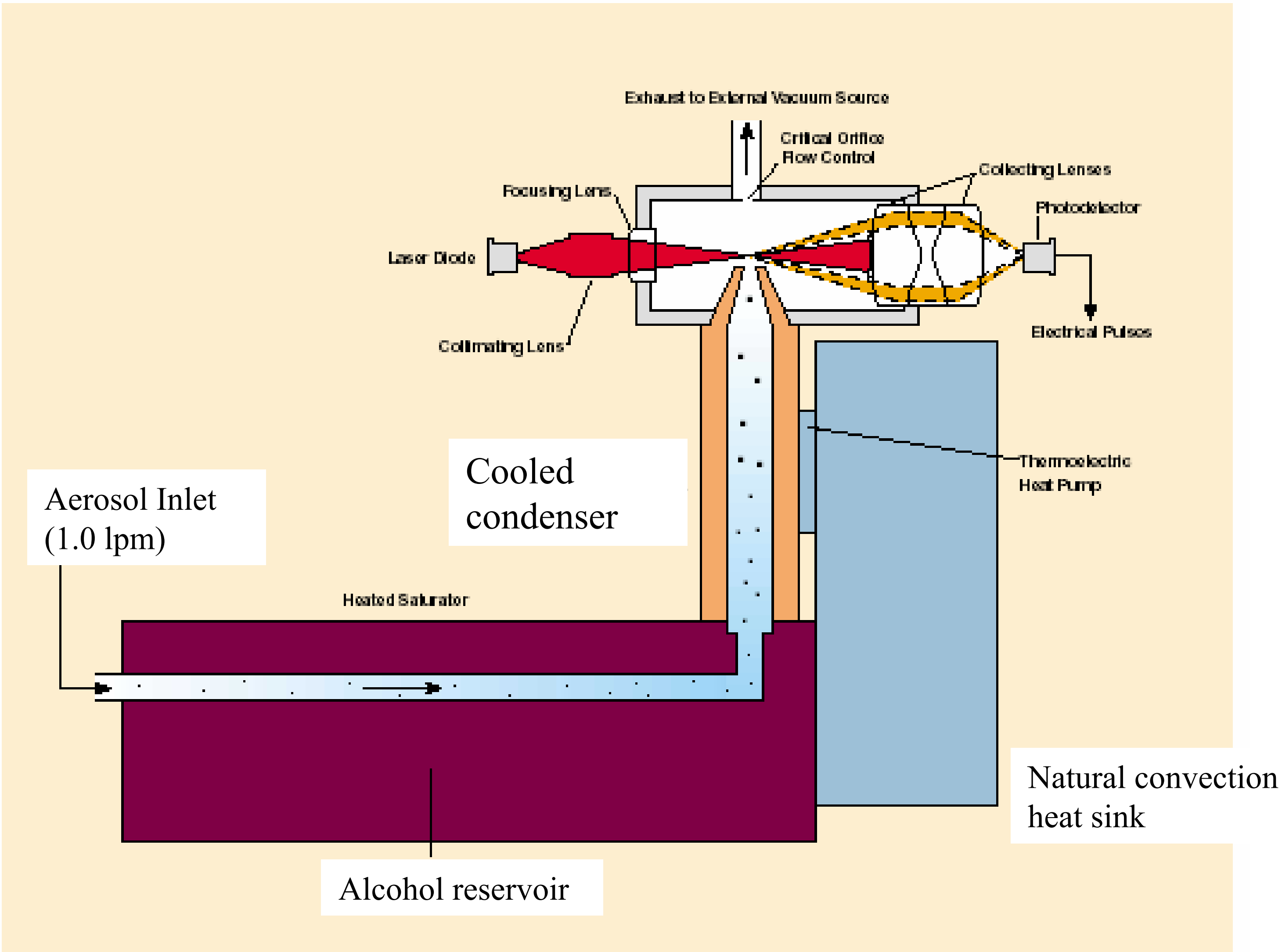


TSI 3080 DMA

Particle counting

- Condensation nucleus counter
  - Particles are grown by condensation
    - Usually a high vapor pressure liquid like Butanol is used
  - Particles are counted as they pass through a light scattering region
  - Popular instrument to measure total aerosol concentration
  - Can count particles of sizes > 2nm
    - Upper limit is dependent on particle transport through the instrument

CNC


Exhaust to External Vacuum Source
Critical Orifice
Flow Control
Collecting Lenses
Photodetector
Focusing Lens
Laser Diode
Collimating Lens
Electrical Pulses
Thermoelectric
Heat Pump
Cooled
condenser
Aerosol Inlet
(1.0 lpm)
Heated Saturator
Natural convection
heat sink
Alcohol reservoir

Brownian motion and Diffusion

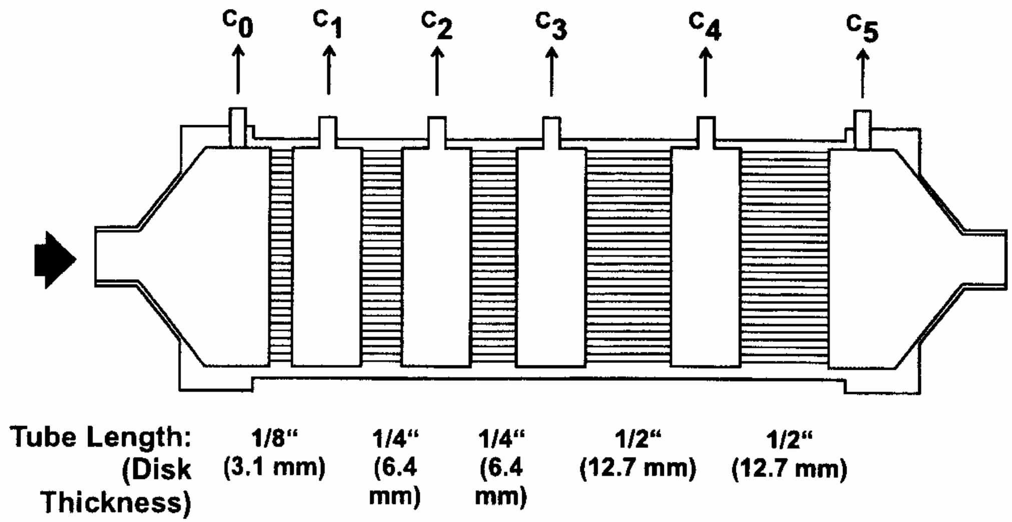
- Brownian motion
  - Random wiggling motion of particles
- Diffusion
  - Net transport of particles in a concentration gradient
- Both are characterized by the particle diffusion coefficient (D)

$$D = \frac{kTC_c}{3\pi\eta d_p}$$

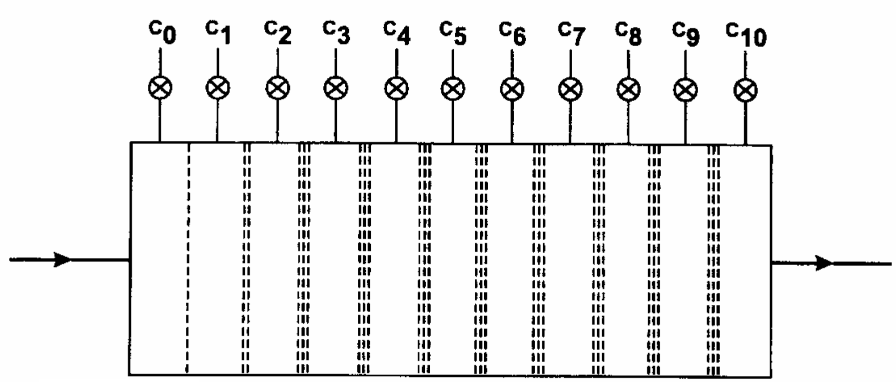
Where k is the Boltzmann constant, T is the temperature, C_c is the slip correction factor, d_p is the particle diameter, η is the gas viscosity

Particle diameter (μm)	Mobility (m/N/s)	Diff Coeff (m^2/s)	Mean thermal vel (m/s)
0.00037	-	2.0×10^{-5}	460
0.01	1.3×10^{13}	5.4×10^{-8}	4.4
0.1	1.7×10^{11}	6.9×10^{-10}	0.14
1.0	6.8×10^{9}	2.7×10^{-11}	0.0044

Diffusion battery



Schematic of a five-stage diffusion battery consisting of a stainless steel collimated hole structure



Schematic of a 10-stage screen-type diffusion battery.

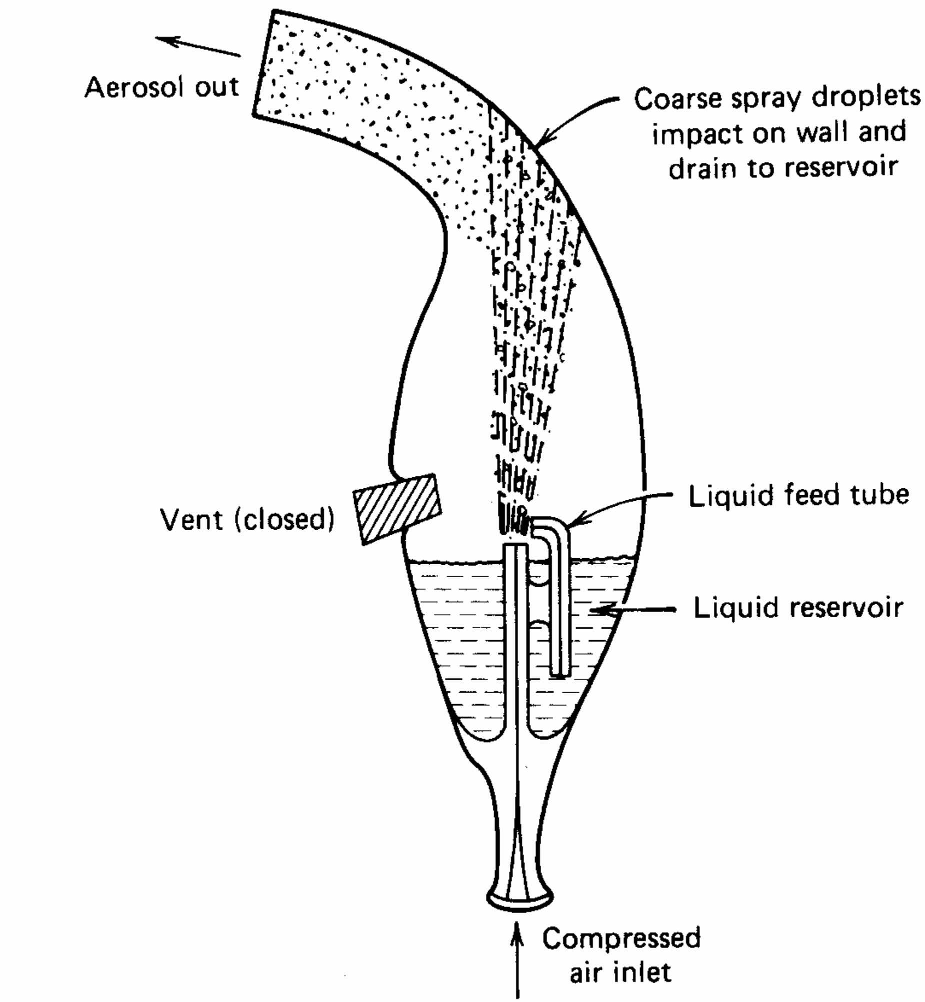
Instrument testing

- Aerosol generation
  - Need to generate aerosols of known sizes and number
- Aerosol conditioning
  - Need to control their charge
  - Need to humidify or dry them

Aerosol Generation

- A distribution of particles has a distribution of sizes
  - Narrow distribution of sizes – Monodisperse
  - Wide distribution of sizes - Polydisperse
- Different size ranges have different techniques for generation
  - Submicron particles (i.e., $D_p < 1\ \mu m$)
    - Nebulizers – both monodisperse and polydisperse
    - Electrospray – both monodisperse and polydisperse nanoparticles
    - Nebulizer + DMA – monodisperse particles
  - Supermicron particles (i.e., $D_p > 1\ \mu m$)
    - Vibrating orifice Generator (VOAG – TSI Inc) – monodisperse
    - Dust feeder - polydisperse

Nebulizer

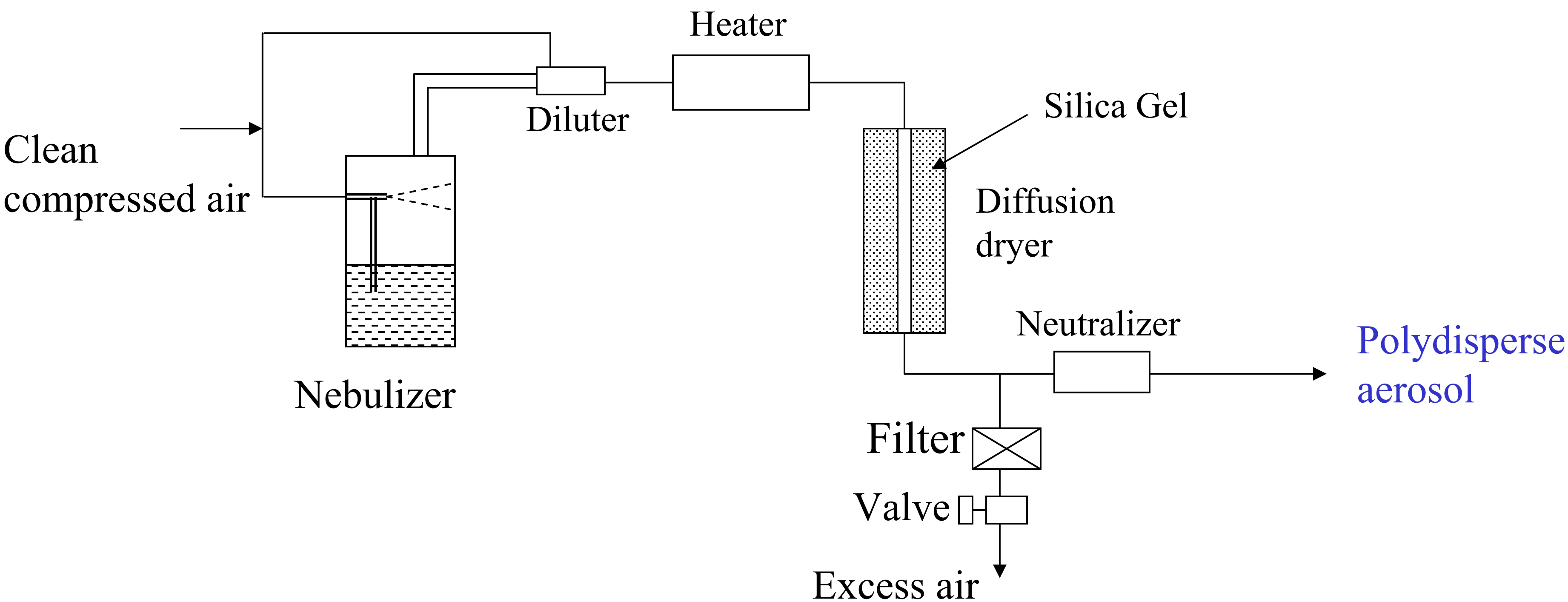


Drawing of a DeVilbiss Model 40 Glass Nebulizer.

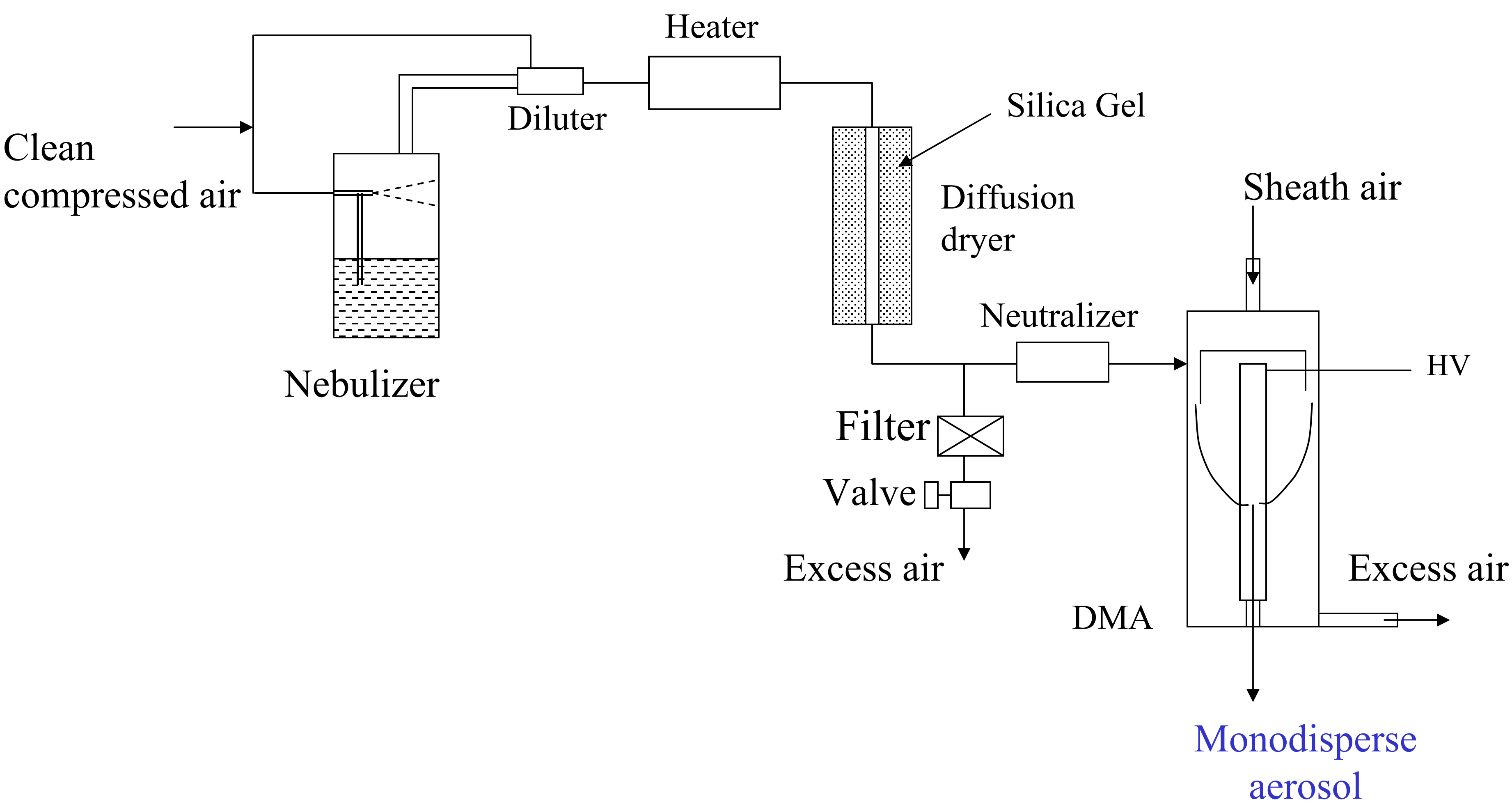
Aerosol Conditioning

- Aerosol dilution
  - Mixing with clean air
- Aerosol drying
  - Heater
    - Especially if water is used in aerosol generation
    - E.g., for experiments with salt and PSL aerosol
  - Diffusion dryer
    - Silica Gel is used to dry aerosols by diffusion of water vapor from the aerosol stream to silica gel
- Aerosol neutralization
  - Aerosols acquire charge during nebulization and other generation techniques
  - To replicate atmospheric conditions, aerosols have to carry a distribution of charges – charge distribution is close to Boltzmann
  - Neutralizers are used – Po^{210} or Kr^{85} are the most popular

Typical aerosol generation setup (Polydisperse aerosol)



Typical aerosol generation setup (Monodisperse aerosol)



Instrumentation research

- Two directions in particle sizing instrumentation
  - Improved resolution and accuracy
    - Required for fundamental research
    - Results in more expensive instrumentation
  - Portable and inexpensive instrumentation
    - For personal monitoring, Wide-spread global monitoring, urban air quality measurements
    - Might result in lower resolution
    - Challenges in flow and particle transport in narrow channels
    - Particle charging questions

References

- Useful books:
  - Aerosol technology, W.C. Hinds, Wiley, 1998
  - Aerosol measurement, P.A. Baron and K. Willeke, Wiley, 2001
- Important journals in the field
  - Aerosol Science and technology (http://www.aaar.org/ASandT.htm)
  - Journal of aerosol science (http://www.elsevier.com)
- Some important aerosol instrumentation manufacturers
  - TSI (www.tsi.com)
  - MSP (www.mspcorp.com)
  - R & P (www.rpco.com)
  - Particle Measuring Systems(www.pmeasuring.com)