Chapter 13

Nanoaerosol

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Nanoaerosol

- Nanoparticles, solid or liquid, suspended in a gas
- At least one dimension is 1-100 nm
- Cross reference: Chapter 4.

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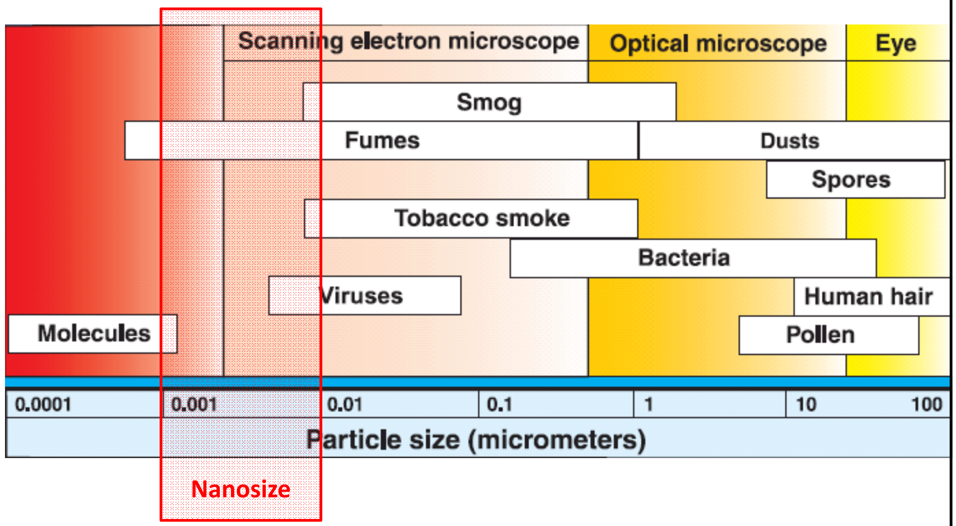
Particle sizes and detection methods



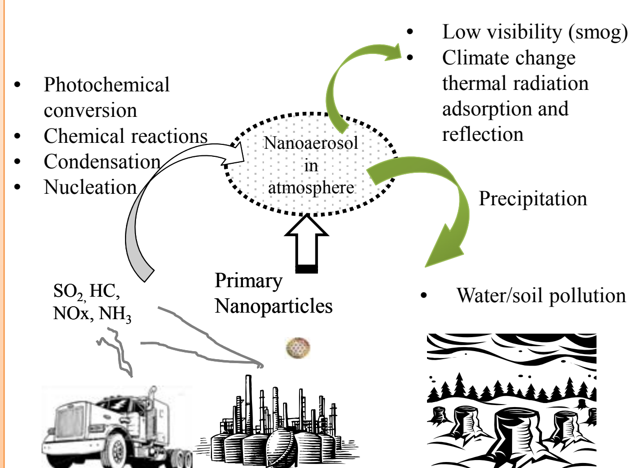
Adapted from: Guidance for Filtration and Air-Cleaning Systems to Protect Building Environments from Airborne Chemical, Biological, or Radiological Attacks, DHHS (NIOSH) Publication No. 2003-136.

Sources of Nanoaerosol

- Fuel combustion
- Nanomaterial manufacturing and utilization
- Secondary atmospheric nanoaerosol

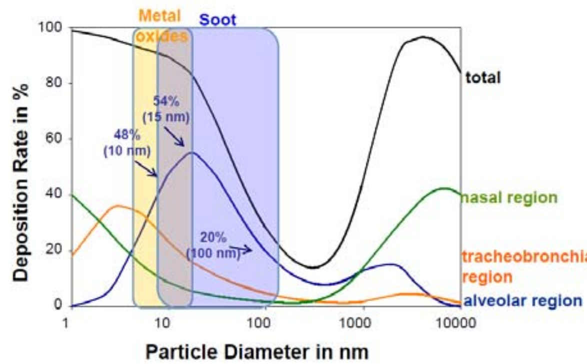
Environmental Impact

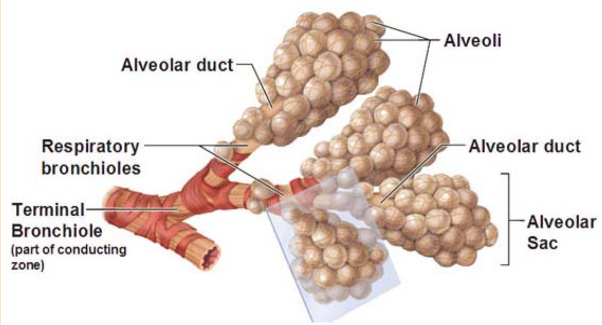
- Low visibility
- Climate change
- Contamination



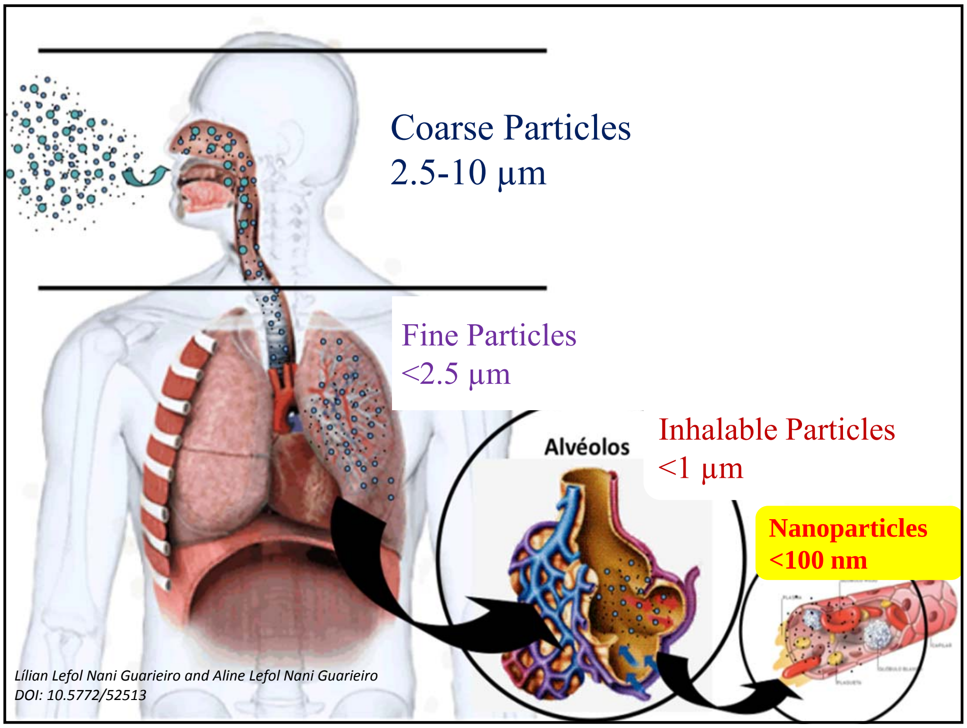
Particle deposition at different locations in the respiratory system

- Nanoparticles deposited deep into the alveolar region





Ulrich et al. 2012, "Particle and metal emissions of diesel and gasoline engines-Are particle filters appropriate measures?."16th Conference on Combustion Generated Nanoparticles 2012, 24.6.2012 – 27.6.2012 in Zürich, Switzerland



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DOI: 10.5772/52513

Table 13-1. Proposed Occupational Exposure Limits of Nanoaerosols

Nanoaerosol	Occupational exposure limit	Parameters
Titanium dioxide	0.1 mg/m^3	0.1 risk level particles \100 nm
General dust	3 mg/m^3	
Photocopier toner	0.6 mg/m^3	Tolerable risk
	0.06 mg/m^3	2009 acceptable risk
	0.006 mg/m^3	2018 acceptable risk
Biopersistent granular materials (e.g. metal oxides)	20,000 $particles/cm^3$	Density>6,000 kg/m3
	40,000 $particles/cm^3$	Density<6,000 kg/m3
Carbon Nanotubes (CNTs)	0.01 f/cm^3	Exposure risk ratio for asbestos
Fibrous	0.01 f/cm^3	3:1; length 75,000 nm
Multi-walled CNTs	0.0025 mg/m^3	Nanocyl product only

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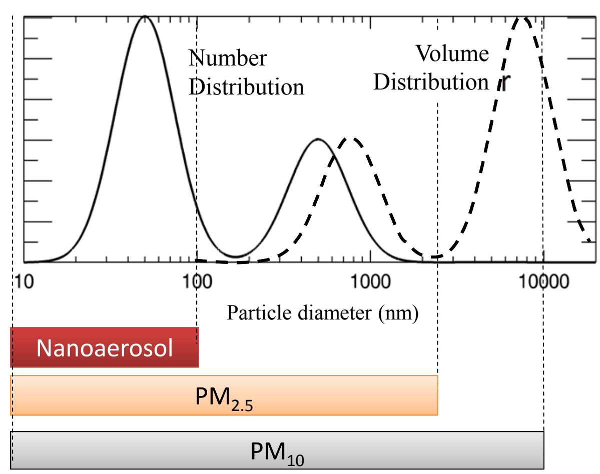
Nanoaerosol

- Nanoaerosol particles are those 1-100 nm in at least one dimension
- Nanoaerosol dominates in number.
- Government regulations are based on mass



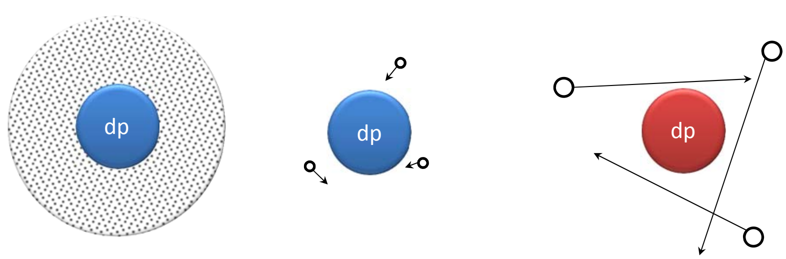
Slipping Effect

- An important assumption of Stokes' law is that there is no slipping between the gas and the rigid particles.
- However, when the particle is getting smaller and smaller, approaching the mean free path of the gas molecules, this assumption is no longer valid.
- The Knudsen Number

$$Kn = \lambda / \left(\frac{d_p}{2} \right) = 2\lambda / d_p$$

λ = mean free path of the gas

The Knudsen Number $Kn = 2\lambda / d_p$



Continuum regime Kn<<1 (large particles)

Transition regime Kn≈1

Non continuum regime Kn>>1 (Nanoparticles)

Cunningham correction factor

- The drag force is reduced by the slipping effect:

$$F_D = \frac{3\pi\mu|u-v|d_p}{C_c}$$

$$C_c = 1 + Kn\left[1.142 + 0.558exp\left(-\frac{0.999}{Kn}\right)\right]$$

$$Kn = 2\lambda/d_p$$

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Nanoaerosol Diffusivity

- General

$$D_p = \frac{kTC_c}{3\pi\mu d_p}$$

- 0.5-2 nm particles

$$D_p = \frac{0.815c_{rms}}{12\pi N(d_g + d_p)^2}\sqrt{1 + \frac{M}{M_n}}$$

- k =1.38x10^{-23} J/K,
- d_g is the gas molecule diameter (0.37 nm for air),
- N is the number concentration of gas molecules ($2.45 \times 10^{25}\ /m^3$ for air at 293 K and 1 atm),
- M is the molar weight of the carrier gas (28.82 for air),
- M_n is the molar weight of nanoaerosol particles,
- c_{rms} is the root mean square velocity of the carrier gas molecules

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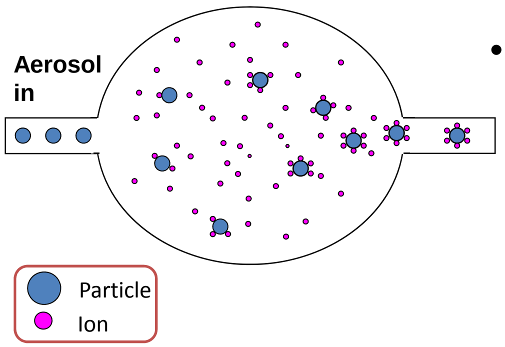
Nanoparticle Charging

- Particles passing through a space filled with ions with be charged



- **Field charging** – ion attached to particles in an electrical field driven by the electrical force
- **Diffusion charging** – ions attached to particles due to Brownian motion of ions (not the electrical field).

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1. Diffusion Charging

$$n = \frac{d_p kT}{2K_E e^2} \ln\left[1 + \left(\frac{N_0 c_i \pi d_p K_E e^2}{2kT}\right) t\right]$$

Under standard conditions,

- K_E=9x10^9 Nm^2/C,
- c_i=240 m/s,
- k =1.38x10^{-23} J/K,
- e =1.6x10^{-19} C.
- A typical concentration of ions is N_0=5x10^{14} ion/m^3,
- The diameters of most airborne particles are smaller than 10 µm and time t is in the order of unit or less

2. Field charging

$$n = \frac{E d_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r + 2}\right)\left(\frac{t}{t + \tau}\right)$$

- E = intensity of the electric field with a typical value of 10^6 V/m,
- $\varepsilon_r = \varepsilon/\varepsilon_0$= relative permittivity or dielectric constant of the particle with respect to a vacuum,
  - ❑ ε_0 =8.854x10^{-12} C/V.m, is the permittivity of a vacuum.
  - ❑ The permittivity of typical particles can be found in handbooks.

Field Charging

$$n = \frac{Ed_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r + 2}\right)\left(\frac{t}{t+\tau}\right)$$

The number of ions that is eventually charged to a particle depends on three factors:

- time *t*,
- the concentration of ions in the charging zone N_0, and
- the electric mobility of these ions B_e, which determines the moving speed of the ions in response to the electric field *E*.

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Saturation Field Charge

$$n = \frac{Ed_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r + 2}\right)\left(\frac{t}{t+\tau}\right)$$

- $t \sim \infty, \quad \frac{t}{t+\tau} \sim 1$

- τ is the charging constant and it varies with the field condition. Typically = 0.003 s

$$n_s = \frac{Ed_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r + 2}\right)$$

$$\tau = \frac{1}{\pi N_0 K_E e B_e}$$

- K_E = 9x10^9 Nm^2/C^2, is a force constant.
- the concentration of ions in the charging zone N_0, and
- the electric mobility of these ions B_e, which determines the moving speed of the ions in response to the electric field *E*.

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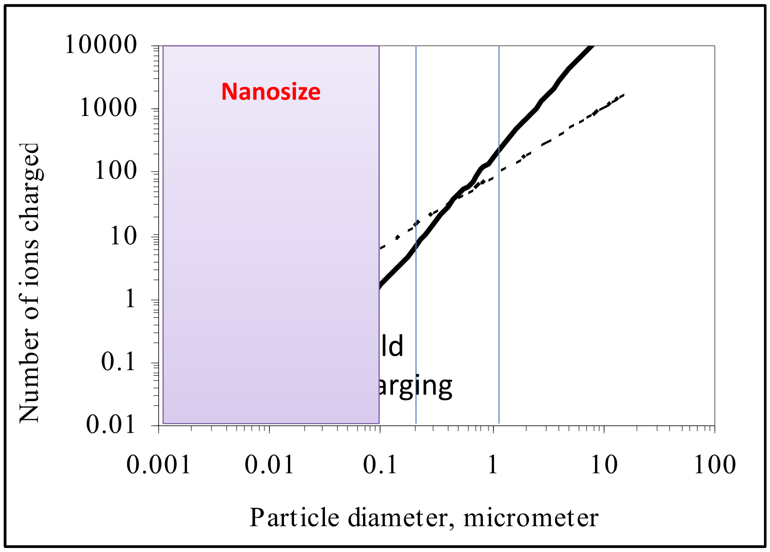
Combined charging

$$n = \frac{d_p kT}{2K_E e^2} \ln\left[1 + \left(\frac{N_0 c_i \pi d_p K_E e^2}{2kT}\right)t\right] + \frac{Ed_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r + 2}\right)\left(\frac{t}{t+\tau}\right)$$



Nanoaerosol Charging

- Nanoaerosol particles are primarily charged by diffusive charging.

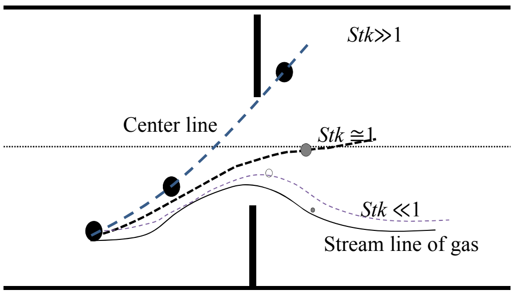
$$n(t) = \frac{d_p kT}{2e^2 K_E} \ln\left(1 + \frac{d_p K_E \bar{c}_i \pi e^2 N_{i0}}{2kT} t\right)$$

where $\bar{c}_i$ is the mean thermal speed of ions (239 m/s at standard conditions T=293 K, P=1 atm), k is Boltzmann constant (1.38×10^{-23} J/K), K_E is a constant of proportionality ($1/4\pi\varepsilon_0 = 9 \times 10^9$ Nm^2/C^2), N_{i0} is ion concentration.

- A nanoparticle smaller than 20 nm will probably acquire 1-2 ions
- If polydisperse nanoaerosol particles pass through a bipolar charger, two nanoparticles of the same size may obtain different charges
- Experimental data show that generally, after charging, sub-20 nm particles carry a negative charge while larger particles carry a positive charge

Stokes Number
Indicates Particle Inertia

$$Stk = \frac{\tau U_0}{d_c} = \frac{\rho_p d_p^2 C_c U_0}{18 \mu d_c}$$



$$C_c = 1 + Kn\left[1.257 + 0.40 exp\left(-\frac{1.10}{Kn}\right)\right]$$

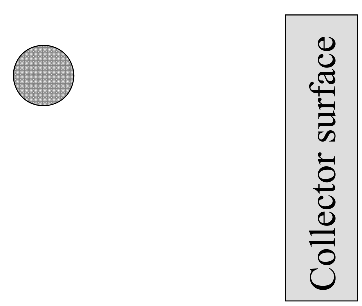
$$Kn = 2\lambda / d_p$$

$$\lambda = \frac{1}{\sqrt{2}\pi N_a}\frac{RT}{Pd^2}$$

$$\mu = \frac{2\sqrt{mkT}}{3\pi^{3/2} d^2}$$

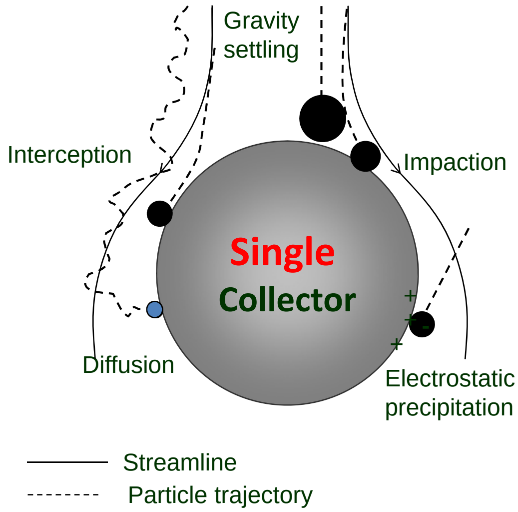
Nanoaerosol Filtration Fundamentals

- Two steps:
  1. Particle transport to a collector, quantified by collision efficiency
  2. Attach to a collector, quantified by adhesion efficiency



$$\eta = \eta_{ts} \cdot \eta_{ad}$$

Five Transport Mechanisms (Single Collector)



- Adhesion efficiency = 1
- Ignored gravitational Settling
- Electrostatic precipitation not considered in literature

Single Fiber Efficiency Per Unit Length of Fiber by Diffusion

$$\eta_D = 0.84Pe^{-0.43}$$

Peclet number $Pe = \dfrac{U_0 d_f}{D_p}$

Diffusion coefficient $D_p = \dfrac{kTC_c}{3\pi\mu d_p}$

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Single Fiber Efficiency per unit length of fiber by Interception

$$\eta_{it} = 0.6\left(\frac{1-\alpha}{Y}\right)\frac{R^2}{1+R}\left(1+\frac{1.996Kn_f}{R}\right)$$

- $\alpha = (1 - porosity)$, is the solidity of filter;
- $R = d_p/d_f$ is the ratio of particle diameter to fiber diameter, and
- Y is the Kuwabara hydrodynamic factor defined below, with slip effect taken into consideration

$$Y = -\frac{ln\alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$$

Example 13.1:
Nanoaerosol transport efficiency

A filter is made of fiberglass with a solidity of 5%, and it is 5-cm thick. The average diameter of the fibers is 5 µm. When the face speed is 0.15 m/s, calculate and plot the fractional transport efficiency per unit length of fiber as a function of particle aerodynamic diameter in the range of 1- 100 nm under standard conditions, by interception and diffusion, respectively.

Example 13.1: Solution

In this problem, the following parameters are considered as constant

$$d_f = 5\ \mu m, \qquad \alpha = 0.05, \qquad Kn_f = \frac{2\lambda}{d_f} = 0.0264$$

$$Y = \frac{ln\alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4} = 1.033$$

$$\underline{\mu = 1.81 \times 10^{-5}\ Pa.s \qquad U_0 = \mathbf{0.05\ m/s}}$$

The following variables can be calculated in an Excel sheet for different particle diameters

$$C_c = 1 + Kn_p\left[1.142 + 0.558exp\left(-\frac{0.999}{Kn_p}\right)\right]$$

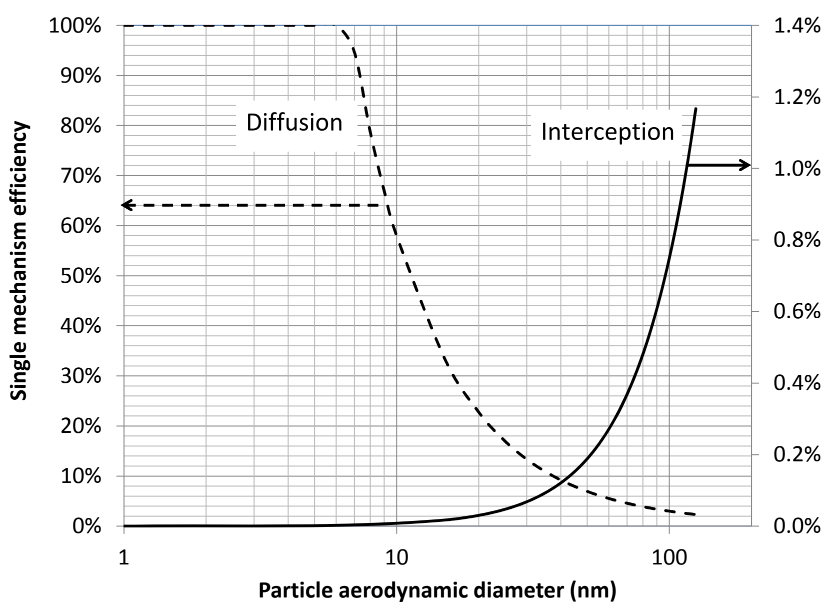
$$R = \frac{d_p}{d_f} \qquad D_p = \frac{kTC_c}{3\pi\mu d_p} \qquad Pe = \frac{U_0 d_f}{D_p}$$

The single fiber filtration efficiency by inertial interception, impaction and diffusion, per unit length of fiber is calculated using

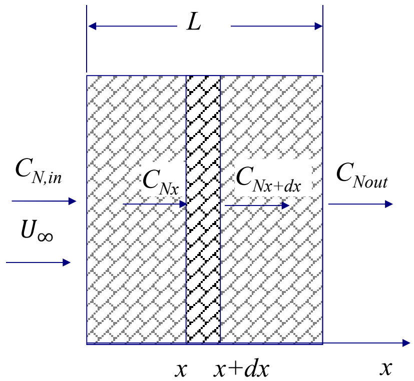
$$\eta_D = 0.84Pe^{-0.43}$$

$$\eta_{it} = 0.6\left(\frac{1-\alpha}{Y}\right)\frac{R^2}{1+R}\left(1 + \frac{1.996Kn_f}{R}\right)$$

Figure 3.3 Calculated Nanoaerosol filtration efficiency (Example 13.1)



Correlation between total single fiber efficiency and overall filtration efficiency



- Within an elemental thickness of *dx*, the solidity, α, from its definition is

$$\alpha = \frac{\left(\pi d_f^2/4\right)\cdot ds_f}{A_c \cdot dx}$$

- A_c is the bulk cross section area of the filter that is normal to the face velocity. It can be determined by the air flow rate

$$A_c = \frac{Q}{U_\infty}$$

- U_∞ is the bulk face speed, or the air speed approaching the filter. It is less than that approaching the fiber within the filter, U_0, because of the existence of solid fibers

$$U_0 = \frac{U_\infty}{1-\alpha} = \frac{Q}{(1-\alpha)A_c}$$

- The number concentration of particles lost per unit volume from the bulk air over the distance *dx* equals to that captured by the fiber with a single fiber efficiency η_{sf} corresponding to an approaching flow rate of $U_0\, d_f \cdot ds_f$, where $d_f \cdot ds_f$ defines the cross section area of the fiber with the length of ds_f and the diameter of d_f

$$Q \cdot dC_N(x) = -\eta_{sf} C_N(x) U_0 d_f \cdot ds_f$$

- all these particles passed through a single fiber with a cross section area of $\left(d_f \cdot ds_f\right)$ with an approaching speed of U_0 and a single fiber efficiency of η_{sf}

$$A_c U_\infty \cdot dC_N(x) = -C_N(x)\eta_{sf} U_0 d_f \cdot \frac{4\alpha A_c \cdot dx}{\pi d_f^2}$$

$$\frac{dC_N(x)}{C_N(x)} = -\left(\frac{U_0}{U_\infty}\frac{\eta_{sf} 4\alpha}{\pi d_f}\right) dx$$

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Overall Nanoaerosol Transport Efficiency of a Filter

$$\frac{dC_N(x)}{C_N(x)} = -\left[\frac{\eta_{sf}4\alpha}{(1-\alpha)\pi d_f}\right]dx$$

$$\int_{C_{N_i}}^{C_{N_o}} \frac{dC_N(x)}{C_N(x)} = \int_0^L -\left[\frac{\eta_{sf}4\alpha}{(1-\alpha)\pi d_f}\right]dx$$

$$P(d_p) = \frac{C_{N_o}}{C_{N_i}} = exp\left[\frac{-\eta_{sf}4\alpha L}{(1-\alpha)\pi d_f}\right]$$

$$\eta(d_p) = 1 - \exp\left[\frac{-\eta_{sf}4\alpha L}{(1-\alpha)\pi d_f}\right]$$

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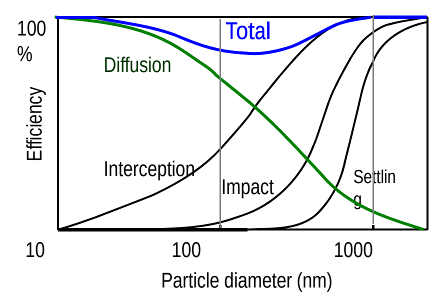
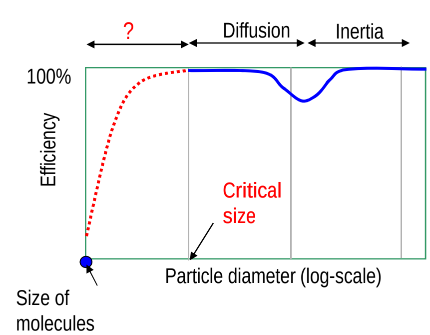
Classical filtration theory

(Adhesion efficiency = 1)

- Relative importance of the mechanisms
  - For nanoparticles diffusion dominates and efficiency increases inversely with particle size for lower end
- "Air" molecules are not (supposed to be) captured by filters
- Filtration efficiency is nearly zero when "particle" size is approaching molecule size
- The curve should drop from maximum efficiency to near zero (Red dashed line)





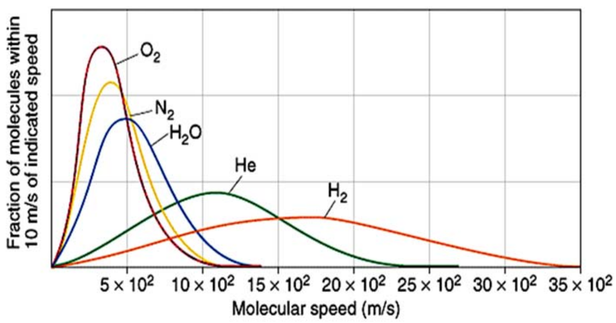
Thermal Speed of Nanoaerosol Particles

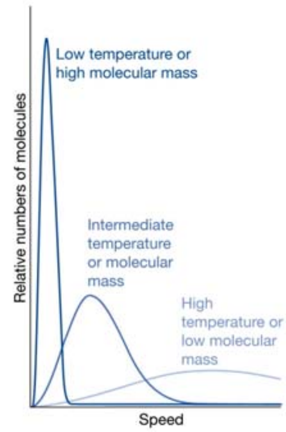
Maxwell and Boltzmann Distribution

$$f(v) = 4\pi v^2 \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left(-\frac{mv^2}{2kT}\right)$$

- *Boltzmann constant*: $k = 1.3807 \times 10^{-23}$ (J/K)

- From gas molecular kinetic (see Chap 2)





Mean thermal speed $(\bar{v}_{im}) = \int_0^\infty v f(v) dv = \sqrt{\frac{8kT}{\pi m}}$

$$\bar{v}_{im} = \int_0^\infty v f(v) = \int_0^\infty v \times 4\pi v^2 \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-mv^2/2kT}$$

$$= \int_0^\infty 4\pi \left(\frac{m}{2\pi kT}\right)^{3/2} v^3 e^{-mv^2/2kT}$$

$$= 4\pi \left(\frac{m}{2\pi kT}\right)^{3/2} \int_0^\infty v^3 e^{-mv^2/2kT}$$

$$\int_0^\infty x^3 e^{-ax^2} dx = \frac{1}{2a}$$

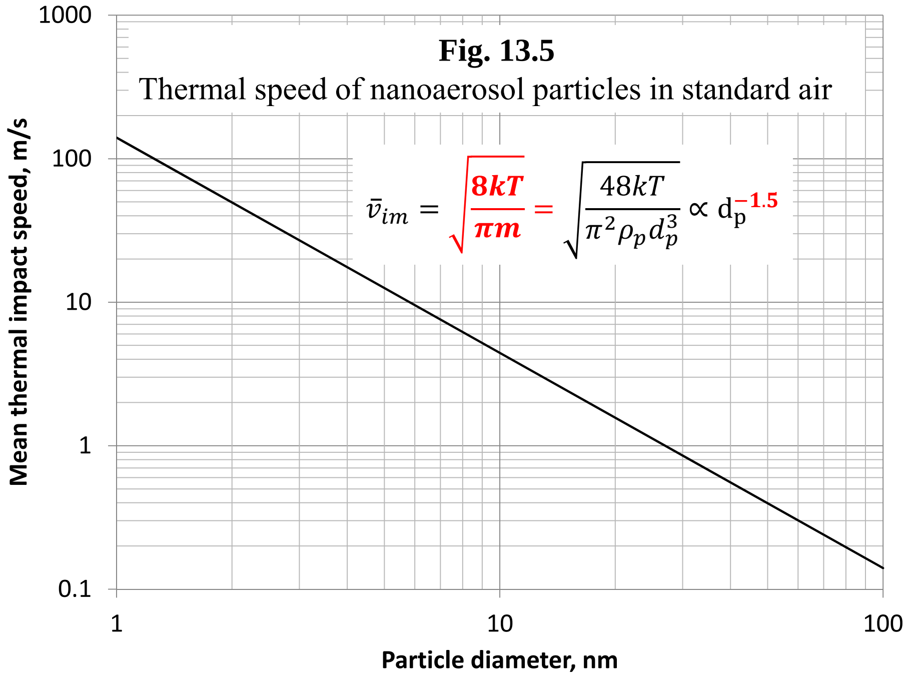
$$\bar{v}_{im} = 4\pi \left(\frac{m}{2\pi kT}\right)^{3/2} \left(\frac{1}{2(m/2kT)^2}\right)$$

$$= 4\pi \left(\frac{m}{2\pi kT}\right)^{3/2} \frac{2k^2T^2}{m^2}$$

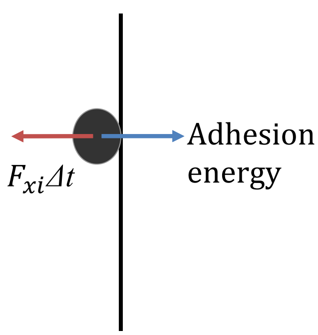
$$= \left(\frac{4\pi \times 2k^2T^2}{(2\pi kT)^{1.5}}\right)\left(\frac{m^{1.5}}{m^2}\right)$$

$$= \left(\frac{2^{1.5} k^{0.5} T^{0.5}}{\pi^{0.5} m^{0.5}}\right)$$

$$= \left(\frac{\mathbf{8kT}}{\pi \mathbf{m}}\right)^{\mathbf{0.5}}$$



Nanoaerosol Particles Colliding on A Solid Surface



With an impact speed of v_{im}, the particle colliding on the solid surface may

- Rebound, when speed is too high
- Adhere , when speed is low

Critical Thermal Speed

- The critical particle speed that enables thermal rebound of aerosol particles is a function of adhesion energy (E_{ad}), the coefficient of restitution (e) and particle mass (m).

$$v_{cr} = \sqrt{\frac{2E_{ad}}{me^2}} = \sqrt{\frac{12E_{ad}}{(\pi\rho_p d_p^3)e^2}}$$

- E_{ad} is the adhesion energy
- $e \leq 0.6$
- Unfortunately, the database for coefficient of restitution for nanoparticles is still not well developed yet.

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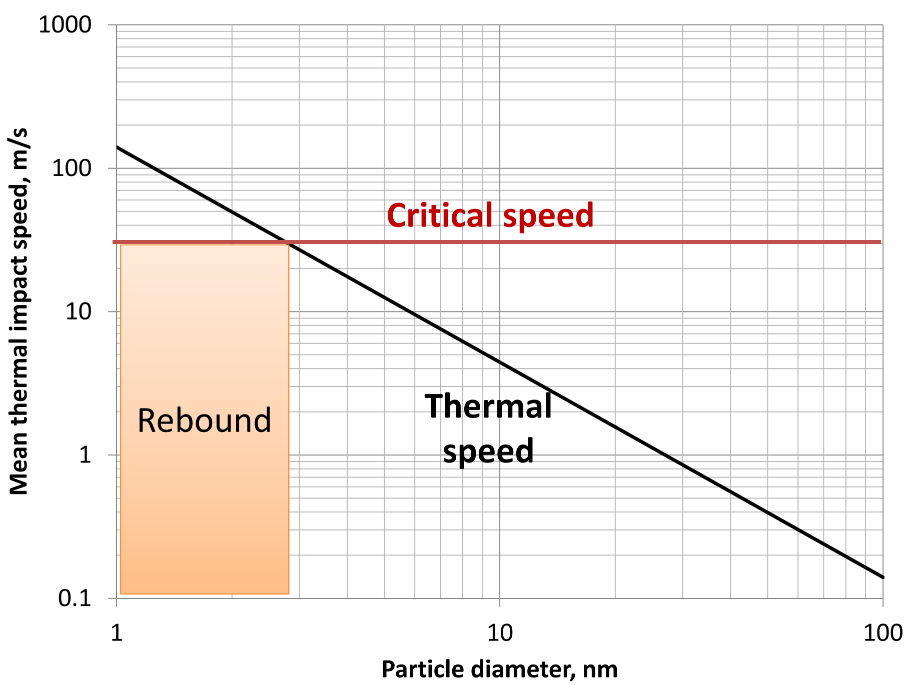
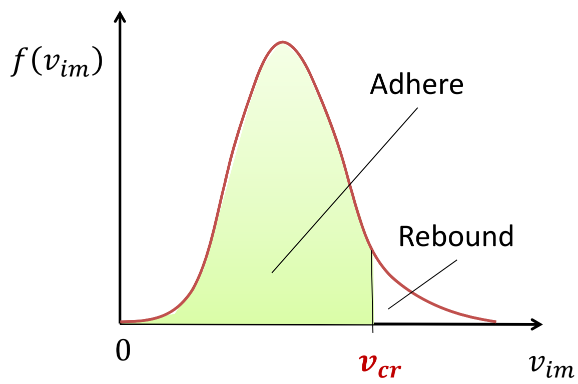


Adhesion Efficiency Analysis

$$\eta_{ad} = \frac{\int_0^{v_{cr}} f(v_{im})dv_{im}}{\int_0^{\infty} f(v_{im})dv_{im}}$$



Adhesion Efficiency Analysis

$$\eta_{ad} = \frac{\int_0^{v_{cr}} f(v_{im})dv_{im}}{\int_0^{\infty} f(v_{im})dv_{im}} = \frac{\int_0^{v_{cr}} v_{im}^2 \exp\left(-\frac{mv_{im}^2}{2KT}\right)dv_{im}}{\int_0^{\infty} v_{im}^2 \exp\left(-\frac{mv_{im}^2}{2KT}\right)dv_{im}}$$

- $\int [x^2\, exp(-ax^2)]dx = \frac{\sqrt{\pi}\mathrm{erf}(\sqrt{a}x)}{4a^{1.5}} - \frac{x \times exp(-ax^2)}{2a}$
- erf is the error function, and $\mathrm{erf}(0) = 0; \mathrm{erf}(\infty) = 1.$
- $x \cdot \exp(-ax^2) \rightarrow 0$ when $x \rightarrow \infty$

$$\int_0^{v_{cr}} v_{im}^2 \exp\left(-\frac{mv_{im}^2}{2KT}\right)dv_{im} = \frac{\sqrt{\pi}\mathrm{erf}\left(\sqrt{\frac{m}{2KT}}v_{cr}\right)}{4\left(\frac{m}{2KT}\right)^{1.5}} - \frac{v_{cr} exp\left(-\frac{m}{2KT}v^2{}_{cr}\right)}{\frac{m}{KT}}$$

$$\int_0^{\infty} v_{im}^2 \exp\left(-\frac{mv_{im}^2}{2KT}\right)dv_{im} = \frac{\sqrt{\pi}}{4\left(\frac{m}{2KT}\right)^{1.5}}$$

$$\boldsymbol{\eta_{ad} = \mathrm{erf}\left(\sqrt{\frac{m}{2KT}}v_{cr}\right) - \sqrt{\frac{2m}{\pi KT}}v_{cr\cdot}\, exp\left(-\frac{m}{2KT}v_{cr}{}^2\right)}$$

Adhesion efficiency analysis (cont…)

$$\eta_{ad} = \mathrm{erf}\left(\sqrt{\frac{m}{2KT}}v_{cr}\right) - \sqrt{\frac{2m}{\pi KT}}v_{cr}.exp\left(-\frac{m}{2KT}{v_{cr}}^2\right)$$

$$\bar{v}_{im} = \sqrt{\frac{8kT}{\pi m}}$$

$$\eta_{ad} = \mathrm{erf}\left(\frac{2}{\sqrt{\pi}}\frac{v_{cr}}{\bar{v}_{im}}\right) - \frac{4}{\pi}\frac{v_{cr}}{\bar{v}_{im}}\exp\left[-\frac{4}{\pi}\left(\frac{v_{cr}}{\bar{v}_{im}}\right)^2\right]$$

$$z = \frac{2}{\sqrt{\pi}}\frac{v_{cr}}{\bar{v}_{im}}$$

$$\eta_{ad} = \mathrm{erf}(z) - \frac{2z}{\sqrt{\pi}}\exp[-z^2]$$

- v_{cr} pending

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$$\mathrm{erf(z)} \approx 1 - \frac{1}{(1 + a_1 z + a_2 z^2 + a_3 z^3 + a_4 z^4)^4}$$

a_1 = 0.278393,
a_2 = 0.230389,
a_3 = 0.000972 and
a_4 = 0.078108.

The maximum error is 5×10^{-4} (Fortran 77 manual).

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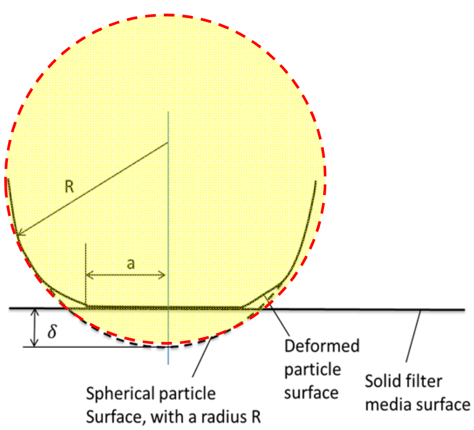
Solid-solid Interfacial Adhesion Energy Analysis for the Determination of v_{cr}

- Several models of adhesion energy (E_{ad}) were developed before and they were summarized by Givehchi and Tan (2014).
- Two of them are introduced here,
  1. JKR model (Johnson, Kendall and Roberts, 1971)
  2. DMT model (Derjaguin-Muller-Toporov, 1974)

Adhesion energy analysis



$$E_{ad} = \Delta\gamma\pi a^2$$

- E_{ad} = the adhesion energy (J)
- a = the contact radius between particle and surface
  - πa^2 =the contact area,
- $\Delta\gamma$ = the specific adhesion energy (J/m^2)

$$\Delta\gamma = \frac{H}{12\pi Z_e^2}$$

- Z_e = 0.4 nm is the equilibrium distance between the bodies.
- H =the Hamaker constant between the particle and the filter surface

$$H = (H_p H_f)^{1/2}$$

Table 13-2.
Material Properties for Thermal Rebound Calculation

Material	Hamaker constant $H_i \times 10^{19}\ J$	Density (kg/m³)	Mechanical constant $(K_i \times 10^{11}\ m^2/N)$ Givehchi (2014)	Mechanical constant $(K_i \times 10^{11}\ m^2/N)$ Wang & Kasper (1991)
Polystyrene	0.79	1005	10.130	8.86
Glass (Dry)	0.85	2180	0.443	-
NaCl	0.7	2165	0.746	2.35
WOx (Tungsten)	1.216	19250	0.071	-
Steel	2.12	7840	0.137	0.139
Nickle			-	0.137
Copper	3.3	8890	0.218	0.216
Fused quartz	0.65		-	0.432

Example 13.2:
Specific adhesion energy

Estimate the specific adhesion energy between NaCl particles and a glass fiber surface

Solution:

For salt and glass fiber filter,

$$H_p = 7 \times 10^{-20}\ J\ ,\ H_f = 8.5 \times 10^{-20}\ J$$

then the Hamaker constant is

$$H = \left(H_p H_f\right)^{1/2} = \sqrt{7 \times 8.5} \times 10^{-20} J = 7.71 \times 10^{-20} J$$

The specific adhesion energy is

$$\Delta\gamma = \frac{H}{12\pi Z_e^2} = \frac{7.71 \times 10^{-20} J}{12\pi (0.4 \times 10^{-9}\ )^2\ m^2} = 0.0128\ J/m^2$$

where $Z_e = 0.4\ nm$

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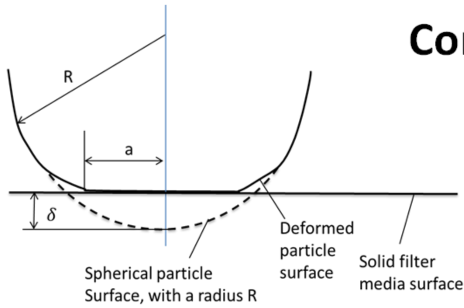
Contact Radius



$$\begin{cases} a = \left[\frac{R^*}{Y^*}(6\Delta\gamma\pi R^*)\right]^{1/3} & \text{(JKR Model)} \\ a = \left[\frac{R^*}{Y^*}(2\Delta\gamma\pi R^*)\right]^{1/3} & \text{(DMT Model)} \end{cases}$$

- R^* = the characteristic radius of two bodies. In this case, they are considered as the nanoaerosol particle and the filter fiber.

$$\frac{1}{2R^*} = \frac{1}{d_p} + \frac{1}{d_f}$$

- Y^* is the composite Young's modulus of bodies with the mechanical constant of K_P and K_f

$$Y^* = \frac{4}{3\pi}\left(\frac{1}{K_p + K_f}\right)$$

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Example 13.3:
Nanoaerosol adhesion efficiency

- *Calculate the adhesion efficiency using the DMT model with the following properties of a glass fiber filter for NaCl nanoparticles 1-100 nm when filter fiber diameter* $d_f = 5\ \mu m$.

Solution:

For salt and glass fiber filter,

$$H_p = 7 \times 10^{-20}\,J \qquad H_f = 8.5 \times 10^{-20}\,J$$

Then the Hamaker constant

$$H = (H_p H_f)^{1/2} = \sqrt{7 \times 8.5} \times 10^{-20} J = 7.71 \times 10^{-20} J$$

And the specific adhesion energy is

$$\Delta\gamma = \frac{H}{12\pi Z_e^2} = \frac{7.71 \times 10^{-20} J}{12\pi(0.4 \times 10^{-9})^2\, m^2} = 0.0128\, J/m^2$$

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With the mechanical constant of

$$K_p = 0.75 \times 10^{-11} \frac{m^2}{N} \qquad K_f = 0.443 \times 10^{-11} \frac{m^2}{N}$$

The composite Young's modulus of bodies

$$Y^* = \frac{4}{3\pi}\left(\frac{1}{K_p + K_f}\right) = \frac{4}{3\pi}\left(\frac{1}{0.75 \times 10^{-11} + 0.443 \times 10^{-11}}\right)$$
$$= 3.51 \times 10^{11}\ (Pa)$$

The characteristic radius of two bodies

$$R^* = \frac{1}{2}\left(\frac{1}{d_p} + \frac{1}{d_f}\right)^{-1}$$

The impact contact area is determined by

$$a = \left[\frac{R^*}{Y^*}(2\Delta\gamma\pi R^*)\right]^{1/3}$$

Then the adhesion energy is

$$E_{ad} = \Delta\gamma\pi a^2$$

Then the critical speed and impact speed are calculated using

$$v_{cr} = \sqrt{\frac{12E_{ad}}{\pi\rho_p d_p^3 e^2}};\ \bar{v}_{im} = \sqrt{\frac{48kT}{\pi^2\rho_p d_p^3}}$$

Then the adhesion efficiency is determined by

$$z = \frac{2}{\sqrt{\pi}}\frac{v_{cr}}{\bar{v}_{im}}$$

$$\eta_{ad} = \mathrm{erf}(z) - \frac{2z}{\sqrt{\pi}}\exp[-z^2]$$

In calculation using spread sheet, the error function is approximated with

$$\mathrm{erf}(z) \approx 1 - \frac{1}{(1 + a_1 z + a_2 z^2 + a_3 z^3 + a_4 z^4)^4}$$

where a_1 = 0.278393, a_2 =0.230389, a_3 = 0.000972 and a_4 = 0.078108.

The results are shown in Figure 13.7.

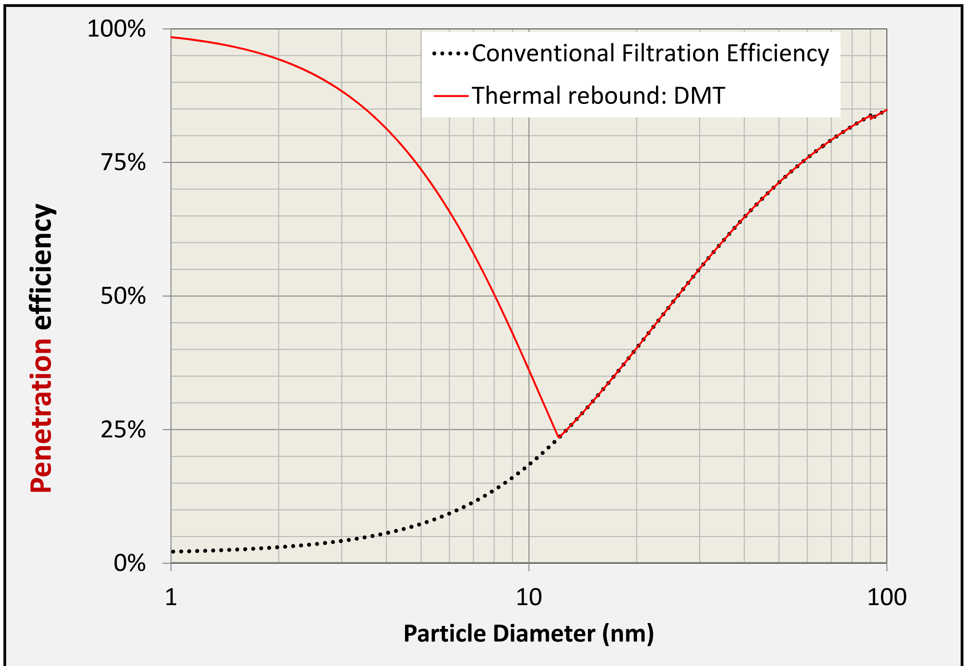
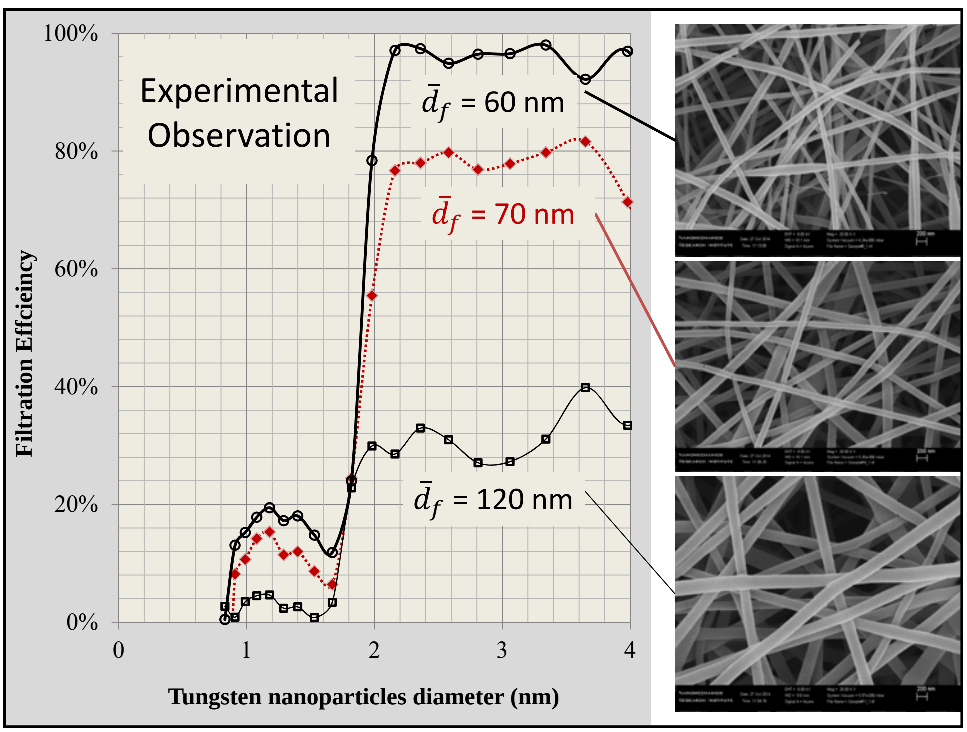


Fig. 13.7 Calculated penetration efficiency using DMT model 49

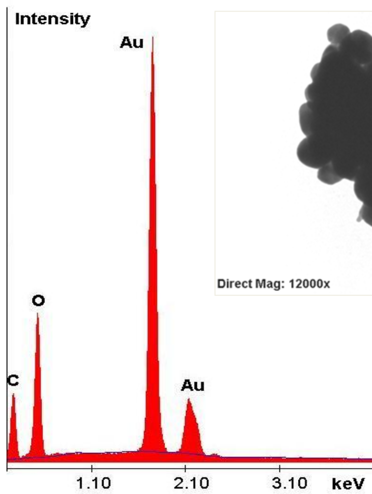


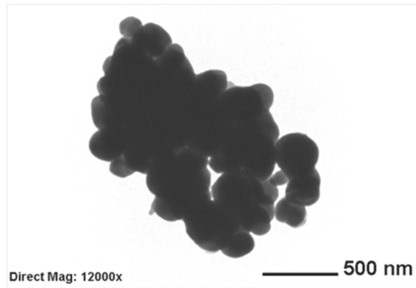
Nanoaerosol Characterization

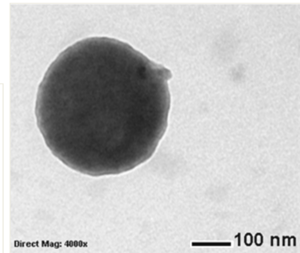
Offline Characterization

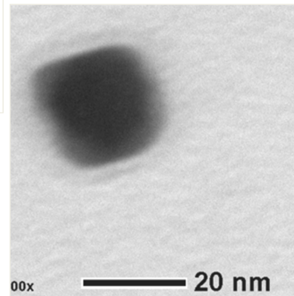
Transmission Electron Microscope Analysis

Scanning Electron Microscope Analysis & Energy Dispersive X-ray Analysis (Chemical composition analysis)



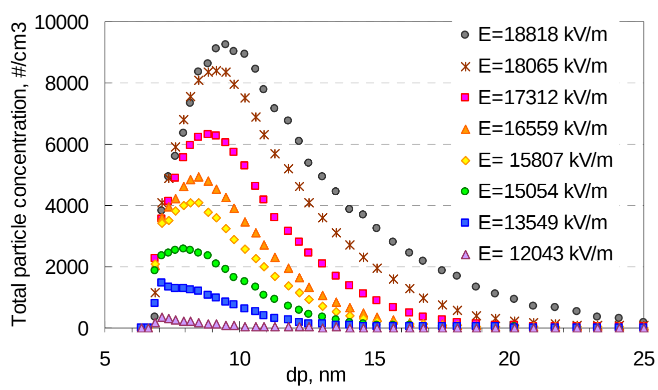






Source:
Alena MSc thesis (2009)

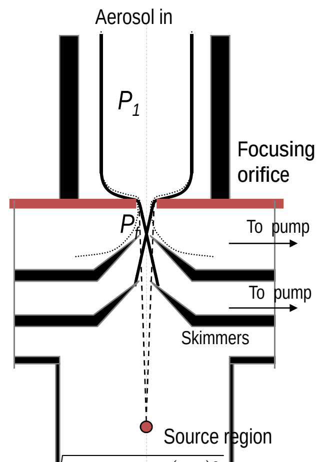
Online Sizing



Aerodynamic particle focusing (APF)

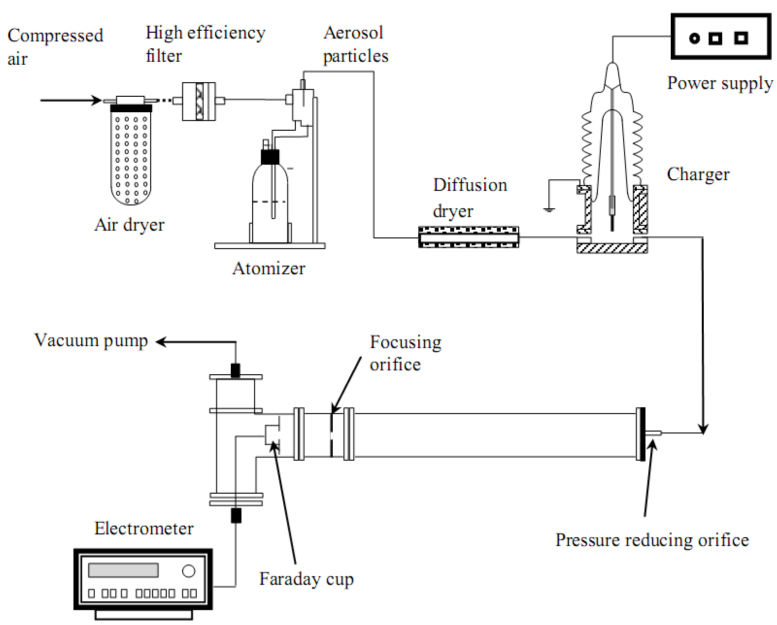
(Graduate students only)

- ❑ Particle beam formed when aerosol passes through an orifice into an evacuated chamber
- ❑ Particle beam has a diameter due to Brownian motion
- ❑ Optimum focused particle d_p^* is a function of Stk_f=1-2, by
- ■ variable orifice geometry: **impractical**
- ■ variable upstream pressure (→ particle mean free path) (3 mm orifice is to keep gas flow continuum at very low pressure)
- ❑ Various focusing devices to enhance transmission efficiency for smaller particles (<10 nm)



$$d_p^* = \sqrt{(1.66\lambda)^2 + (d_p^m)^2} - 1.66\lambda$$

$$d_p^m = \frac{18\mu Stk_f}{\rho_p v_f} \qquad \lambda_f = \lambda_0 \frac{p_0}{p_f}\frac{T_f}{T_0}$$



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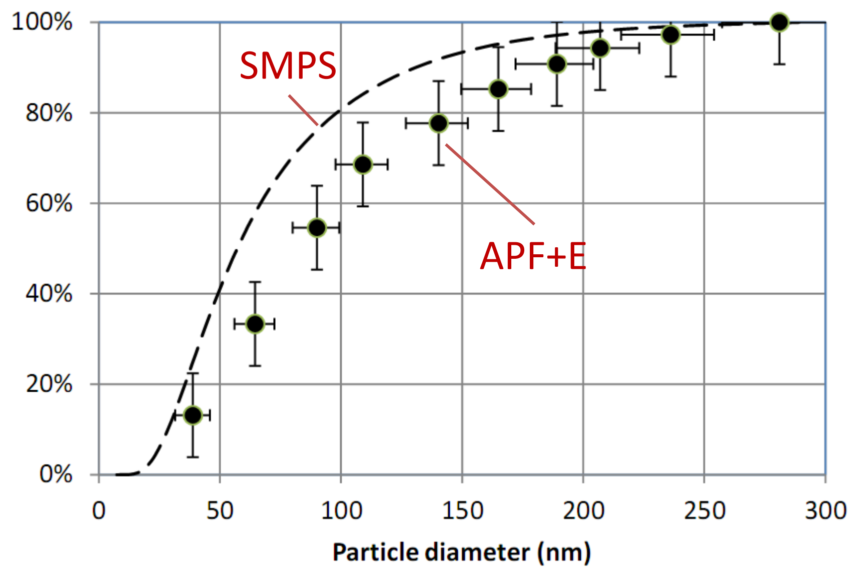

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Nanoaerosol Generation

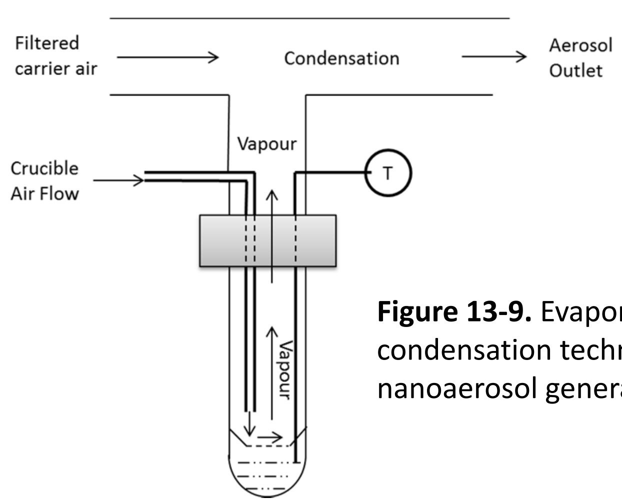

Figure 13-9. Evaporation-condensation technique for nanoaerosol generation

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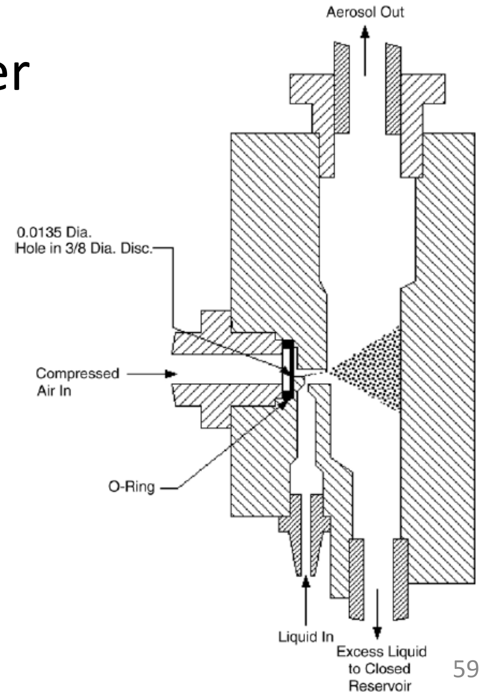
TSI Atomizer



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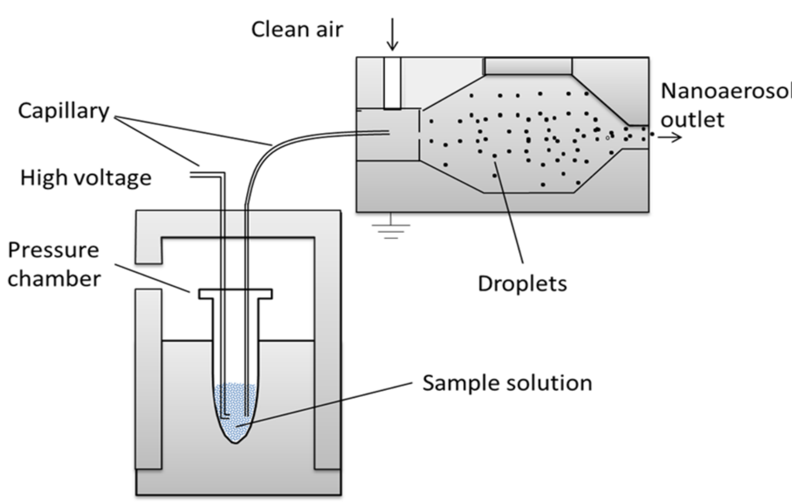
Electrospray



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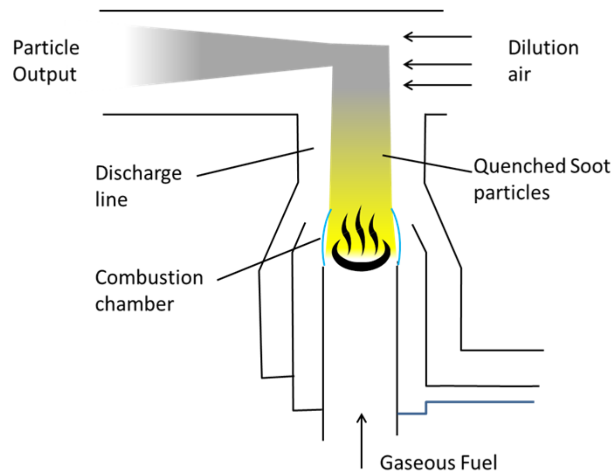
Combustion soot



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