DUST REMOVAL FROM AIR AND WASTE/FLUE GAS

THE HAZARD POTENTIAL OF PARTICULATES

H & S – Health and Safety

It is determined by several parameters including:

- Chemical composition
- Size
- Crystalline nature
- Flammability and explosivity → concern many small-size dust…also in the food industry!

***Nanoparticle**:*

particle with a nominal diameter smaller than 100 nm

CONTROL OF PARTICULATE EMISSIONS

1) DRY TECHNIQUES

- Removal by gravitational settling
    - Cyclones (centrifugal collectors)
- Filtration
    - Baghouse (fabric filter) [*and cartridge filters: but, fewer applications*]
- Electrostatic removal
    - Electrostatic precipitators (ESP)

2) WET TECHNIQUES *[we do not use them to this specific task]*

- Scrubbers (wet) - WS
    - Venturi scrubbers (*also packed/plate/spray scrubbers, but less specific*)
- Electrostatic removal - ESP
    - Wet Electrostatic precipitators (WESP) [few applications in EU]

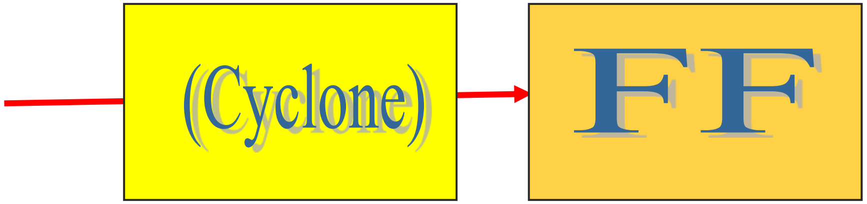
HD: high dust configuration (example: Waste incinerator plant of Brescia)
LD: Low dust configuration (example: Waste incinerator plant of Padua)

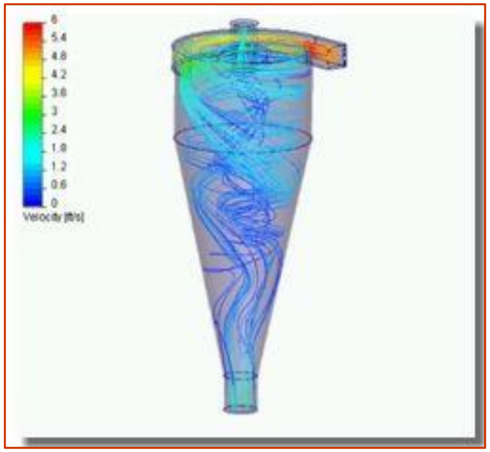
CLEANER AND PLE-CLENEARS

PRE-CLEANERS - example: cyclones

1. **preserve downstream cleaner(s) – (e.g. FF)**
2. **avoid cleaners overload, and a too frequent regeneration**
3. **improve overall dust collection efficiency** (°)
4. **sometimes installed for safety reason** (*e.g. fire prevention of FF, particles still burning in the flue-gas of wood combustion plants)*

(°) low advantages for fine particles!





Waste Gas Dedusting

Technologies available:

1. **DRY** (*EF / FF*)
2. **WET**

Generally, we prefer DRY TECHNIQUES for removal of both particulate and gaseous pollutants (*)!

WET TECHNIQUES ARE ALSO IMPORTANT:

- **WET SCRUBBERS** (mainly for the removal of reactive gaseous pollutants, e.g. H_2S, SO_2, HX, NH_3, ...);
- ***Wet FGD*** *(Flue Gas Desulphurization concerns Power Plants fuelled by High-S fuels, such as Coal and Oil). FGD is a particular application of Wet Scrubbers. Very important for* SO_2 *removal from power plants flue gases.*

(*) **Only Inorganic acid gases** (HX, SOx and few others) can be removed by $NaHCO_3$ or $Ca(OH)_2$;
Organic micro-pollutants (and some inorganic micro-poll., e.g. Hg) can be removed by PAC.

PHYSICS of PM CONTROL DEVICE

Unlike gases, which flow with the air, particles are subjected to a number of forces that can be exploited for controlling particulate matter emissions.
THUS, a basic understanding of the PM behavior in fluids is required.

Water/ wastewater

In liquid effluent treatment, PM is removed primarily by sedimentation and/or filtration

APC

In Air Pollution Control, PM is separated from the surrounding fluid making use of several physical mechanisms, among which:

- Gravitational settling
- Inertial impaction
- Centrifugal inertial force
- Electrostatic attraction

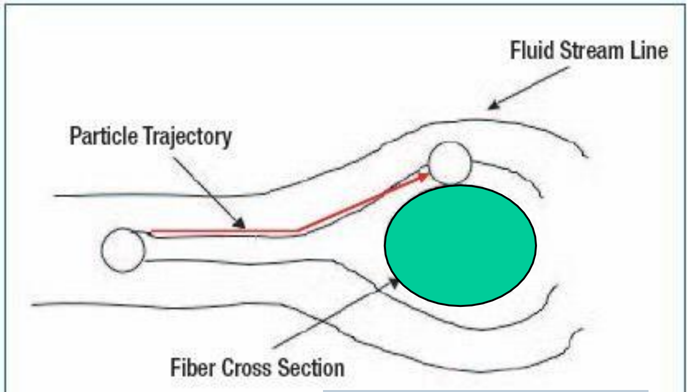
- These forces cause the particles to **accelerate away** from the direction of the mean fluid flow, toward the direction of the net force.
- Taking advantage of this motion, the particles move toward a collecting surface and are subsequently collected and removed.

PM CONTROL DEVICES

There are several different classes of particulate control equipment:

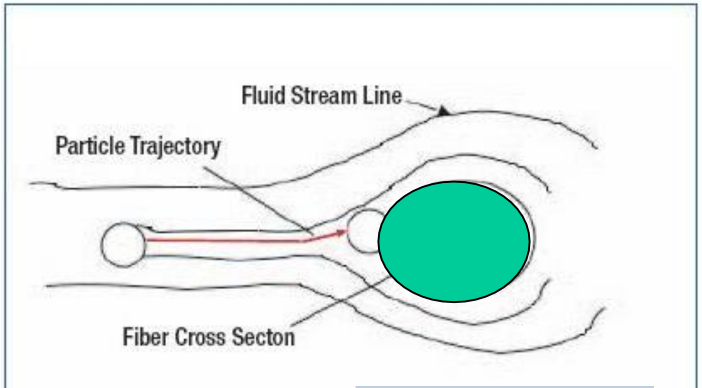
Mechanical separators	**GRAVITY SETTLER**: chamber in which the gas velocity is slowed, allowing particles to settle out by gravity. **CYCLONE**: tube in which the gas stream is forced to flow in a spiral pattern, causing the larger particles to collide with the tube wall owing to centrifugal force. PM slide down the wall to the bottom of the cyclone, where they are removed.
Electrostatic Precipitators	Gas is traveled between two charged plates. PM carried by the gas acquire a charge when passing through the resulting electrical field. As a result, particles are attracted to the plate having opposite charge. PM is periodically removed by rapping to shake off the accumulated dust layer.
Fabric Filters (Baghouse)	Same principle as vacuum cleaner. Gas is forced through a cloth bag. Particles are hold by the fabric and accumulates on it. PM is periodically removed from the cloth by shaking or by reversing the air flow.
Wet Scrubbers	PM is removed by impaction and interception by droplets of water. The larger, heavier water droplets are separated from the gas by gravity; Then solid particles are separated from the water

Removal mechanism by impactation, interception and diffusion

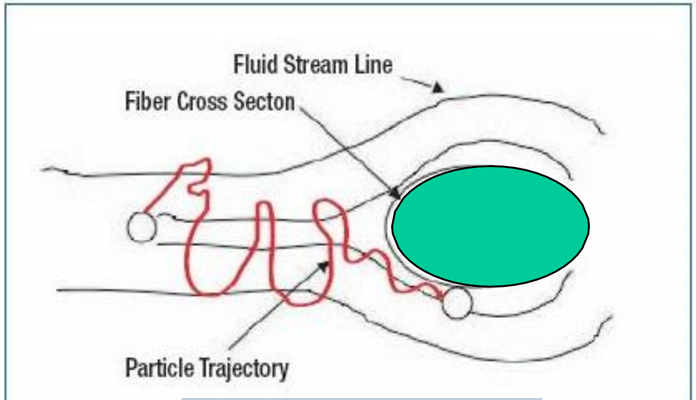


Interception

Coarser particles



Direct impact



Diffusion impact

Finer particles

Impaction (direct impact) of participles occurs when the center of mass of a particle that is diverging from the fluid streamlines strikes a stationary object.

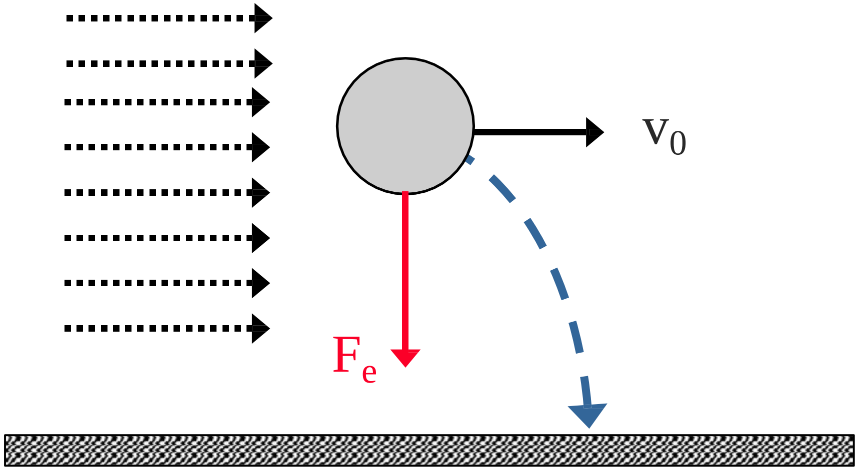
Interception occurs when the particle's center of mass closely misses the object, but, because of its finite size, the particle strikes the object.

Collection of particles by diffusion occurs when small particulates (which are subject to random motion about the mean path and would usually miss the object even considering their finite size) happen to «**diffuse**» toward the object while passing near it.

Once striking the object by any of these means, particles are collected only if there are short range forces (van der Waals, electrostatic, chemical..) strong enough to hold them to the surface.

Removal mechanism application of external forces

Application of external forces (gravitational, centrifugal, electrostatic)



The application of external forces cause the particles to accelerate away from the direction of the mean fluid low (v_0), toward the direction of net force

Technologies:
cyclones (centrifugal force),
electrostatic precipitators (electrostatic force)

Gravitational force F_G and buoyancy force F_B

For a particle released into quiescent air with an initial downward velocity of zero, the gravitational force acting on the particle can be expressed as:

$$F_G = m_p g = \rho_p V_p g$$

F_G = GRAVITATIONAL FORCE [N]
m_p=particle mass [kg]
g=particle acceleration due to gravity [9,8 m/s^2]
ρ_p = particle density [kg/m^3]
V_p= particle volume [m^3]. For spherical particles,

$$V_p = \pi \frac{d_p^3}{6} \quad \Rightarrow \quad F_G = \pi \frac{d_p^3}{6} \rho_p g$$

A particle suspended in a fluid is subjected to a Buoyancy force (F_B) that resists gravity (in the opposite direction of gravity). F_B is equivalent to the weight of the fluid that would otherwise occupy the volume of the object, i.e. the displaced fluid. The greater the buoyancy, the more likely a particle will remain suspended in the air. This can be expressed as:

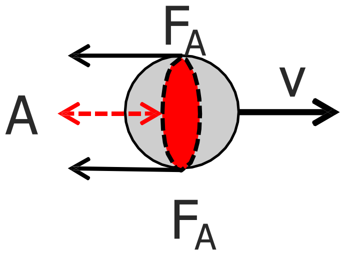
$$F_B = m_F g = \rho_F V_F g$$

F_B = BUOYANCY FORCE [N]
m_F = mass of the displaced fluid [kg]
g = acceleration due to gravity [9,8 m/s^2]
ρ_F = fluid density [kg/m^3]
V_F= volume of the displaced fluid [m^3]. For spherical particles,

$$V_F = \pi \frac{d_p^3}{6} \quad \Rightarrow \quad F_B = \pi \frac{d_p^3}{6} \rho_F g$$

Drag force F_A or (F_D)

$$F_A = C_D A \rho_f v^2/2$$



Drag force =
forza di attrito

Where:
C_D = drag coefficient (dependent on Reynolds number)
A = particle cross section projected in the direction of motion
ρ_f = fluid density
v = fluid velocity
usual reference: equivalent spherical particle

Low Re (creeping flow, laminar conditions)

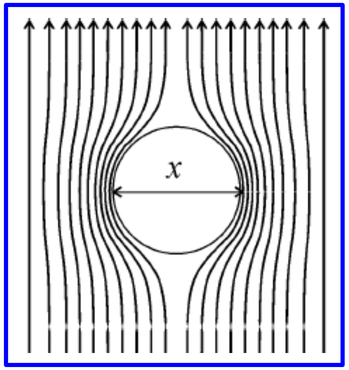
$C_D = 24/Re$
strictly applicable for $Re \leq 0.1$ ($Re = \rho_f \cdot v \cdot d_p/\mu_f$)

- air at 20°C: $\rho_f = 1.2$ kg/m³, $\mu_f = 1.8 \cdot 10^{-5}$ kg/m·s → d_p (μm) ≤ 1.5/v (m/s)

most general situation in particulate removal practice

- sphere: $F_A = 3\pi\mu_f d_p v$ (Stoke's law)

Laminar
(creeping) flow



Drag force F_A or (F_D)

Three particle flow regions exist: laminar, transition, and turbulent.

laminar

Laminar flow is defined as the flow in which the fluid moves in layers smoothly over an adjacent particle surface. The flow is considered laminar for low values of the particle Reynolds number (Re <1-2), (STROKES REGIME).

Transition

For particle Reynolds numbers between 1-2 and 500-1000, the flow is in the transition region, i.e. the flow can be either laminar or turbulent, depending on the local conditions.

Turbulent

Turbulent flow is characterized by erratic motion of fluid, with a violent interchange of momentum throughout the fluid near the particle surface. The flow is turbulent for much greater values of the particle Reynolds number (e.g. Re > 500-1000).

In most air pollution control applications, particles less than 100 µm are in the laminar flow region. Transition and turbulent flow conditions are relevant primarily to the gravity settling of large agglomerates in fabric filters and electrostatic precipitators.

Fluid particle dynamics

Higher Re (deviations from Stoke's regime) → semiempirical equations

Re	C_D
Re ≤ 2 (Stokes)	24/Re
2 < Re ≤ 500 (intermediate)	$C_D = \frac{18.5}{Re^{0.6}}$
Re > 500 (Newton)	0.44

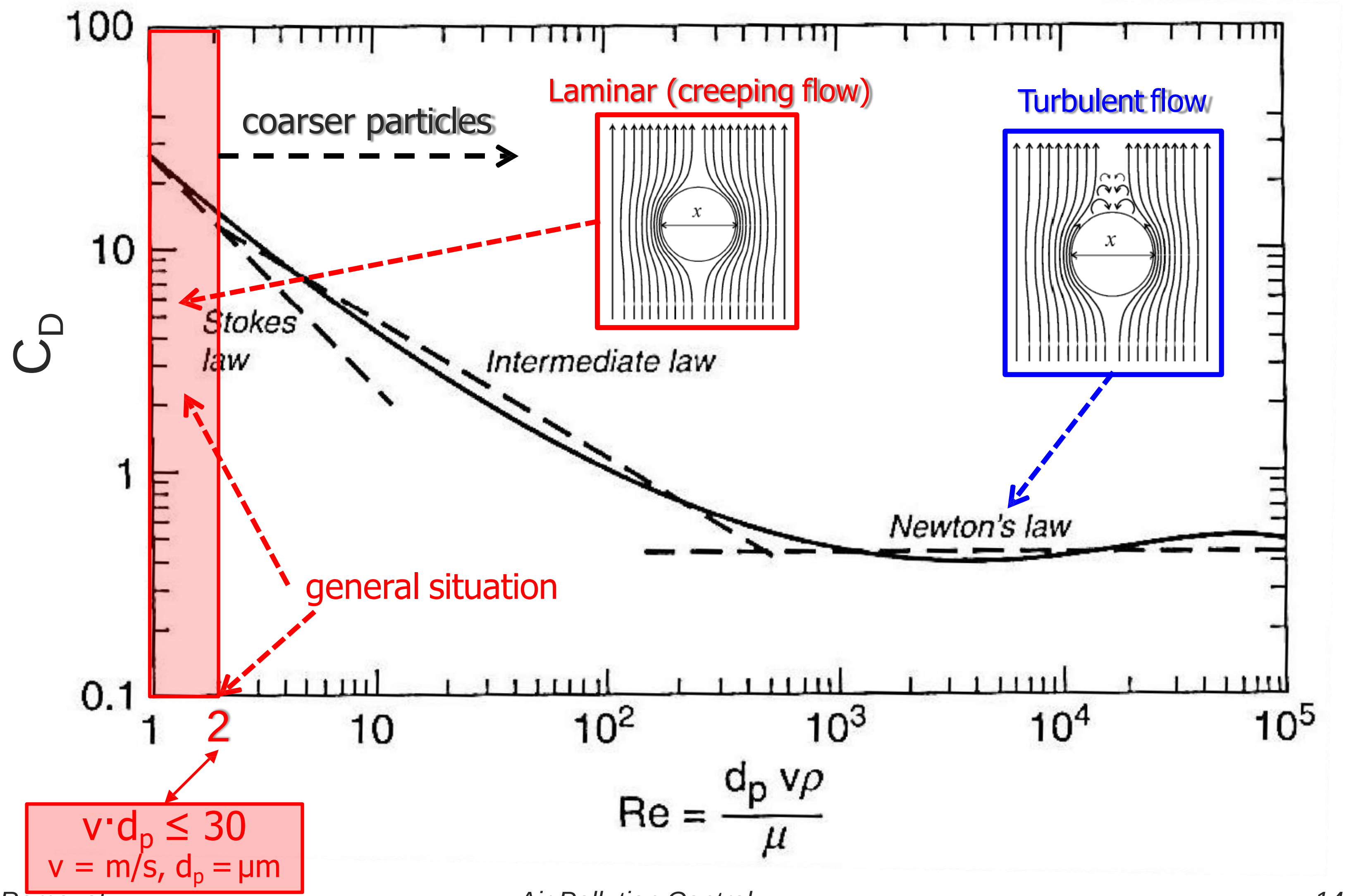
$$C_D = \alpha \cdot Re^{-\beta}$$

- Stokes: $\alpha = 24$, $\beta = 1$
- Intermediate: $\alpha = 18.5$, $\beta = 0.6$
- Newton: $\alpha = 0.44$, $\beta = 0$

These equations apply to particles with diameters >1 μm, i.e. those where the gas is "continuous" around the particle.

Fluid particle dynamics

Higher Re (deviations from Stoke's regime) → semiempirical equations



coarser particles

Laminar (creeping flow)

Turbulent flow

general situation

$v \cdot d_p \leq 30$

v = m/s, d_p = μm

Fluid particle dynamics

- Small particles (deviation from Stoke’s regime)
  - particle dimensions comparable with mean free path of flue gas molecules (average travel distance between successive collisions)
  - transport fluid behavior different from a continuous medium (hyp. Stokes)
    - drag force is lowered
- Empirical corrections: Cunningham factor Cu
  - applicable in Stoke’s regime for smaller particles

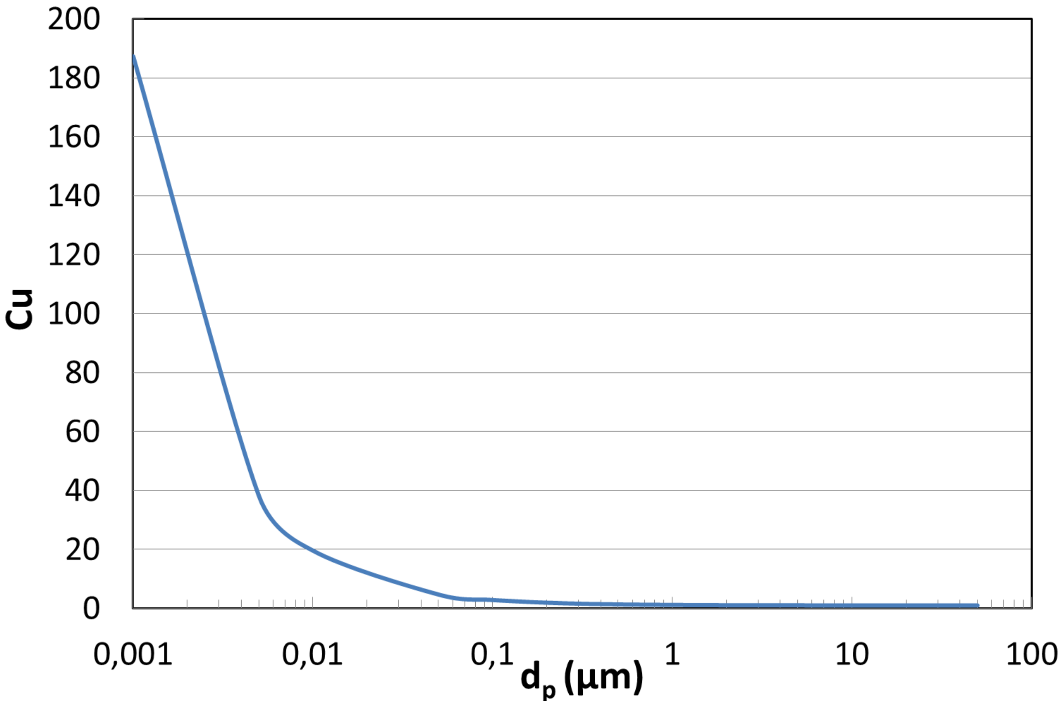
$$C_D = 24/(Re \cdot Cu)$$

$$\boxed{Cu = 1 + \frac{6.2 \cdot 10^{-4}}{d_p} \cdot T}$$

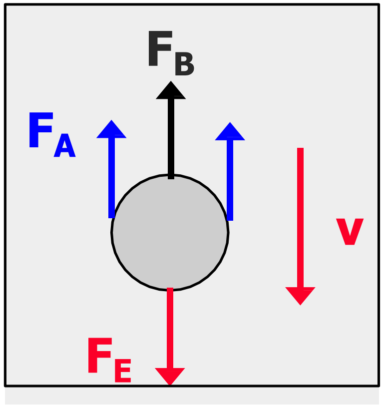
$d_p <\approx 0{,}1\text{-}1\ \mu m$

At laminar condition

$$F_D = \frac{3\pi\, \mu\, d_p v_r}{Cu}$$



Fluid particle dynamics - General equation of particles motion in fluids



Conservation of momentum: $\Sigma_i F_i = m_p \cdot dv/dt$

F_A = drag force

F_B = buoyancy force (negligible in gases)

F_E = external force (for example gravitional force)

- As the particle accelerates due to $F_E = F_G$, its velocity increases.
- As a consequence, drag force increases, proportionally to the square of the velocity.
- At some point, velocity will become high enough that the F_A will be as large as the F_G. At this point, the gravitational and drag force balance, i.e. the net force is zero, and the particle will no longer accelerate, reaching a constant velocity.
- This constant velocity is known as the **terminal settling velocity (v_t)**.

Fluid particle dynamics - General equation of particles motion in fluids

$$\sum F = m_p \cdot a_p = m_p \cdot \frac{dv}{dt}$$

$\sum F$ = sum of all forces acting on a particle [N];
m_p = particle mass [kg];
a_p = particle acceleration [m/s^2];
v = velocity [m/s];

When a particle is in motion relative to a fluid, at least one external force must exist, which is opposed by the drag force F_A. Thus the Newton's second law of motion can be also written as:

$$F_e - F_A = m_p \cdot a_p = m_p \cdot \frac{dv}{dt}$$

F_e = net external force [N];

$$F_A = \frac{3\pi\mu d_p v}{Cu}$$

For a spherical particle in a Stokes regime (that is: Re<1),

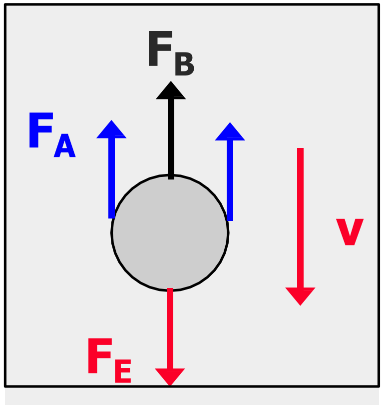
$$F_e - \frac{3\pi\mu d_p \cdot v}{Cu} = m_p \cdot \frac{dv}{dt} \qquad \frac{dv}{dt} + \frac{3\pi\mu d_p \cdot v}{Cu \cdot m_p} = \frac{F_e}{m_p} \qquad \frac{dv}{dt} + \frac{3\pi\mu d_p \cdot v}{Cu \cdot \left[\frac{4}{3}\pi(\frac{d_p}{2})^3\right]\rho_p} = \frac{F_e}{m_p}$$

$$\frac{dv}{dt} + \frac{18\mu}{Cu \cdot \rho_p d^2{}_p} v = \frac{F_e}{m_p}$$

$$\tau = \frac{Cu \cdot \rho_p d^2{}_p}{18\mu}$$

Characteristic time or relaxing time

Fluid particle dynamics - General equation of particles motion in fluids



Conservation of momentum: $\Sigma_i F_i = m_p \cdot dv/dt$

F_A = drag force
F_B = buoyancy force (negligible in gases)
F_E = external force (for example gravitional force)

Stokes regime for spherical particles in free flow (F_E = gravity)

$F_E - F_A = m_p \cdot dv/dt$

$m_p g - 3\pi \mu_f d_p v/Cu = m_p \cdot dv/dt$ With: $m_p = \rho_p \cdot (\pi d_p{}^3/6)$ (spherical particle)

Dividing all terms by $3\pi \mu_f d_p/Cu$ and rearranging

$$\tau\, dv/dt = g \cdot \tau - v$$

where $\tau = \dfrac{\rho_p d_p^2 Cu}{18\mu}$ “relaxing” time: time required for drag force to obtain a velocity v* reduced by a factor of 1/e (≈ 37%) of the the settling velocity (*see next slide*)

Fluid particle dynamics - General equation of particles motion in fluids

$$\tau\frac{dv}{dt} = g\cdot\tau - v$$

- steady particle (v=0) at initial conditions (t=0): equations describing the time evolution of v and x are as follows:

$$v = \tau g\left[1 - \exp\left(-t/\tau\right)\right]$$

$$x = \int_0^t v dt = \tau g t + \tau^2 g\left[\exp\left(-t/\tau\right) - 1\right]$$

When $t=\tau$ $v=v^*$

$v^*=\tau g^*[1-\exp(-1)]=\tau g^*[1-1/e)]$

  - at regime ($t >> \tau$), $\exp(-t/\tau) \rightarrow 0$:

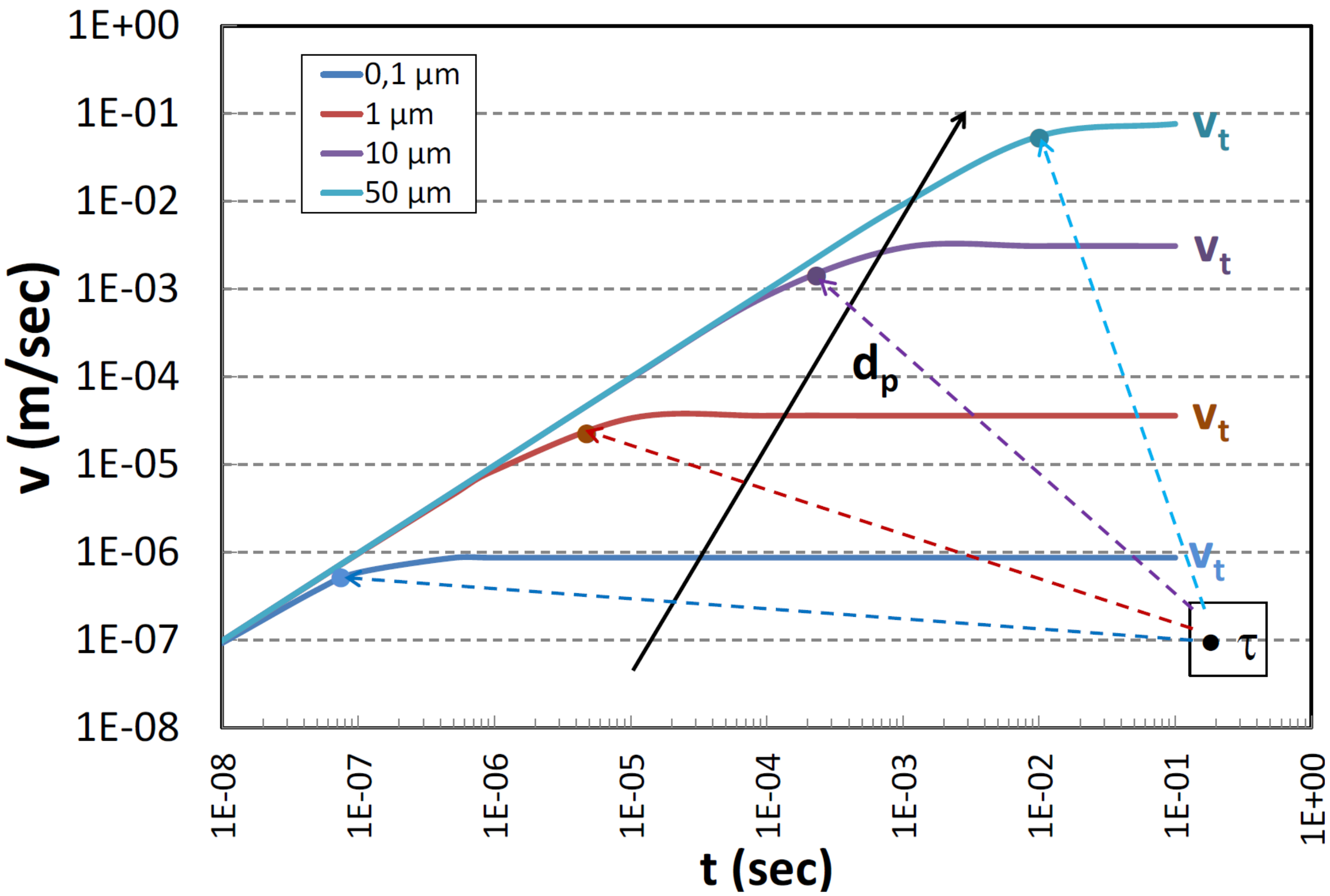
$$\boxed{v_t = \tau g = d^2{}_p \rho_p g Cu/18\mu}$$

$v^*/v_t=\tau g[1-\exp(-1)]/ \tau g= 1-1/e$

Terminal settling velocity: constant velocity of a free flowing particle when gravity force balances drag forces

Practical conditions: for $t \geq 5\tau$, $v=v_t \rightarrow$ particle motion becomes uniform with constant velocity v_t

Fluid particle dynamics - General equation of particles motion in fluids



We can see that after five characteristic times, the particle's velocity is virtually equal to its terminal velocity. If the characteristic time is small, the terminal velocity is attained very rapidly so the transient portion of settling time (acceleration) could be ignored

Terminal settling velocity

Terminal settling velocity (v_t) can thus be derived from Newton's law assuming that the balance between forces is achieved:

$$\Sigma F = F_G - F_D = m_p \cdot a_p = m_p \cdot \frac{dv_r}{dt} = 0$$

Where $F_G = \pi \frac{d_p^3}{6} \rho_p g$

At Laminar flow conditions:

$$v_t = \frac{Cu\, d_p^2 \rho_p\, g}{18\mu}$$

At Transition flow conditions :

Theodore and Buonicore (1988)

$$v_t = \frac{0.153 d_p^{1.14} \rho_p^{0.71} g^{0.71}}{\mu^{0.43} \rho_g^{0.29}}$$

At Turbulent flow conditions :

Theodore and Buonicore (1988)

$$v_t = 1.74 \left(\frac{d_p \rho_p g}{\rho_g} \right)^{0.5}$$

A consistent set of units must be used in these equations. For example:

vt [ft/s];	vt [cm/s];
dp [ft];	dp [cm];
rp [lbm/ft^3];	rp [g/cm^3];
g [ft/s^2];	g [cm/s^2];
m [lbm/ft/s];	m [g/cm/s];

The slip correction (Cunningham factor) and Reynolds numbers can now be used to determine the flow region in which the particles are settling in the pollution control equipment.

A characteristic value K can be used, as defined in the following:

$$K = d_p \left(\frac{g\, r_p r_g}{m^2} \right)^{0.33}$$

Laminar	If K <2.62
Transition	If 2.62 <K <69.12
Turbulent	If K >69.12

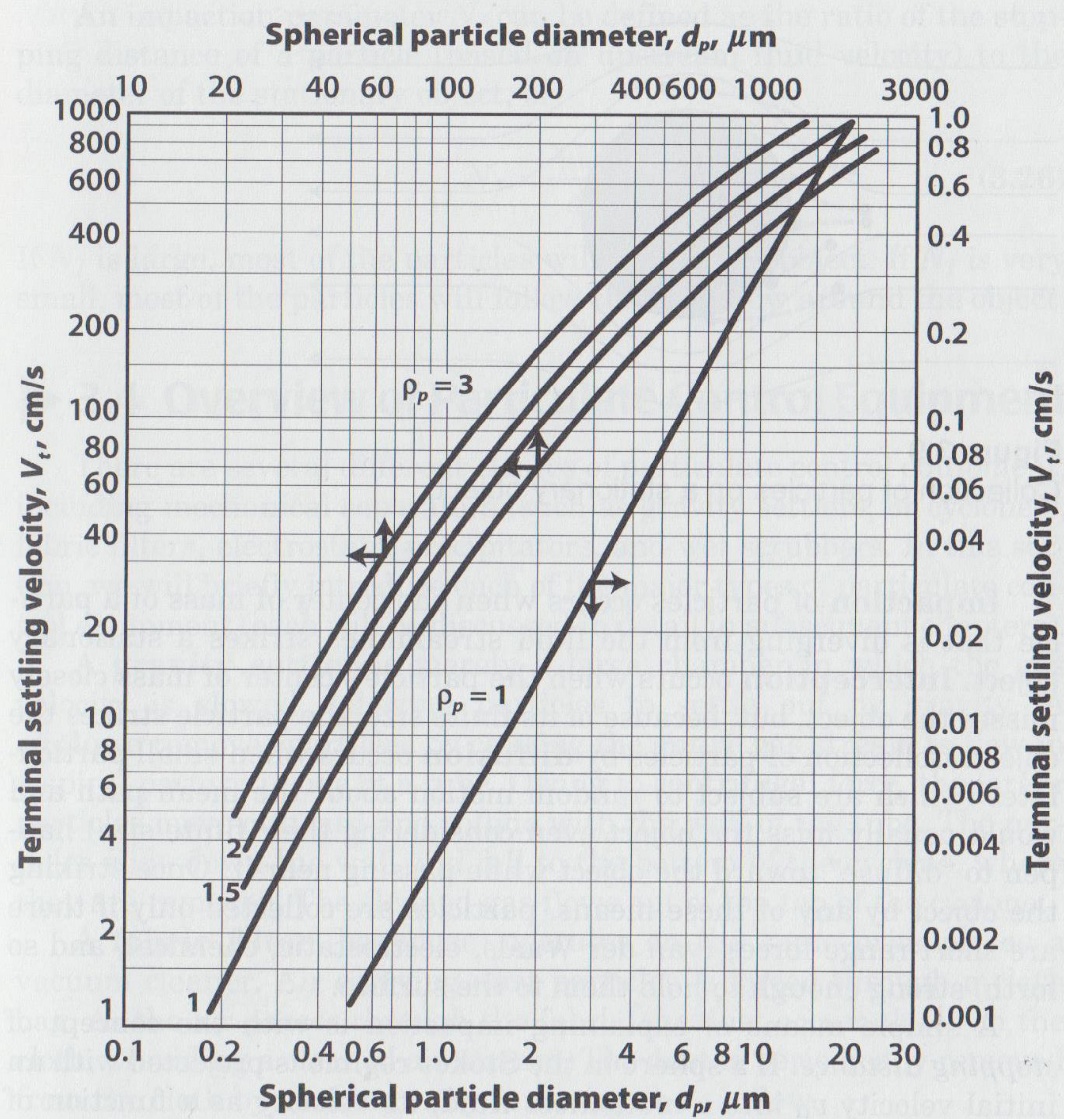
Terminal settling velocity

For quick reference is convenient (and it is also accurate) to determine settling velocity by using a chart.

NB:

The top and left side axes must be used for larger particles;

The bottom and right side axes must be used for smaller particles.



Terminal settling velocity of spherical particles in air at STP (particle density given in g/cm^3).
David Cooper & Alley (2011)

Exercise. Terminal settling velocity v_t

1) Calculate the terminal velocity for a **10** µm particle in air.

DATA:
$\rho_g = 1.2 \times 10^{-3}$ g cm^{-3};
viscosity $\mu = 1.8 \times 10^{-4}$ g cm^{-1}s^{-1};
particle density $\rho_p =$ **1.0** g cm^{-3};
T=20°C.

2) Calculate the terminal velocity for a larger (**100** mm) and heavier particle in air.

DATA:
density $r_g = 1.2 \times 10^{-3}$ g cm^{-3};
viscosity $m = 1.8 \times 10^{-4}$ g cm^{-1}s^{-1};
particle density $r_p =$ **2.0** g cm^{-3};
T=20°C.

Terminal settling velocity

The previous equations have been used to calculate the terminal settling velocities of a wide range of particles with physical diameters ≥0,1 µm (Table 30.5). It can be stressed that terminal settling velocities are negligible for the very fine PM, i.e. diameters <2.5 mm and even for much of the “coarse” PM fraction, i.e. < 10 mm.

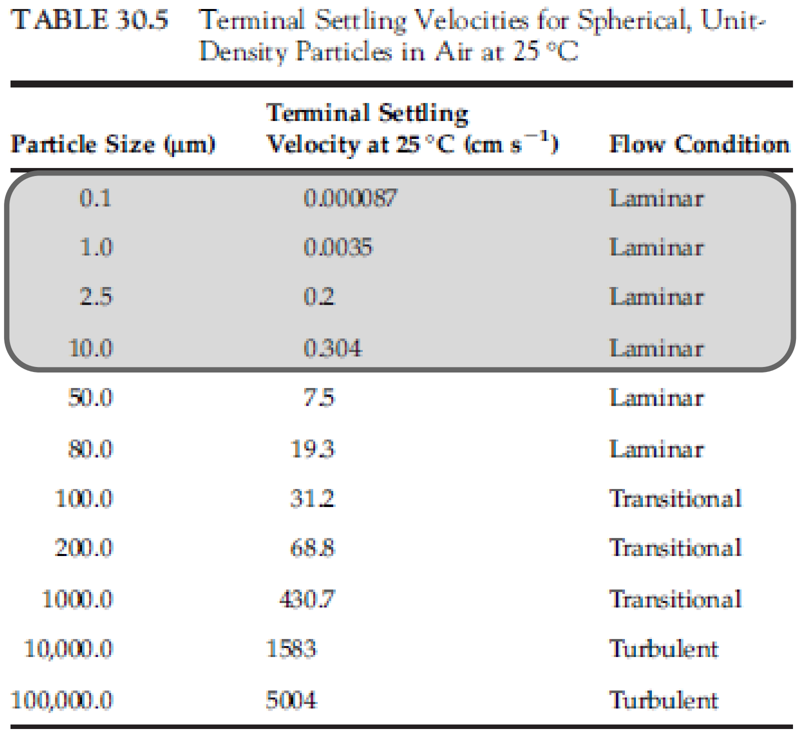


TABLE 30.5 Terminal Settling Velocities for Spherical, Unit-Density Particles in Air at 25 °C

Particle Size (µm)	Terminal Settling Velocity at 25 °C (cm s^{-1})	Flow Condition
0.1	0.000087	Laminar
1.0	0.0035	Laminar
2.5	0.2	Laminar
10.0	0.304	Laminar
50.0	7.5	Laminar
80.0	19.3	Laminar
100.0	31.2	Transitional
200.0	68.8	Transitional
1000.0	430.7	Transitional
10,000.0	1583	Turbulent
100,000.0	5004	Turbulent

(Vallero, 2014)

- PM control devices that employ only gravitational settling are then used primarily for very coarse PM;
- Gravity settlers are useful for initial separation and as precleaners, designed to decrease the larger size particle fraction before entering a next stage of treatment, or in front of air movers and other ancillary equipments.
- They are particularly useful to remove large agglomerated masses or clumps of dust that have been collected on fabric filter, precipitator plates, or other collection surfaces.

Terminal settling velocity

Examples of terminal gravitational settling velocities for spheres of specific gravity of 2.0 g/cm^3.

Coarse sand grain (diameter =1000 μm): v_t= 600 cm/s. This velocity is much higher than common vertical wind velocities, so that it is rare for the wind to blow such particles up or hold them up once they are in the air.

→ A factory emitting sand-sized particles would be a nuisance only to its neighbors and would not contribute much to regional air pollution: almost all of the particles would settle to the ground near the plant.

Small particle (diameter = 1 μm): v_t= 0.006 cm/s. The vertical movements of outdoor air (and even in most rooms) normally exceed this value, so particles having this size do not settle but rather move with the gas and

→ remain in suspension for long periods

Generally:
DUST: settles out of the atmosphere quickly because of its gravitational settling velocity
SUSPENDABLE PARTICLES settle so slowly that they may be considered to remain in the atmosphere until they are removed by precipitation.
AEROSOLS: as the previous term, indicates particles small enough to remain suspended in the atmosphere. <u>This terms in particular means: they behave as if they were dissolved in the gas.</u>

DIFFERENT FORCES WOULD THEN BE REQUIRED TO REMOVE SMALL PM

Fluid particle dynamics – impaction principle

When a flowing fluid approaches a stationary object (such as fabric filter thread, Large water droplet, Metal plate)

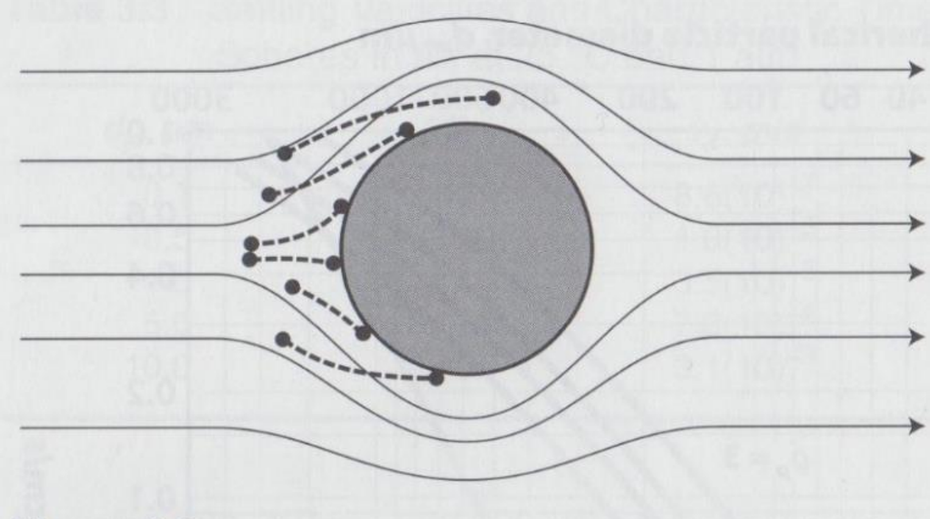


Figure 3.9
Collection of particles on a stationary object.

➔ The fluid flow streamlines will diverge around it.

➔ Particles in the fluid, according to their inertia, can either:

- ✓ follow streamlines exactly;
- ✓ diverge from the fluid streamlines and continue in their original directions.

If the particles have enough inertia and are located close enough to the stationary object, they can be collected by it because they will:

- collide with it (Impaction or interception)
- or diffuse into it

Fluid particle dynamics – impaction principle

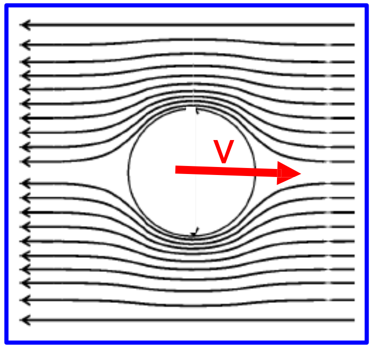
A simple means of explaining IMPACTION is with the concept of STOPPING DISTANCE.

If a sphere in the Stokes regime is projected with an initial velocity v_0 into a motionless fluid, the stopping distance is the total distance traveled by the particle before it comes to rest.

$$\tau\frac{dv}{dt} = g\cdot\tau - v$$

free flowing particle at initial velocity v_0 with gravity negligible

$$\tau\frac{dv}{dt} = \cancel{g}\tau - v \rightarrow \frac{dv}{dt} = -\frac{v}{\tau} \qquad \int_{v_0}^{v}\frac{dv}{v} = -\frac{1}{\tau}\int_{o}^{t} dt \quad \left[\begin{array}{c} v = v_o \exp(-t/\tau) \\ x = v_o\tau\,[\,1 - \exp(-t/\tau)] \end{array}\right.$$



- at regime ($t\rightarrow\infty$), finite value of distance x:

  $X_s = v_o\,\tau = v_0\,\rho_p\,d_p{}^2 Cu/18\mu$ Stoke's stopping distance

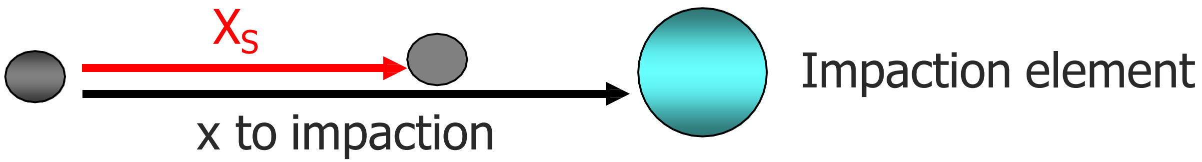
- relaxing time τ: for $t=\tau$, $v = v_o/e$

Fluid particle dynamics – impaction principle

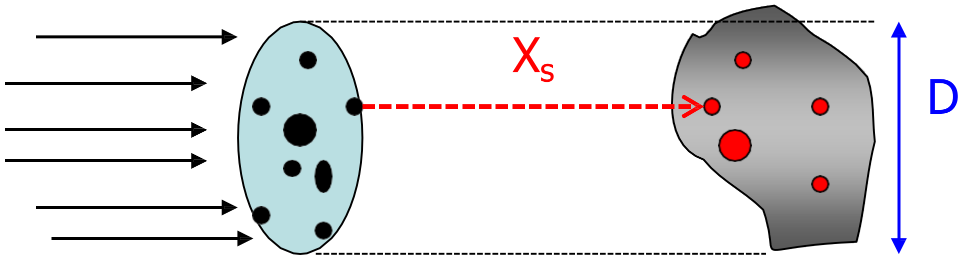
distance x travelled by particle in terms of stopping distance X_s

$$x/X_s = 1 - \exp(-t/\tau)$$

Particle stops before impacting fixed (plate, wall) or mobile (water drop) impaction element → no capture



Fluid particle dynamics - General equation of particles motion in fluids



Gas stream section S
“swept” by obstacle

Impaction
obstacle

INERTIAL
IMPACT

Capture efficiency E_c= retained particles/total particles in S

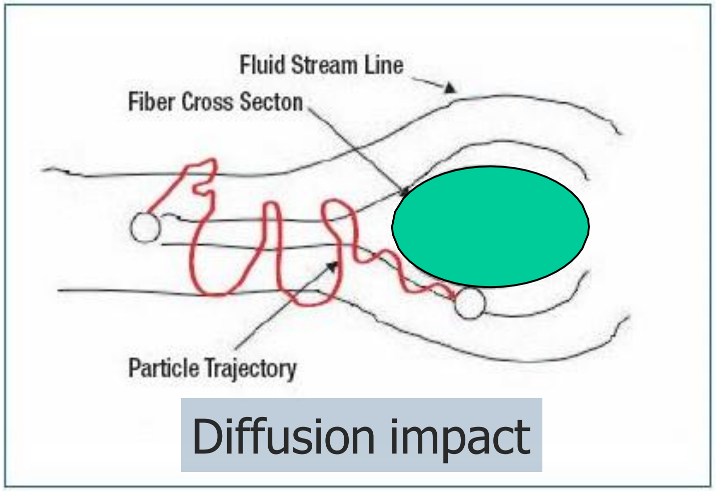
- Empirical description of E_c with N → impact number: non dimensional parameter related to capture efficiency

$$N = X_s/D \rightarrow \qquad N = \frac{Cu \rho_p d^2 v_p}{18 \mu D}$$

X_s = Stoke’s stopping distance; D = obstacle diameter

Fluid particle dynamics - General equation of particles motion in fluids

DIFFUSIAN
IMPACT



Diffusion impact

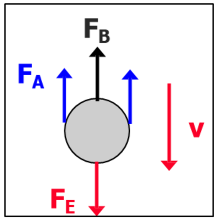
- Brownian motions (random collisions with gas molecules) make impact collection by obstacles more efficient
- significant for very fine particles (nearly < 0.1 µm)
- semi empirical description with introduction of diffusivity D

$$D = \frac{kTCu}{3\pi \mu d_p}$$ with k = Boltzmann constant, T = temperature (K)

What to learn from fluid particle dynamics

In order to describe the **impaction principle** we applied the fluid particle dynamics

- spherical particles
- drag force (FA) and external force (FE) (for example gravitional force) are balanced
- FB buoyancy force is negligible in gases
- steady particle (v=0) at initial conditions (t=0)



➢ at regime (t >> τ)

$$\tau \frac{dv}{dt} = g \cdot \tau - v$$

$$\boxed{v_t = \tau g = d^2_p \rho_p g Cu / 18\mu}$$

After a transient period (very small, few milleseconds or less) the velocity of the particles becomes uniform and equal to the **terminal settling velocity**

- spherical particles
- Only drag force is considered
- steady particle (v=v0) at initial conditions (t=0)

➢ at regime (t >> τ)

$$\tau \frac{dv}{dt} = g \cdot \tau - v$$

$$\boxed{X_s = v_o \tau = v_0 \rho_p d_p{}^2 Cu / 18\mu}$$

If a sphere is projected with an initial velocity v0 into a motionless fluid, at regime it comes to rest at a distance called "**Stoke's stopping distance**" (Xs)

In order to describe the **diffusion impact principle** we have to consider the diffusivity coefficient

COMPARISON OF DUST REMOVAL SYSTEM

Dust removal system	Typical dust emission concentrations	Advantages	Disadvantages
Cyclone and multi-cyclone	Cyclones: 200–300 mg/m^3 Multicyclones: 100–150 mg/m^3	Robust, relatively simple and reliable. No moving parts. Applied in waste combustion, often as pre-cleaners.	Only for pre-dedusting. Relatively high energy consumption (compared to ESP).
Electrostatic precipitators (ESP), dry	< 5–25 mg/m^3	Relatively low power requirements. Can use gas temperatures in the range of 150–350 °C, but effectively limited to 200 °C by PCDD/PCDF issue.	Formation of PCDD/ PCDF if used in range 450°–200° C.
Electrostatic precipitators *(ESP), wet*	< *5-20 mg/m^3*	*Able to reach low pollutant concentrations.*	*Mainly applied for post-dedusting.* *Generation of process waste water.* *Increase of plume visibility.*
Bag filter	< 1 mg/m^3	Layer of dust (cake) acts as an additional filter and as an adsorption reactor.	▪ Relatively high energy consumption *(compared to ESP).* ▪ Sensitive to condensation of water and to corrosion.

Be careful! FILTRATION EFFICIENCY REFERS TO THE ACTUAL VOLUME. If the gas is at 200 °C and the measured (effective) dust concentration in the cleaned gas is, **c_M = 5 mg/m^3**, the legal conc. would be: **c_R** = 5 x 473/273 = **8.7 mg/Nm^3.**
→ *Prefer, whenever possible, lower gas temperatures to maximize filtration efficiency!*

COMPARISON OF DUST REMOVAL SYSTEM

Efficiency vs. particle size

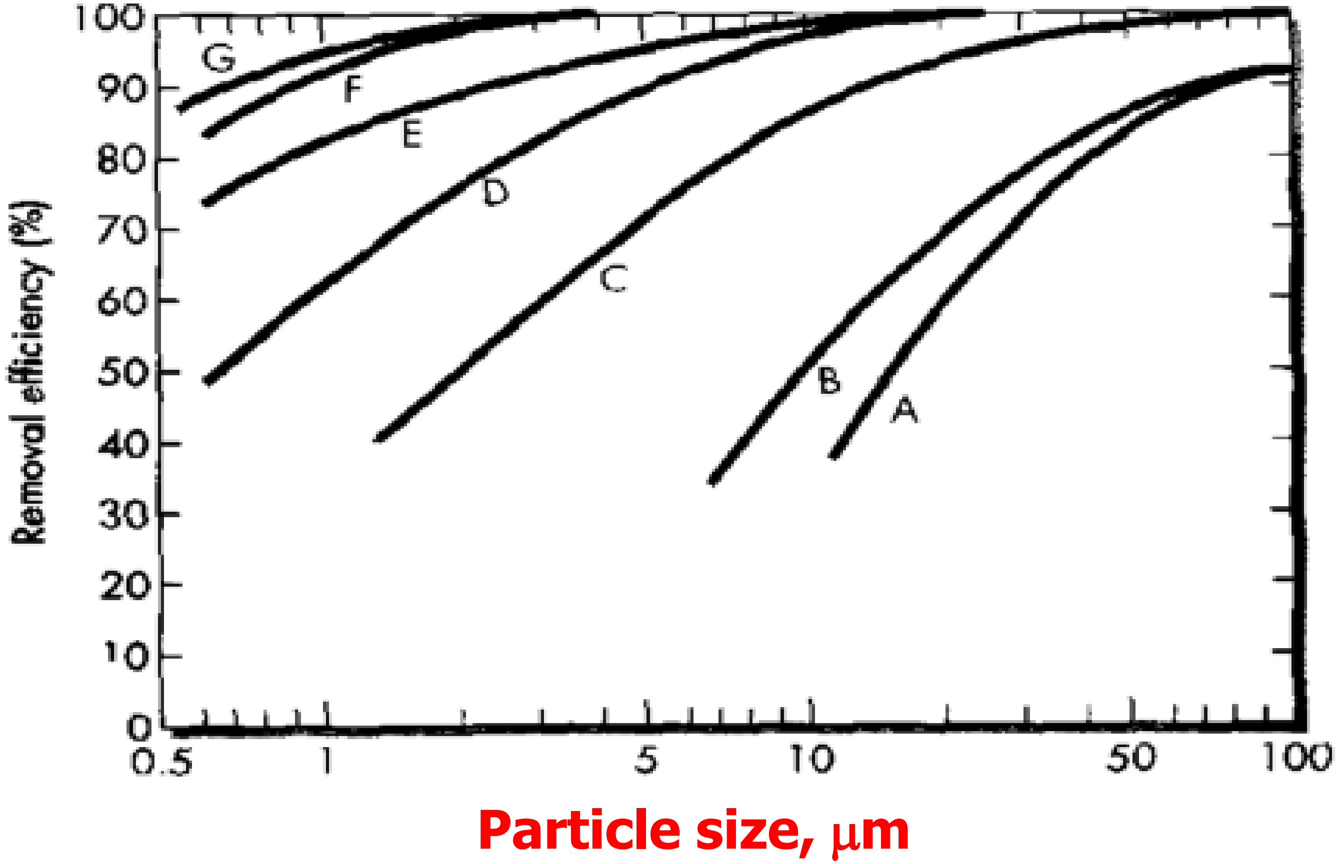
EFFICIENCY
PARTICULATE CONTROLS

	EFFICIENCY (%)		
CONTROL	5 µm	2 µm	1 µm
CYCLONE (MED EFF)	30	15	10
CYCLONE (HIGH EFF)	75	50	30
ESP	99	95	85
BAGHOUSE	99.8	99.5	99
SCRUBBER	99.7	99	97

Removal efficiencies (%)

	Particle size in µm		
	<2.5	2.5-6	6-10
Cyclone	10	35	50
ESP	95	99	>99.5
Fabric filter	99	99.5	>99.5
Venturi scrubber	90	95	99

COMPARISON OF DUST REMOVAL SYSTEM



A	Settling Chamber	E	Spray Tower Wet Scrubber
B	Simple Cyclone	F	Venturi Scrubber (wet)
C	High efficiency cyclone	G	Bag Filter
D	Electrostatic Precipitator		

Collection Efficiency

Fraction of incoming particles collected

Fractional Efficiency, $\eta(d)$: Efficiency vs. diameter

Overall Efficiency, η_o

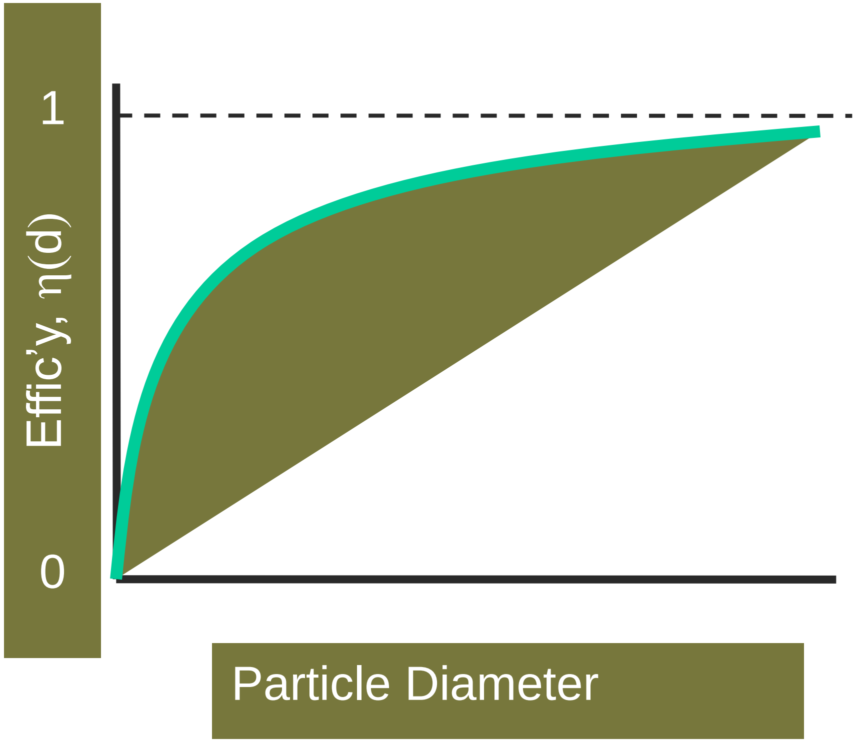
Depends on:

Fractional efficiency, *$\eta(d)$,*

and on

Size distribution, F(d)

$$\eta_o = \int_0^\infty \eta(d)\,\mathbf{F}(d)\,\mathbf{d}(d)$$



Overall collection efficiency

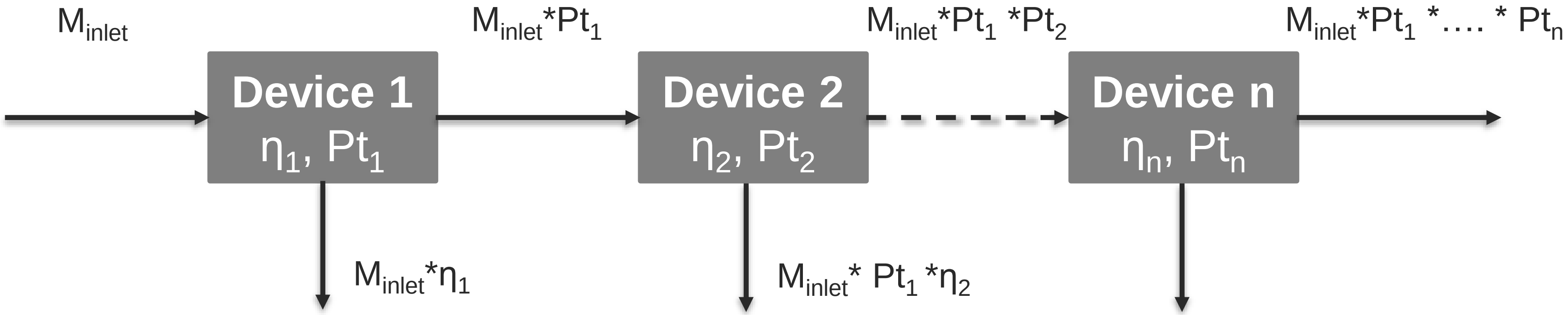
The overall collection efficiency of a system composed of two or more devices in series is not simply the sum nor the product of the efficiencies of each device.

The simplest way to to approach this problem is to define the penetration (**Pt**) of a device as the mass fraction that is not collected (that is the fraction that penetrates through the device).

The overall penetration of a system is simply the product of the penetration of all of the individuatl devices.

$$P_t = 1 - \eta$$

$$P_{t,tot} = \prod_{i=1}^{n} P_{t,i}$$



M_{inlet}

M_{inlet}*Pt_1

M_{inlet}*Pt_1 *Pt_2

M_{inlet}*Pt_1 *…. * Pt_n

Device 1
η_1, Pt_1

Device 2
η_2, Pt_2

Device n
η_n, Pt_n

M_{inlet}*η_1

M_{inlet}* Pt_1 *η_2

Isokinetic Sampling Method

If the fluid is homogenous, the sampling is relatively simple since the fluid has the same consistency throughout the flow area. This is not the case with fluids having entrained particles.
Particle concentration changes because of the flow pattern inside the fluid stream.

Let us consider the example of measuring particulate emission from a coal fired power plant. The norm in most of the countries around the world is around 50 mg/Nm^3. Non-compliance results in stiff penalties and even closure of the plant. To prove that the plant is running at these levels, particulate samples from the flue gas ducts are analyzed. The key step is getting the correct sample. There are two major problems in getting a correct sample.

- The large cross section area of the flue gas duct results in flow segregation due to many reasons. Taking a large number of samples from points across the duct avoids the effect of this segregation.
- The sample is drawn out of the flue gas duct by suction from each point through a sampling tube. If the sampling velocity at the point of sampling is less than the fluid velocity, then all the particles, especially the smaller size particles, will not enter the sampling tube. If the velocity is more, then more particles will enter the tube, again especially the smaller particles. Both conditions produce samples with wrong concentration. Ideally, the flow of the sample through the sampling system should be such that the velocity at the sampling point inlet is the same as the velocity of flue gas at that point. **This is called Isokinetic Sampling**.

Source: https://www.brighthubengineering.com/power-plants/98903-what-is-isokinetic-sampling/ (accessed on 29-04-2019)

SUMMARY

- Control of PM is influenced by fundamental properties such as PM size range and physical behavior
- The particles of air pollution interest are mostly in the size range [0.01-10 µm]
- Most particles of air pollution interest are in the size range where the Stokes equation for F_D can be used with satisfactory accuracy
- PM control devices that employ only gravitational settling are used primarily for very COARSE PM. Different forces (electrostatic, centrifugal) are required to remove SMALL PM
- Particles smaller than about 2 mm are generally secondary pollutants (mainly produced by condensation or chemical reaction of gases/vapors) Coarser particles are primary pollutants (enter the atmosphere mainly as particles).
- Even if most of the fine particle in the atmosphere are secondary particles, nonetheless, the CONTROL of primary particles is a major part of air pollution control engineering.