14 Gas cleaning

In the earlier chapters unit operations that cause particles to become entrained in gas stream were covered; examples include fluidisation, pneumatic conveying and grinding. In the next chapter the effect of dust in the working environment is described. In certain workplaces removal of particles down to very low sizes and concentrations is essential, such as within operating theatres, during fabrication of electronic equipment and production of pharmaceutical grade materials. Hence, a critically important subject is the removal of particles from gas streams. The subject is significantly different from solid-liquid separation because the fluid medium is much less viscous than a liquid and this influences the forces that are most relevant to the trajectory analysis.

In many industrial processes sedimentation is the primary mechanism for particle removal from a gas stream. Thus, gas fluidised beds have the characteristic shape illustrated in Figure 7.2: the increase in the bed diameter leads to a decrease in the gas velocity above the bed and particles will fall back into the fluidised bed. However, finer particles may still be *carried over* with the gas, i.e. *entrained* in the gas flow, and additional particle/gas separation equipment is required. The material presented in Chapter 5 is appropriate to calculate the sedimentation rates of particles in gases, this chapter covers other relevant mechanisms.

14.1 Target; grade and overall efficiencies

To remove a particle from a gas stream it must be encouraged to hit a target and then to stick to it. The gas then passes on leaving the particle removed from it. Targets can be made from many objects including: liquid drops, fibres, larger particles, plates and walls. There is an enormous range of equipment based on one, or more, of these targets. Clearly, for the particle to be removed the target needs to have the property of retaining the particle from the flow but, if the targets are reused it must then be encouraged to release the particle when required during a cleaning cycle. There is often confusion between the different types of efficiencies used to describe the process. The simplest is the *single target efficiency*, which can be represented by Figure 14.1. The single target (e.g. a fibre) efficiency is (η_s)

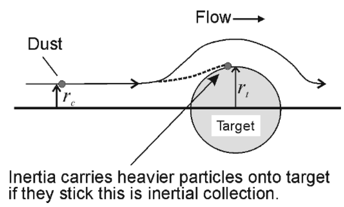
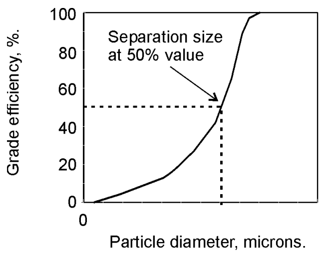


Fig. 14.1 Particle collected on a target from a gas streamline and single target efficiency

$$\eta_s = \frac{r_c}{r_t} \tag{14.1}$$

where the particle is collected by inertial separation: the gas can easily change direction and does so round the fibre, but the particle has much greater inertia and will continue moving towards the fibre, possibly contacting it. If it does so, and sticks, it will be removed from the gas stream. All particles of a critical size starting from $r=0$ to $r=r_c$ are captured, particles starting their trajectory from $r=r_c$ to $r=r_t$ will not be collected. Clearly, $r_c=f(x)$ or more accurately a function of the inertia provided by the particle and fluid system.

The *grade efficiency* is the collection efficiency for a given particle size range and would be calculated by dividing the mass of particles in a grade retained in the device compared to the mass entering the dust collection equipment for the size range. In most cases, it is easier to remove larger particles; hence, the grade efficiency curve for dust collection is at, or approaching, 100% for large particles and lower for finer particles. An example grade efficiency curve is provided in Figure 14.2.



The sharpness of separation is:

$$\frac{x_{25\%}}{x_{75\%}}$$

A steeper curve gives a sharpness approaching one and a better separation between fine and coarse cuts.

Fig. 14.2 Grade efficiency – note a different definition from a classifier: here the intention is to remove particles hence a good grade efficiency occurs with the larger particles. Efficiency is still based on a size range – or grade.

The grade efficiency considers collection of particles in as many grades as are defined, but the *overall collection efficiency* is a single value that represents the total mass retained compared to the total mass challenging the dust removal equipment. Hence, it may be deduced using the grade efficiency curve if the total dust mass flow rate entering the device is known. The total mass flow rate of dust leaving can be calculated and the overall efficiency is the total mass retained divided by the total mass entering.

14.2 Collection mechanisms

Considering Figure 14.1, the dust collection mechanism was inertial separation. The inertia is a property of the system, and not just the particle; the significance of the direction change of the gas, viscosity of the gas and velocity of the gas entraining the particle all influence the likelihood of the particle *inertially separating* from the gas streamline and hitting the target. Hence, a measure of the inertia of a system needs to contain all these parameters and it is called the Stokes Number (Stk)

$$\mathrm{Stk} = \frac{x u_g \rho_s}{9 \mu D} \tag{14.2}$$

where it is assumed that the particle starts its trajectory at the same speed as the gas (u_g) and D is a characteristic dimension of the system. In the case of Figure 14.1 the obvious dimension would be the fibre diameter. The Stokes number is dimensionless and is not to be confused with the Stokes' settling velocity.

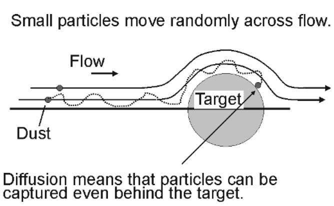


Fig. 14.3 Particle captured by diffusional mechanism on a fibre

Another very common dust collection mechanism is diffusional collection. This is illustrated on Figure 14.3 and is more relevant to the capture of very small particles. The dust is subject to bombardment by molecules of gas and, as the particle is small, the momentum of the gas can induce particle motion (Brownian motion). Hence, it is possible for a dust particle to be small enough to follow the gas streamline around the target, i.e. not collected inertially, but it may be pushed onto the target after it has passed it because of molecular bombardment, as illustrated in Figure 14.3.

Inertial collection mechanisms are important with larger particles and diffusional collection for smaller; hence, there is a minimum on a plot of target efficiency against particle size, Figure 14.4. Other mechanisms that are important include: bounce (re-entrainment), sieving/straining, sedimentation, electrostatic and thermophoretic forces. Bounce occurs when the particle has sufficient inertia so that the forces attempting to retain the particle on the target are insufficient to do so and the particle bounces off.

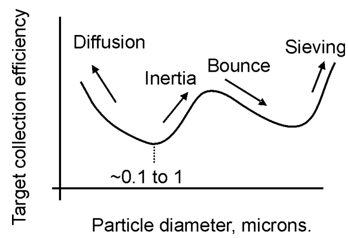


Fig. 14.4 Different collection mechanisms and particle size range

The Stokes number can be explained by considering a force balance in the axial direction (*z* axis or direction), considering just the forces of inertia and drag. Calling the particle and gas velocities: U_p and u_g respectively and using the Stokes drag expression is valid

$$F = ma = m\frac{dU_\mathrm{p}}{dt} = 3\pi\mu x(u_\mathrm{g} - U_\mathrm{p}) \tag{14.3}$$

Using the product of volume and density for mass, and expanding particle velocity gives

$$\frac{x^2\rho_\mathrm{s}}{18\mu}\frac{d^2z}{dt^2} + \frac{dz}{dt} - u_\mathrm{g} = 0 \tag{14.4}$$

The above equation can be rendered dimensionless as follows:

$$z^* = \frac{z}{r_\mathrm{t}} \qquad U^* = \frac{u_\mathrm{g}}{U_\mathrm{o}} \qquad \tau = \frac{U_\mathrm{o}}{r_\mathrm{t}}t$$

where U_o is the mainstream (initial) gas velocity, hence

$$\frac{x^2\rho_\mathrm{s}U_\mathrm{o}}{18\mu r_\mathrm{t}}\frac{d^2z^*}{d\tau^2} + \frac{dz^*}{d\tau} - U^* = 0 \tag{14.5}$$

which is a dimensionless equation where the Stokes number is

$$\frac{x^2\rho_\mathrm{s}U_\mathrm{o}}{18\mu r_\mathrm{t}} = \mathrm{Stk} \tag{14.6}$$

The difference between equations (14.2) and (14.6) is in the characteristic dimension, which is based on a diameter and radius respectively. Hence, the associated constant is18 for a radius and 9 for a diameter. The Stokes number is very important in modelling and scale-up of equipment sizes because, if the collection mechanism is primarily due to inertia, there will be a unique function between particle collection efficiency and the Stokes number, see Figure 14.5 for an example. Thus, if this relation is known it is possible to predict the collection efficiency for one set of particles from a knowledge of efficiency for another set of conditions. This is used in the scale-up of gas cyclones, where the collection efficiency is *transposed* between a test cyclone and an industrial unit, see Problem 6.

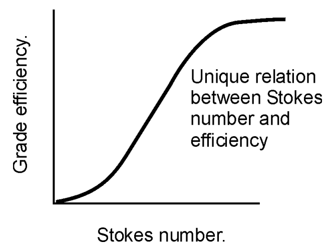


Fig. 14.5 For inertial collection only – a unique relation between Stokes number and collection efficiency

Another parameter used to characterise the inertia of a particle is the stop distance, which can be considered to be the distance required for a particle to come to a halt when it is injected into a stationary gas at the velocity U_o. Again the only forces considered here are inertia and drag. The particle weight is insignificant. Integrating the dimensional force balance, equation (14.4), provides an expression for the particle velocity as a function of time (assuming $u_g=0$ and $U_p=U_o$ as a boundary condition). Expanding velocity into distance with time then permits the integration to be repeated providing an equation for the stop distance (z_s)

$$z_s = \frac{x^2 \rho_s U_o}{18\mu} \tag{14.7}$$

i.e. the stop distance is the product of the Stokes number and the target radius (or characteristic linear dimension).

Regardless of the mechanism bringing about the collection it is possible to conduct a critical trajectory analysis. For laminar flow conditions, this procedure is very similar to clarification and is illustrated in Problem 2. However, gas flow rates are usually very high and the resulting fluid flow is normally turbulent. A critical trajectory analysis is still possible, but must be conducted within the boundary layer outside of the turbulent flow. The trajectory is illustrated in Figure 14.6. The time taken to travel radially is again equated to the time taken to travel axially, albeit very small amounts

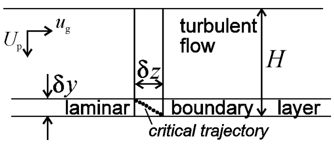


Fig. 14.6 Critical trajectory within a boundary layer

$U_p = \dfrac{\delta y}{\delta t}$ and $u_g = \dfrac{\delta z}{\delta t}$ Thus, equating the times and rearranging

$$\delta y = \frac{U_p}{u_g}\delta z \tag{14.8}$$

The proportion of particles removed from a system (-dN/N) is simply assumed to be equal to the ratio of the volume from which they are captured, compared to the total volume (where W is channel width)

$$-\frac{dN}{N} = \frac{W\delta y \delta z}{WH\delta z} = \frac{U_p}{u_g}\frac{\delta z}{H} \tag{14.9}$$

The negative sign is required for particle removal. The particle velocity towards the wall could be due to electrophoresis (in an electrostatic precipitator), thermophoresis (due to a temperature gradient such as in a chimney) and simple gravity sedimentation. Regardless of the mechanism for deposition the mathematical analysis is identical. Integrating equation (14.9), under the boundary conditions that $N=N_o$ at $z=0$ and $N=N$ at $z=L$ provides

$$\frac{N}{N_o} = \exp\left(-\frac{U_p L}{u_g H}\right) \tag{14.10}$$

Equation (14.10) provides an expression for the fraction of particles remaining in gaseous suspension at a distance L down the dust collection device, with turbulent flow. The expression for particle collection efficiency (η) is one minus this value

$$\eta = 1 - \frac{N}{N_o} = 1 - \exp\left(-\frac{U_p L}{u_g H}\right) \tag{14.11}$$

Equation (14.11), when applied to dust collection by means of an electrostatic precipitator, is known as the *Deutch Equation*.

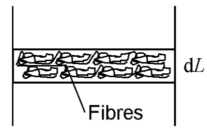


Fig. 14.7 Fibres in a differential slice within a HEPA filter

14.3 Dust collection material balance

A material balance can be written for particle collection in a system, such as capture in a fibrous filter designed for *high efficiency particulate air* filtration (HEPA). These are typically thick fibrous pads of greater than 95% porosity that capture particles by diffusion. However, the following analysis can be adopted to any system involving a target, such as a spray tower. The fibrous filter is illustrated in Figure 14.7 and a material balance is as follows
mass input - mass output = accumulation

Using α_f for the packing density of fibres, i.e $1-\varepsilon = \alpha_f$
the volume of fibres in height dL is: $\alpha_f A\mathrm{d}L$
The length of fibres in dL is fibre volume over fibre area, i.e.

$$\frac{\alpha_f A\mathrm{d}L}{(\pi/4)d_f^{\,2}}$$

where d_f is the diameter of the fibre. The projected area to the gas flow is the product of the length and diameter of the fibre, thus

$$\frac{4\alpha_f A\mathrm{d}L}{\pi d_f}$$

Now it is generally true that the mass of dust removed in a differential layer per unit time, i.e. the accumulation, is the product of (SI units of kg s^{-1})

Interstitial velocity	x	Projected area of target	x	Mass concentration of the dust	x	Efficiency of collection

$$\frac{U_g}{1-\alpha_f}.\frac{4\alpha_f A\mathrm{d}L}{\pi d_f}.C\rho_s.\eta_s$$

where η_s is the single target (fibre) collection efficiency - NOT the overall collection efficiency.
Now, from a mass balance:

rate of dust input into layer is $\quad Cu_g\rho_s A$

rate of dust output from layer is $\quad \left[Cu_g + u_g\frac{\partial C}{\partial L}\mathrm{d}L\right]\rho_s A$

hence accumulation is $\quad -u_g \mathrm{d}C\rho_s A$

taking a fixed instant in time so that the partial becomes a full differential and equate with above expression for accumulation to give

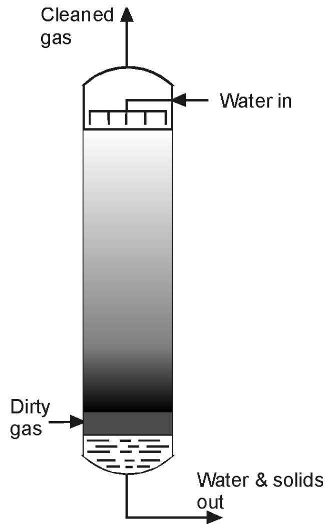


Fig. 14.8 A spray tower for dust removal

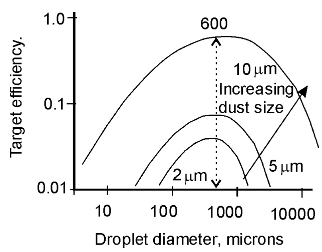


Fig. 14.9 Target efficiency within a spray tower

$$-\frac{dC}{C}=\frac{4\eta_s\alpha_f dL}{\pi d_f(1-\alpha_f)}$$

Integrate from $C=C_o$ at $L=0$ to $C=C$ at $L=L$ to give

$$\eta=1-\frac{C}{C_o}=1-\exp\left[-\frac{4\eta_s\alpha_f L}{\pi d_f(1-\alpha_f)}\right] \quad (14.12)$$

note single target efficiency varies according to Figure 14.4 and usually has a minimum at approx 0.4 μm.

Similarly, for a spray tower (Figure 14.8), a mass balance on dust entering and leaving a layer of depth dz in a spray tower gives

$$-u_g A\frac{\partial N}{\partial z}dz=\text{accumulation}$$

where u_g is the superficial gas velocity, A is the cross-sectional area and N is the dust concentration (kg m^{-3}). Using

mass flow rate per unit area x target area x efficiency of capture (or target efficiency)

The mass flow rate per unit area is: $Nu_g/(1-\alpha_s)$, the projected area of the spray drops is: $A\alpha_s dz3/2x$ and the target efficiency is: η_s, where α_s is the volume fraction of the liquid in the tower and x is the liquid droplet size.

Combining the equations for accumulation and integrating under appropriate boundary conditions provides the following expression for the overall efficiency (η), based on the tower height (H)

$$\eta=1-\exp\left[-\frac{3\alpha_s\eta_s H}{2(1-\alpha_s)x}\right] \quad (14.13)$$

Equation (14.13) shows that the collection efficiency for the tower depends on the liquid droplet diameter and the target efficiency. The latter is dependent on the dust particle diameter, but it is generally found that the optimum liquid drop diameter is approximately the same for all dust diameters and is about 600 μm. This is illustrated in Figure 14.9. Rain has a diameter close to this value; thus rainwater is efficient in removing particles suspended in air.

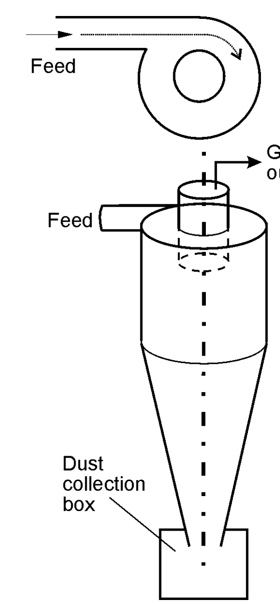


Fig. 14.10 A gas cyclone

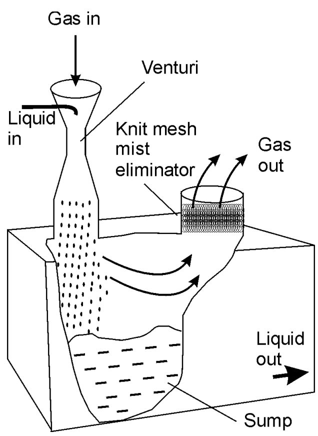


Fig. 14.11 Venturi scrubber

14.4 Equipment types

The principles of operation of many of these devices were discussed in the last section. In essence, the dust particles must be made to travel to a surface in the device and to stick at that surface. The equipment types are described very briefly in the following.

Settlement chambers often contains multiple plates, may be called louvre collector. Coarse particles may be collected even in turbulent flow. *Centrifugal collectors* such as a gas cyclone (Figure 14.10): inertial separation between the particles and the carrier gas causes particles (of greater inertia) to be thrown out of the gas stream and collected on a surface, wall, etc. *Scrubbers* capture particles on liquid droplets (spray tower) or liquid surfaces (packed or tray tower). A *venturi scrubber* achieves capture in the throat of a specially designed venturi (Figure 14.11). The particle collection mechanism is primarily inertial interception. *Fibrous and bag filters* capture particles on a fibre. The filter has a very high porosity (>90%), hence a low pressure drop. A significant depth may be required (often 5 cm). Bag filters have many (thinner) bags in parallel. Principle collection mechanisms are inertia and diffusion. *Gravel bed filters* capture particles on larger ones, which then need to be taken off line and cleaned - similar to a deep bed filter. Principle collection mechanisms are inertia and diffusion. *Electrostatic precipitators* use electrostatic forces to induce particle motion onto a collection surface, see Figure 14.12.

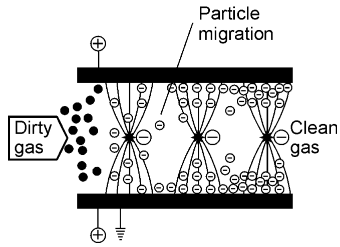


Fig. 14.12 Principle of an electrostatic precipitator – the external plate is usually at Earth's potential to avoid electric shocks

Table 14.1 Industrial Gas Cleaning Devices and Mechanisms

Equipment	Collection efficiency (%) at following sizes:				
	50 μm	5 μm	1 μm	High temperature	Relative cost*
Inertial collector	95	16	3	yes	1
Medium efficiency cyclone	94	27	8	yes	3
Low resistance cellular cyclone	98	42	13	yes	2
High-efficiency cyclone	96	73	27	yes	4
Impingement scrubber	98	83	38	no	7
Self-induced spray deduster	100	93	40	no	5
Void spray tower	99	94	55	no	11
Fluidised bed scrubber	>99	99	60	no	8
Irrigated target scrubber	100	97	80	no	6
Electrostatic precipitator	>99	99	86	yes	9
Irrigated electrostatic precipitator	>99	98	92	no	13
Flooded-disc scrubber - low energy	100	99	96	no	10
Flooded-disc scrubber - medium energy	100	>99	97	no	15
Venturi scrubber - medium energy	100	>99	97	no	14
High efficiency electrostatic precipitator	100	>99	98	yes	16
Venturi scrubber - high energy	100	>99	98	no	18
Shaker type fabric filter	>99	>99	99	no	12
Reverse jet fabric filter	100	>99	99	no	17
Ceramic filter elements	100	>99	>99	yes	18

*relative cost per 1000 m^3 of gas treated - the lower value the better

Figure 14.12 illustrates an electrostatic precipitator, where the voltage difference between two electrodes is several thousand but, as the air is non-conducting, the current flow is minimal. Hence, they are energy efficient devices to induce particle motion towards the collection plate, which also acts as an electrode. Dust enters the precipitator and is subject to a high potential gradient and picks up an electric charge. It then moves towards the collecting electrode and deposits. Periodic removal of the dust is important in order to prevent the charge on the dust reversing; leading to re-entrainment of it in the gas flow. Their use is restricted to dust that has the right electrical conduction properties: not too low or a charge will not be induced and not too high as charge reversal will take place too easily. They have very large throughputs and low pressure drops and are very common on power stations. Table 14.1 compares some of the operating conditions for several devices.

There is considerable interest in the treatment of hot gases, without having to use techniques that require the temperature to be reduced. Treatment with a water based system would require temperature reduction to significantly below 100°C before contact, to avoid excessive flashing of the water at atmospheric pressure. If a hot temperature can be maintained the gas plume will rise further from a chimney, which will help dilute and disperse any discharges made from the chimney. This is preferable to having any discharge leave the chimney and immediately sink back to the ground. The same net amount of pollution will be provided in either scenario, but dilution and dispersion is preferable to a high local concentration. Hence, techniques such as electrostatic precipitators, which do not require a reduction in the gas temperature and can process very large gas flows, have become commonplace at fossil fuelled power stations.

Another consideration is in the need to avoid secondary pollution. Thus, spray towers may be adequate for low temperature dust removal, but it may be argued that they solve a gas/solid pollution problem and create a liquid/solid pollution problem instead. Hence, additional equipment is required for solid/liquid separation if spray towers are used.

14.5 Summary

There are many different types of gas cleaning devices available for both high throughput industrial use as well as small scale high purity applications. The latter usually rely on high efficiency particulate air (HEPA) filters that may be several centimetres thick, but posses a very high porosity between the fibres. Deposition takes place within the fibre matrix. For high throughput industrial use, such as mineral processing and fossil fuel power generation, gas cyclones may be used as a pre-treatment technique because they are maintenance free and have a low pressure drop followed by electrostatic precipitators or special design filters. Ceramic candle filters are becoming popular in high temperature applications, such as foundries, as they can withstand corrosive gases, abrasive particles and high temperatures. It is also worthy of note that the human body provides efficient particle removal surfaces in both the nose and upper respiratory tract: nasal hair helps capture particles by inertial impact and

diffusion and further inertial collection takes place in the throat and whenever the air flow changes direction before entering the lungs.

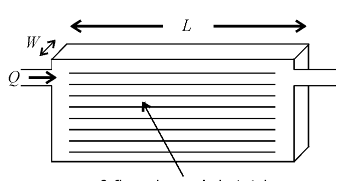
14.6 Problems

Separation span
For the *separation size* and *sharpness* of separation see Figure 14.12 the *separation span* is: $\dfrac{x_{25\%} - x_{75\%}}{x_{50\%}}$

1. 1100 kg of powder was fed at a uniform rate to a classifier and 583 kg was recovered in the fine product. The cumulative undersize particle size distributions were determined by sieving, as given in two columns of the following table. Complete the grade efficiency table, sketch the grade efficiency curve and find the separation size.

Particle diameter (μm)	Weight % undersize Feed (%)	Fines (%)	Mass in grade (kg)	Mass in grade (kg)	Grade Efficiency (%)
850	98.2				
600	95.5	100			
420	91.8	99.7	40.7	1.749	4.3
300	85.9	98.2	64.9	8.745	13
210	75	92.6	119.9	32.648	27
150	47.7	71			
100	24.5	42.5	255.2	166.155	65
75	8.2	15.1	179.3	159.742	89
53	1.8	3.4	70.4	68.211	97

The settling chamber below is to be used to collect particles 50 μm diameter and 2000 kg m^{-3} density from a stream of 10 m^3 s^{-1} of standard air*. The chamber is 1.5 m high and wide. Use Stokes' settling equation and*: μ of 1.8x10^{-5} Pa s, and ρ of 1.2 kg m^{-3}.



2. See the box and diagram for details on this question.

i) The particle settling velocity (m s^{-1}):
a: 0.00303 b: 0.151 c: 1.51x10^{-6} d: 0.00272

ii) The residence time horizontally is, where n is the number of channels, (s):
a: $1.5WL/Q$ b: $1.5WL/nQ$ c: $1.5WLn/Q$ d: $1.5WLn/nQ$

iii) The residence time vertically is (assuming settlement over the full height of a channel) (s):
a: 110000 b: 61.2 c: 1.10 d: 55.1

iv) Using a critical trajectory model, the length of the chamber for 100% collection efficiency at 50 μm is (m):
a: 20 b: 10 c: 5 d: 2

v) The characteristic linear dimension to use in a flow Reynolds number calculation is the hydraulic mean diameter which is 4x the area open to flow divided by the wetted perimeter. The hydraulic mean diameter of the above settling chamber system is (m):
a: 0.3 b: 1.5 c: 0.60 d: 0.33

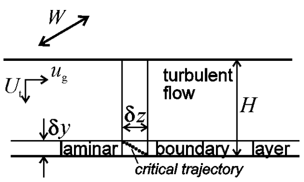
vi) The flow Reynolds number is:
a: 440000 b: 180000 c: 99000 d: 89000

vii) The number of trays required to bring the flow into the laminar regime is:
a: 644000 b: 385 c: 175 d: 36

viii) Assuming 100% collection of 50 μm particles, what will be the collection efficiency (%) for 25 μm particles?

a: 100 b: 50 c: 25 d: 0

3. Please refer to Question 2. The flow through the 9 channel settling chamber is turbulent but we can assume that the particles are deposited at their terminal velocity within the laminar boundary layer. This is illustrated by the accompanying figure.



The figure represents the flow on one of the tray surfaces. The critical particle trajectory approach (residence times horizontally and vertically are equal) may still be employed, but the analysis has to be restricted to the laminar boundary layer. The following symbols are used on the figure: u_g is the horizontal gas and particle velocity, U_t is the terminal particle velocity in the boundary layer and H is the channel height.

i) Using the critical particle trajectory approach the boundary layer height (δy) is:

a: δz b: $\frac{U_t}{u_g}\delta z$ c: $\frac{u_g}{U_t}$ d: $\frac{u_g}{U_t}\delta z$

ii) The most appropriate equation for the fractional volume inside the laminar layer compared to the total volume of the flow channel is - where W is the channel width is:

a: $\frac{\delta y \delta z W}{H \delta z W}$ b: $\frac{\delta y}{H}$ c: $\frac{u_g}{U_t}\frac{\delta z}{H}$ d: $\frac{U_t}{u_g}\frac{\delta z}{H}$

Note that the answers to parts (i) and (ii) could be written as differentials due to the linear relation between δy and δz inherent in the critical particle trajectory model. You will need to integrate the differentials in the following part.

iii) Using N for the number of particles, the fractional number of particles removed in δx is -dN/N, equate this with the fractional volume given in part (ii), and write down the equation for the number of particles left in suspension at a distance L in the channel.

Ans: $N=N_o$...

iv) The fractional number of particles still in suspension at distance L is N/N_o, hence the fractional particle REMOVAL or efficiency (η) is:

Ans: $\eta = 1 - ...$

where N_o is the initial number of particles at L=0.

v) The gas velocity along the settling chamber (i.e. axially) is (m s^{-1}):

a: 3.33 b: 4.44 c: 6.67 d: 17.8

vi) The length of settling chamber required to remove 99% of the 50 μm particles is (m):

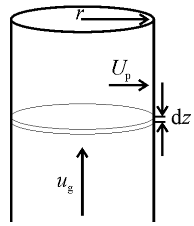
a: 23 b: 90 c: 34 d: 17

vii) The settling chamber length required to remove 100% of the 50 μm particles is (m):

a: 46 b: 64 c: ∞ d: 100

viii) The removal efficiency for 25 μm particles using the length from (vi) is (%):

a: 25 b: 58 c: 68 d: 78



Considering a chimney of cylindrical symmetry the radial (U_p) and axial (u_g) velocities are

$U_p = \dfrac{dr}{dt}$ and $u_g = \dfrac{dz}{dt}$

4. Please refer to Question 3, you will need to apply the same logic: the flow up a chimney is turbulent but we can assume that particles are deposited at some velocity within the laminar boundary layer.

i) Using the concept of the fraction of particles removed ($-dN/N$) is equal to the fraction of the volume occupied by the differential ring dr within the slice dz, over which the capture takes place, as you did in the previous tutorial, derive an equation in which $N/N_o = f(u_g, r, L, Q)$, where Q is the axial air flow rate and L is the chimney height.

$N=N_o$...

ii) The thermophoretic velocity of a particle in a temperature gradient may be assumed to be

$$U_p = \frac{-0.036}{T}\frac{dT}{dr}$$

where U_p is velocity in cm s^{-1}, z is distance in cm and T is temperature in degrees absolute. The temperature gradient at the wall of a chimney is 315^{o}C per cm, and the temperature of the bulk gas is 1000^{o}C (assume T=1273 K). The drift velocity towards the wall is (feet s^{-1}):

a: 0.00037 b: 0.00055 c: 0.00029 d: 0.00069

iii) The chimney is 3 feet in diameter and 50 feet tall, and gas is flowing at 500 cubic feet per minute (cfm). The inlet dust concentration is 1 milligram per cubic foot, the outlet concentration is (milligram per cf) - NB convert cfm to cubic feet per second first:

a: 0.984 b: 0.967 c: 0.970 d: 0.979

iv) The dust mass deposited on the chimney wall over 28 days is (g):

a: 0.66 b: 13.8 c: 330 d: 655

The deposit thickness ½ way up chimney - using above physical data:

v) The dust concentration ½ way up the chimney (milligram per cf):

a: 0.984 b: 0.992 c: 0.985 d: 0.990

vi) The equation for mass of solids deposited per unit time is:

a: $\rho_s 2\pi r dz \dfrac{dr}{dt}(1-\varepsilon)$ b: $\rho_s 2\pi r dz \dfrac{dr}{dt}$ c: $\rho_s (1-\varepsilon) dr^3 / dt$

where ε is the deposit porosity, dr is the deposit thickness and ρ_s is the solid density.

vii) The mass of particles removed from the gas stream AT THE SAME TIME is:

a: $\pi r^2 \rho_s \dfrac{dz}{dt}$ b: $2\pi r^2 dz \dfrac{dN}{dt}$ c: $\pi r^2 \dfrac{dN}{dt}$ d: $\pi r^2 dz \dfrac{dN}{dt}$

viii) A mass balance in layer dz within the chimney provides the following result

$$-u_g \frac{dN}{dz} = \frac{dN}{dt}$$

and the differential form of your answer to Part (vi) gives another equation for $-dN/dz$, combine these two equations and your answers to (ii) and (iii) to give an equation for the rate of increase in deposit thickness with time d*r*/d*t*=f[u_g, N (at z=0.5L), ρ_s, (1-ε)]:

$$\frac{dr}{dt} = ...$$

s.g. is specific gravity – or relative density: relative to water at 1000 kg m^{-3}

ix) The dust s.g. and deposit porosity are 2.6 and 0.5, the deposit thickness after 28 days is (μm):

a: 2.9 b: 5.8 c: 11 d: 5760

5. *Spray tower*

Combining the equations for accumulation and integrating under appropriate boundary conditions provides the following expression for the overall efficiency (η)

$$\eta = 1 - \exp\left[-\frac{3\alpha_s \eta_s H}{2(1-\alpha_s)x}\right]$$

i) A spray tower reduces the concentration of a dust emission from 0.009 to 0.00135 g m^{-3}, the overall collection efficiency is (%):

a: 85.0 b: 82.4 c: 15.0 d: 17.6

ii) The spray tower uses 1.5 m^3 of water per hour and the residence time of a drop in the tower is 30 seconds, the volume of water in the tower at any instance is (m^3):

a: 0.75 b: 1.5 c: 0.0125 d: 0.0083

iii) The tower is 15 m high and 5 m in diameter, the volumetric concentration of the liquid drops is (-):

a: 0.0051 b: 0.0025 c: 4.2x10^{-5} d: 2.8x10^{-5}

iv) The liquid drops are 150 μm in diameter; target efficiency is (%):

a: 1.0 b: 1.1x10^{-4} c: 30 d: 85

iv) How could the overall efficiency of the tower be improved?

ANS (include a sketch of efficiency against drop diameter if necessary):

6.

Geometrically similar cyclones can be compared or scaled using the *stokes number*:

$$\text{Stk} = \left(\frac{x^2 u_g \rho_s}{9\mu D}\right)$$

i.e. collection efficiency is a unique function of Stokes number. If the Stokes number is maintained constant then the collection efficiency will also be a constant.

Air Classified (AC) fine test dust was used in a model 8 inch diameter gas cyclone and the following collection efficiencies were obtained when operating with an inlet velocity of 18 m s^{-1}

Particle diameter (μm):	1	3	5	7	9	11	22
Collection efficiency (%):	20	45	60	72	79	84	100

The specific gravity of the dust was 2.6 and the viscosity of the gas was 1.8x10^{-5} Pa s.

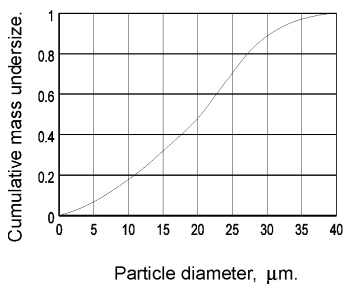
An industrial cyclone of similar geometry to the model but 5 ft in diameter is to be used to remove dust of specific gravity 1.8, contained in a gas stream at 120°C - viscosity 2.2x10^{-5} Pa s, with an inlet velocity of 66 feet per second. The size distribution of the industrial dust is provided in the figure on the next page.

i) Calling the model cyclone test Stk$_A$ and the industrial application Stk$_B$ fill in the missing terms in the following (using subscript A and B where appropriate):

$$\frac{\mathrm{Stk}_A}{\mathrm{Stk}_B} = unity = \left(\frac{\quad}{}\right) / \left(\frac{\quad}{}\right)$$

ii) Now rearrange the above equation to provide the appropriate TRANSFORM in order to change the particle size in system A into that in system B which provides the same efficiency, i.e.

$$x_B = \left(\frac{\quad}{}\right)^{(\ )} x_A$$



iii) The transform value, i.e. the constant of proportionality between x_B and x_A, used to convert particle diameter is:

a: 0.46 b: 1.90 c: 2.82 d: 3.45

iv) The inlet concentration of the dust is 200 g m^{-3}, estimate the dust concentration in the emission by completing the following table

x_A	Efficiency η	$\bar{x}_B$	size range	$N_3(x_B)$	$n_3(x_B)$	Mass in grade (g m^{-3})	Mass not collected (g m^{-3})
1	20	3.45	0 to 6.9				
3	45		to				
5	60		to				
7	72		to				
9	79		to				
11	84		to				
					Totals:		

v) The overall collection efficiency is (%):

a: 60 b: 70 c: 80 d: 90

vi) If the pressure drop in the model cyclone was 4.5 inches of water gauge (WG) the pressure drop in the industrial cyclone will be (WG)

a: 3.6 b: 4.0 c: 5.0 d: 5.6

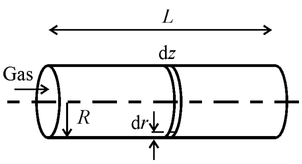
vii) Increasing the temperature of the inlet stream will alter the gas viscosity. If the gas is air the viscosity will:

a. INCREASE b. DECREASE

viii) By considering the terms in the Stokes number, write below some ways that may be used to improve the collection efficiency of the cyclone:

1)
2)
3)
4)

> Most of the pressure drop in a cyclone is due to setting up the centrifugal head, i.e. $\Delta P \propto \rho u_g^{\,2}$
> The proportionality constant is the *number of velocity heads.* The relation is valid for geometrically similar cyclones, i.e. independent of cyclone diameter.



Modelling is again based on the assumption that the flow is turbulent with particles deposited at some velocity within the laminar boundary layer. Considering a tube the axial (u_g) and radial (w) velocities are

$$u_g = \frac{dL}{dt} \qquad w = \frac{dr}{dt}$$

7. See the diagram of a tube within an electrostatic precipitator.

i) Using the critical particle trajectory model (residence times in the differential layer are equal) the distance dr is:

dr =

ii) Now using the concept of the fraction of particles removed ($-dN/N$) is equal to the fraction of the volume occupied within dL by the differential layer dr, i.e. the part over which capture takes place (as you have done in previous questions) derive an equation in which $N/N_o = f(u_g, R, L, w)$, where L is the tube length:

$N = N_o$...

iii) An electrostatic precipitator consisting of 100 tubes each of length 5 m and internal diameter 10 cm is operating on a power station flue gas. The total gas flow rate is 300 m^3 min^{-1}. The axial velocity in the precipitator is (m s^{-1}):

a: 1.6 b: 0.11 c: 3.2 d: 6.4

iv) Tests show that the collection efficiency for 5 μm particles is 99.10%, the radial, or drift (w), velocity of particles of this diameter is (m s^{-1}):

a: 0.0003 b: 0.15 c: 0.3 d: 0.6

v) The force due to an electrostatic field is:

$$pE_C E_P x^2 / 4$$

where p is a constant dependent on the dielectric properties of the system, x is the particle diameter, E_C and E_P are the charging and precipitating electric field strengths. Ignoring all forces other than electrostatic and fluid drag, the drift velocity is:

a: $\dfrac{pE_C E_P x^2}{12\mu\pi}$ b: $\dfrac{pE_C E_P x}{12\mu\pi}$ c: $\dfrac{12\mu\pi}{pE_C E_P x}$ d: $\dfrac{12\mu\pi}{pE_C E_P x^2}$

hint Q7.(v)
Use the fluid *drag* expression given by Stokes

vi) The collection efficiency of particles 2 μm in diameter is (%):

a: 99.1 b: 84.8 c: 77.2 d: 92.5

8. Assuming the axial flow through the above precipitator is laminar, rather than turbulent, how long would the precipitator need to be to achieve the same collection efficiency for 2 μm particles? Use the physical and flow data given above, and answer in metres:

a: 0.6 b: 1.3 c: 3.3 d: 5.2

This question is solved by a similar technique used for centrifuges - take r_1=0