Gas-Solid Separation

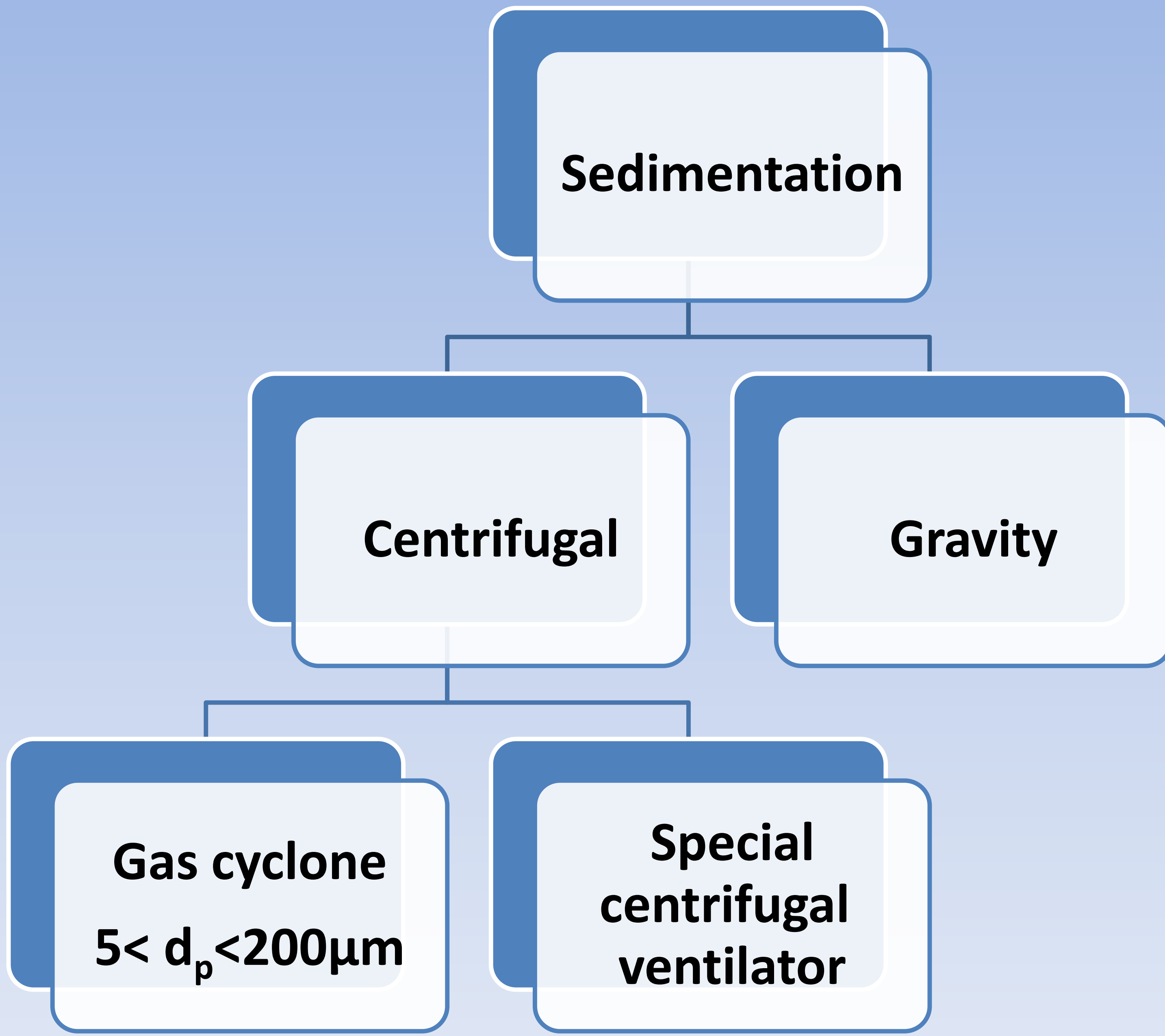
Gas cyclones

Separation of solid from gas

Degassing

dust separation

- Sedimentation
- Collision
- Filtration
- Electrical
- Combined methods



Sedimentation
Centrifugal
Gravity
Gas cyclone
5< d_p<200µm
Special centrifugal ventilator

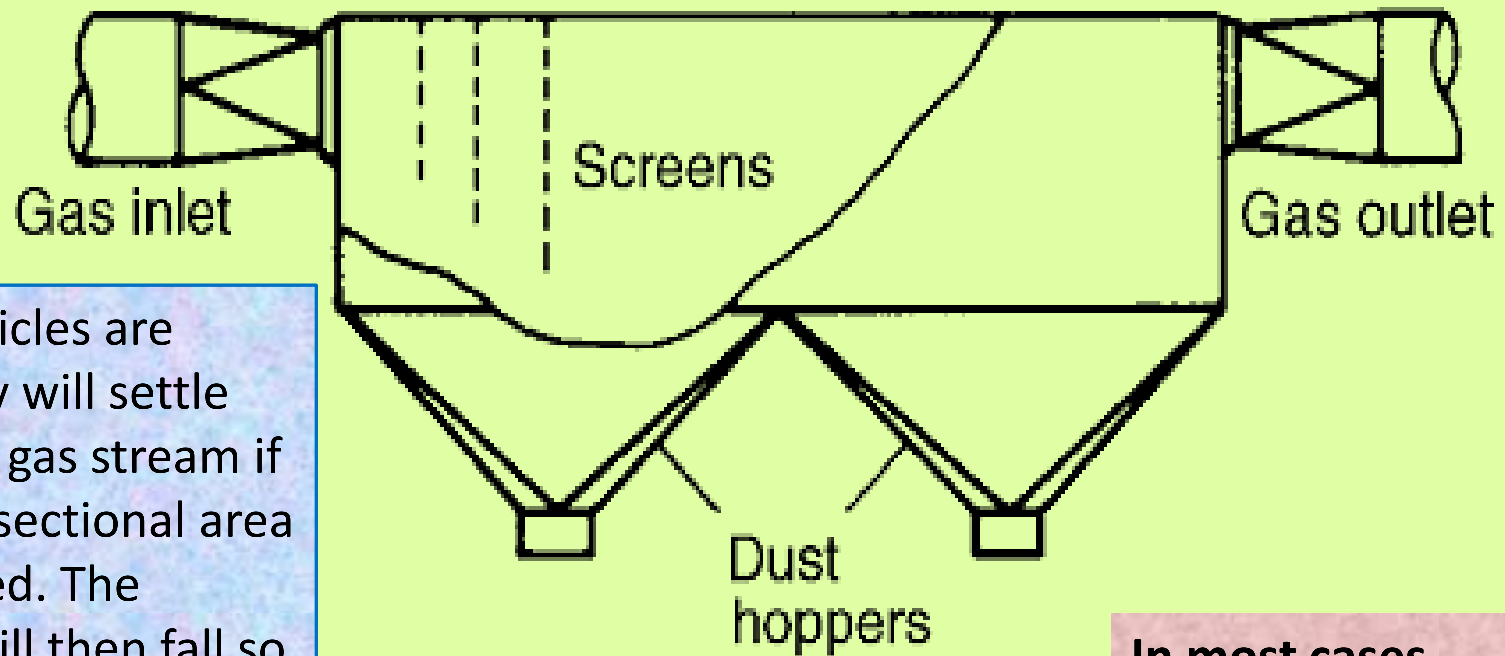
Note

- **It is recommended to separate the coarsest particles firstly with a simple device**

Settling by gravity
(Gravity separators)

- **Applicable for 100µm or more~ called dust separator**
- **Performance can be improved by inserting horizontal partitions.**
- **Disadvantage: separators required very large volume to decrease the gas velocity to low value to allow fine particles to settle.**

Settling chamber

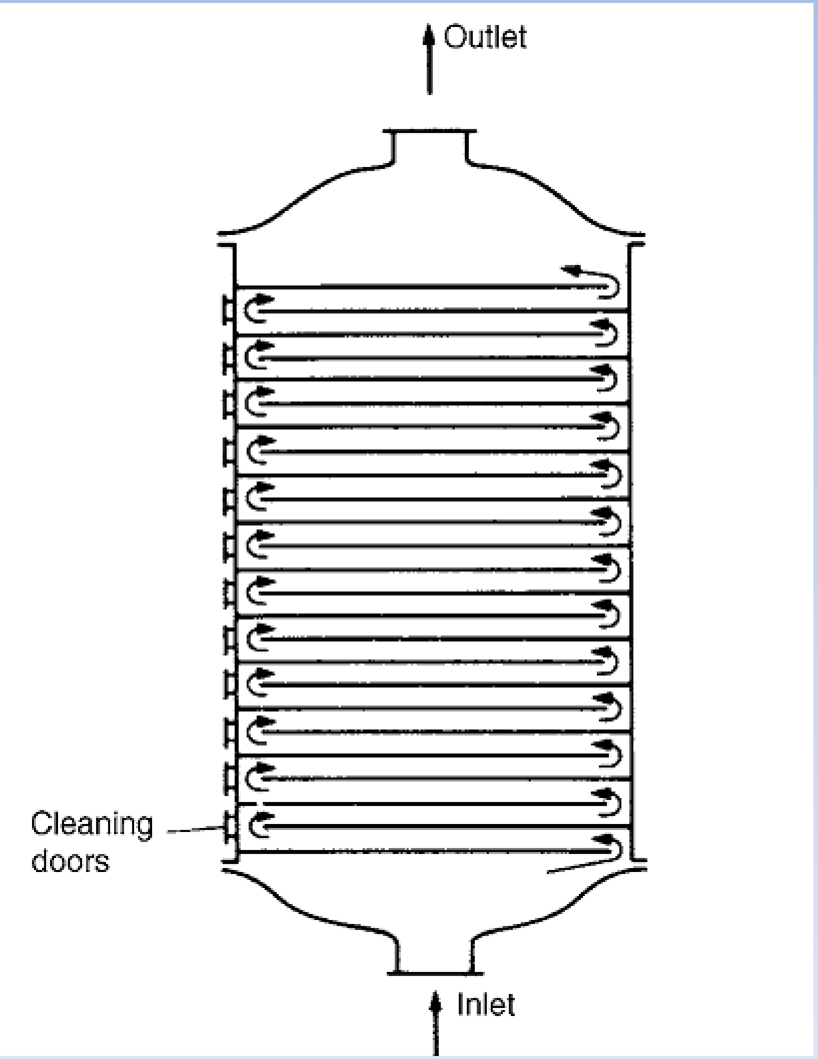


If the particles are large, they will settle out of the gas stream if the cross-sectional area is increased. The velocity will then fall so that the eddy currents which are maintaining the particles in suspension are suppressed.

In most cases baffles or screens are introduced to enhance particles separation.

Tray separator

❖Dust removal from sulphur dioxide produced by the combustion of pyrites.
❖Gas stream is forced through a series of trays in which the solid particles will settle over the trays.



CENTRIFUGE SEPARATION

How to create centrifuge separation

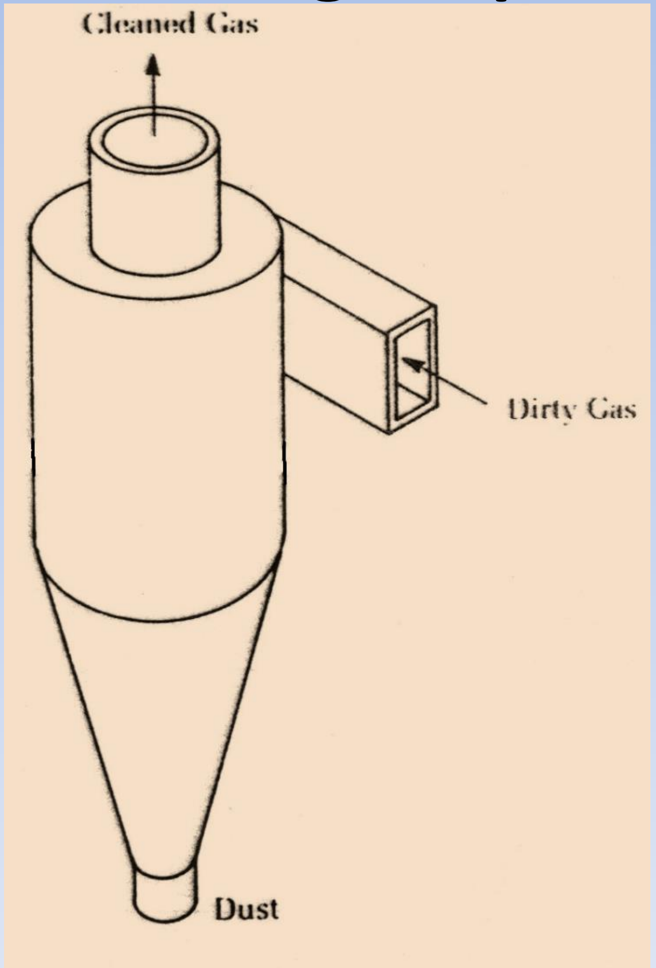
1. **Entering the gas tangentially with high velocity into a cylindrical space or**
2. **Bringing the gas into rotation via using a revolving impeller.**

NB the first way leads to the use of cyclones whilst the second to centrifugal ventilators of special construction.

Gas cyclones

The body of cyclone takes the following shape

- Completely cylindrical
- Entirely conical
- Cylindrical + conical



Note

The main principle of solid separation depends on the transformation of the linear gas velocity into vortex where the solid particles are thrown to the periphery of the cyclone while the gas ejected from the central region.

There are three openings:

1. An axial gas outlet.
2. A particulate discharge port.
3. A gas-solid inlet (usually rectangular in shape).

Sizing gas cyclones

Based on the theory given in chapter 3, there are two opposed forces:

1. **Centrifugal force ~ causes the particles to move in the direction of the cyclone wall; the gas flowing towards the core of the cyclone (*the gas tends to carry fine particles to the center and remove them through the overflow*).**

2. **Inward radial drag force ~ depends on the quantity of air fed to the volume of the cyclone. This ratio also determines the residence time in the cyclone.**

The equation of sedimentation in a centrifugal field developed in ch. 3 will be used. This eq. is:

$$\frac{dr}{dt} = \frac{d^2\omega^2(\rho_s - \rho)r}{18\mu} \qquad (1)$$

Where r is the instantaneous distance of the particle from the vertical axis of the cyclone. Multiplying both sides by r and ignore ρ; the density of gas because it is very small compared with the solid density ρ_s .

Hence eq. 1 becomes

$$r\frac{dr}{dt} = \frac{d^2(\omega r)^2 \rho_s}{18\mu} \qquad (2)$$

Now replacing ωr *term by its equivalent* U_t, *which is the tangential velocity of particle.*

$$r\frac{dr}{dt} = \frac{d^2 U_t^{\ 2} \rho_s}{18\mu} \qquad (3)$$

Assume U_t is constant.

$$\int_{r_i}^{r_o} r\,dr = \frac{d^2 U_t^{\ 2} \rho_s}{18\mu} \int_0^t dt \qquad (4)$$

$$\frac{r_o^{\ 2} - r_i^{\ 2}}{2} = \frac{d^2 U_t^{\ 2} \rho_s t}{18\mu} \qquad (5)$$

where r_i : inner radius of rotating stream

r_o: radius of cylinder

Assume n is the number of turns required for a particle to travel the distance across the gas stream and so separate from it. The required time for these turns can be determined from angular velocity, ω, via this relation

$$t = \frac{2\pi n}{\omega} \qquad (6)$$

Eq. (6) can be written in the following form

$$t = \frac{2\pi n r_o}{(r_o \omega)} \qquad (7)$$

The denominator of this eq. represents the tangential velocity at its highest value when the particle reaches the wall of cyclone.

$$\therefore \qquad t = \frac{2\pi n r_o}{U_t} \qquad (8)$$

Substituting t into eq. (5)

$$r_o^{\,2} - r_i^{\,2} = \frac{2\pi d^2 U_t\, r_o\, n\, \rho_s}{9\mu} \qquad (9)$$

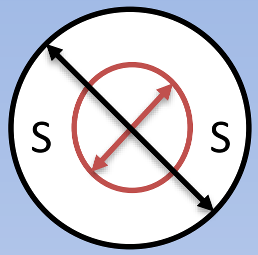
- **If the tangential velocity of the particle has a value similar to the average velocity of the gas stream, u, just before it enters the cyclone, then eq. 9 becomes**

$$r_o^{\,2} - r_i^{\,2} = \frac{2\pi d^2 u\, r_o\, n\, \rho_s}{9\mu} \qquad (10)$$

- **Let S is the width of the gas rotation; $S = r_o - r_i$ then**

$$r_0^{\,2} - r_i^{\,2} = (r_0 - r_i)(r_0 + r_i) = S(r_0 + r_i) \qquad (11)$$

- *Or in terms diameter*



$$r_o^{\,2} - r_i^{\,2} = S\,\frac{(D_o + D_i)}{2}$$

but

$$D_o + D_i = 2(D_o - S)$$

∴ Do – 2S =Di
Do + Di = Do +Do – 2S
=2Do – 2S = 2(Do-S)

$$\therefore \quad r_o^{\,2} - r_i^{\,2} = S\,(D_o - S) \qquad (12)$$

*Substituting for this eq, in eq.*10 *and taking* $r_o = D_o / 2$

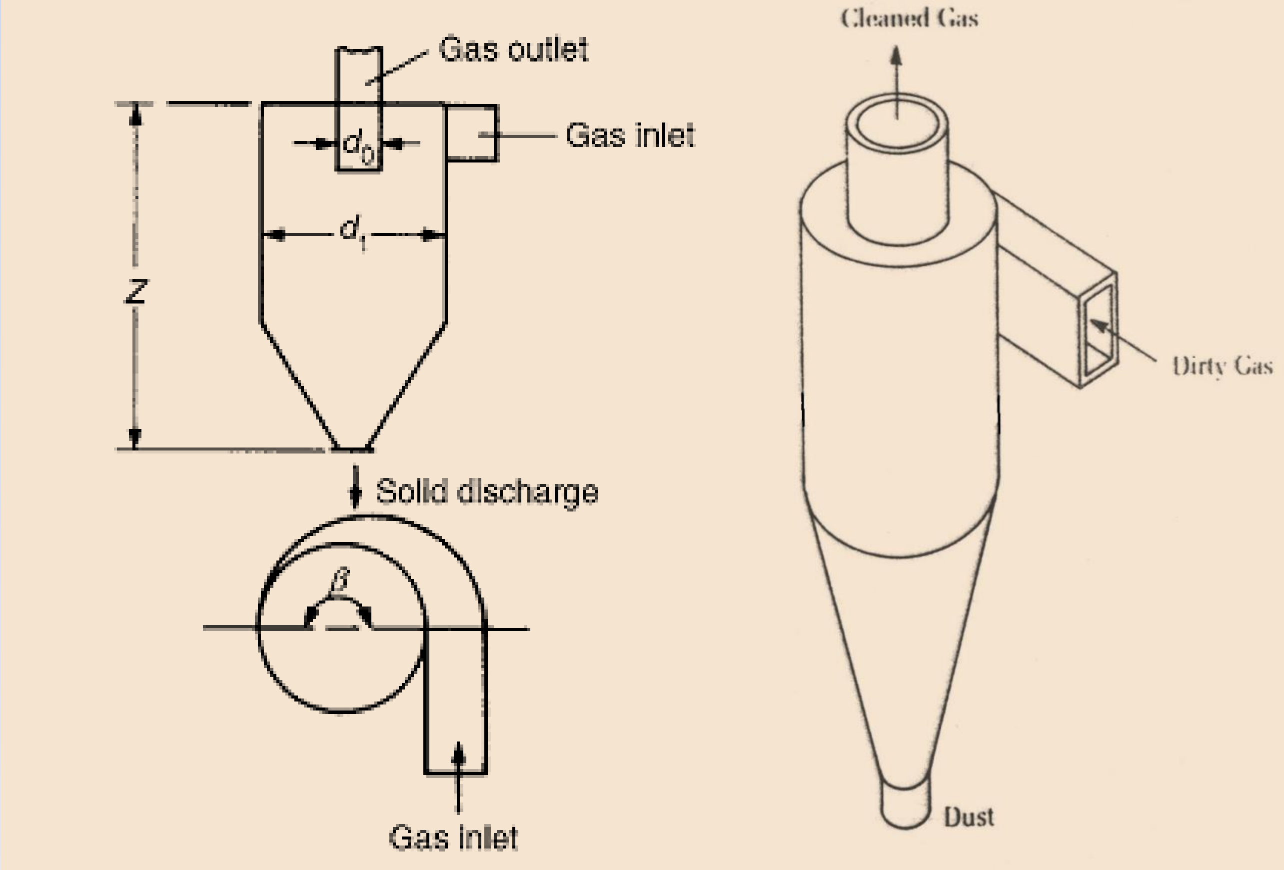
$$\therefore \quad S\,(D_o - S) = \frac{\pi\, d^2 u\, D_o\, n\, \rho_s}{9\,\mu} \qquad (13)$$

Note

Experimental studies have shown that the number of turns, n, which the gas stream makes before it leaves the cyclone range between 0.5 and 5.

Terminal velocity of a particle, fluid properties and the geometry of cyclone separator

Consider the two principal forces acting in a cyclone, namely the centrifugal force acting outwards and the frictional drag force of the gas acting inwards.



- The centrifugal force for a spherical particle rotating at radius r is:

$$\frac{m u_t^2}{r} = \frac{1}{6} \pi d^3 \rho_s \frac{u_t^2}{r} \qquad (14)$$

The inward radial force due to friction is

$$3\pi \mu \mathrm{d} \mathrm{u}_{\mathrm{r}}$$

where u_{r} is the radial component of the velocity of the gas.

At equilibrium

$$\frac{\pi d^3 \rho_s u_t^2}{6 r} = 3\pi \mu d u_r \qquad (15)$$

Or

$$\frac{u_t^2}{r} = \frac{18 \mu u_r}{d^2 \rho_s} \qquad (16)$$

- **But the free falling velocity or terminal velocity, u_o, is ($\rho_s >> \rho$):**

$$u_o = \frac{d^2 g \rho_s}{18\mu} \qquad (17)$$

- Substituting for u_o in eq. (16)

$$\frac{u_t^2}{r} = \frac{u_r}{u_o} g$$

OR

$$u_o = \frac{u_r}{u_t^2} r g \qquad (18)$$

- **As u_o becomes higher, the radius of rotation becomes also greater.**
- **If it is assumed that a particle will be separated provided it tends to rotate outside the central core of diameter $0.4d_o$, the terminal falling velocity of the smallest particle which will be retained is found by substituting $r = 0.2d_o$ in equation (see figure; d_o diameter of gas core outlet)**

$$r = 0.2\, d_o \qquad (19)$$

- **Substituting in previous equation**

$$u_o = \frac{u_r}{{u_t}^2} 0.2 d_o \, g \qquad (20)$$

- **It is found that $u_r \approx$ constant at a given radius. However, it can be found from volumetric flow rate of gas per cylindrical surface area of flow at radius r:**

$$u_r = \frac{G}{2\pi \, r \, z \, \rho} \qquad (21)$$

- **u_t can be found from the following experimental relation:**

$$u_t = u_{to} \sqrt{\frac{d_t}{2r}} \qquad (22)$$

- where

  u_{to}: tangential velocity at circumference

  u_t : tangential velocity at radius r

  d_t: diameter of cyclone

- Moreover, it is found that u_{to}= the velocity of the gas which enters the cyclone.
- Now equation 20 becomes

$$u_o = \frac{0.2\, G\, d_o\, g}{\pi\, \rho\, z\, d_t\, u_{to}^{\;2}} \qquad (23)$$

- If A_i is the cross-sectional area of the gas inlet
$G = A_i \rho u_{to} \Rightarrow u_{to} = G / A_i \rho$, by substitution

$$u_o = \frac{0.2 A_i^2 d_o \rho g}{\pi z d_t G} \qquad (24)$$

- See text for The effect of the arrangement and size of the gas inlet and outlet.
- If there is a large proportion of fine material present, a bag filter may be attached to the clean gas outlet.
- Alternatively, the smaller particles may be removed by means of a spray of water which is injected into the separator.
- For more details see the text.

Example

A cyclone separator, 0.3 m in diameter and 1.2 m long, has a circular inlet 75 mm in diameter and an outlet of the same size. If the gas enters at a velocity of 1.5 m/s, at what particle size will the theoretical cut occur?

The viscosity of air is 0.018 mN s/m^2, the density of air is 1.3 kg/m^3 and the density of the particles is 2700 kg/m^3.

Solution

Using the data provided:

cross-sectional area at the gas inlet, $A_i = (\pi/4)(0.075)^2 = 4.42 \times 10^{-3}\ \text{m}^2$

gas outlet diameter, $d_0 = 0.075$ m

gas density, $\rho = 1.30\ \text{kg/m}^3$

height of separator, $Z = 1.2$ m, separator diameter, $d_t = 0.3$ m.

Thus: mass flow of gas, $G = (1.5 \times 4.42 \times 10^{-3} \times 1.30) = 8.62 \times 10^{-3}$ kg/s

The terminal velocity of the smallest particle retained by the separator,

$$u_0 = 0.2 A_i^2 d_0 \rho g / (\pi Z d_t G)$$

Eq. 24

$$u_0 = [0.2 \times (4.42 \times 10^{-3})^2 \times 0.075 \times 1.3 \times 9.81]/[\pi \times 1.2 \times 0.3 \times 8.62 \times 10^{-3}]$$

$$= 3.83 \times 10^{-4}\ \text{m/s}$$

- Use is now made of Stokes' law to find the particle diameter, as follows:

$$u_0 = d^2 g(\rho_s - \rho)/18\mu$$

$$d = [u_0 \times 18\mu/g(\rho_s - \rho)]^{0.5}$$

$$= [(3.83 \times 10^{-4} \times 18 \times 0.018 \times 10^{-3})/(9.81(2700 - 1.30))]^{0.5}$$

$$= 2.17 \times 10^{-6} \text{ m or } \underline{\underline{2.17\ \mu\text{m}}}$$