

Design and analysis of cyclone dust separator

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ABSTRACT: Cyclones have often been regarded as low-efficiency collectors. However, efficiency varies greatly with particle size and cyclone design. Advanced design work has greatly improved cyclone performance. This paper have discussed the design parameters required to construct a high performing cyclone through the application of the classical cyclone design, However, the pressure drop in this design does not consider any vertical dimensions as contributing to pressure drop, This is a misleading in that a tall cyclone would have the same pressure drop as a short one as long as cyclone inlets and outlets dimensions and inlet velocities are the same.

Texas cyclone design model was used to obtain an accurate pressure drop and sizing of cyclone, The Texas cyclone approach to design cyclones was to initially determine optimum inlet velocities (design velocities) for different cyclone designs, hence using the inlets velocity a cyclone dimension can be determined.

Keywords: Cyclone, Inlet velocity, pressure drop, sizing

I. INTRODUCTION

Cyclone separator is a method of removing particulate from an air, gas or liquid stream without the use of filters, through vortex separation. Rotational effects and gravity are used to separate mixtures of solids and fluids. The method can also be used to separate fine droplets of liquid from a gaseous stream.

A high speed rotating (air) flow is established within cylindrical or conical containers called a cyclone. Air flows in a helical pattern, beginning at the top (wide end) of the cyclone and ending at the bottom (narrow) end before exiting the cyclone in a straight stream through the centre of this cyclone and out the top. Larger (denser) particles in rotating stream have too much inertia to follow the tight curve of fall to the bottom of the cyclone where they can fall to the bottom of the stream, and strike the outside wall, then fall to the bottom of the cyclone where they can be removed. In a conical system, as the cyclone, the rotational radius of the stream is reduced, thus separating smaller particles. The cyclone geometry, together with flow rate, defined the cut point of the cyclone. This is the size of particle that will be removed from the stream with 50% efficiency. Particles larger than the cut point will be removed with a greater efficiency and smaller particles with a lower efficiency.

An alternative cyclone design used a secondary air flow within the cyclone to keep the collected particles from striking the Walls, to protect them from abrasion. The primary air flow containing the particulars enters from the bottom of the cyclone and in forced into spiral rotation by stationary Spinner vanes. The secondary air flow enters from the top of the cyclone and move downward the bottom, intercepting the particulate from the primary air. The secondary air flow also allows the collector to optionally be mounted horizontally because it pushes the particulate towards the collection area, and does not rely solely on gravity to perform this function .

Large scale cyclones are used in sawmills to remove sawdust from extracted air. Cyclones are also used in oil refineries to separate oils and gases, and in the cement industry as component of kiln pre-heaters. Cyclones are also used in industry rial and professional kitchen ventilation for separating the grease from the exhaust air in extractions hoods. Cyclones are increasingly used in the house hold, as the core technology in bag-less. Despite its simple operation, the fluid dynamics and flow structures in a cyclone separator are very complex. This equipment is a setting chamber in the form of a vertical cylinder, so arranged that the particles laden air spirals round the cylinder to the outside wall. Cyclones are very popular because there are no moving parts that can wear out or break, with no moving part involved and mainly consisting of a drum with a funnels on the bottom and inlet including export.

In the agricultural processing industry, 2D2D (Shepherd and Lapple, 1939) and 1D3D (Parnell and Davis, 1979) cyclone designs are the most commonly used abatement devices for particulate matter control. The D's in the 2D2D

designations refer to the barrel diameter of the cyclone. The numbers preceding the D's relate to the length of the barrel and cone sections, respectively. A 2D2D cyclone has barrel and cone lengths of two times the barrel diameter, whereas the 1D3D cyclone has a barrel length equal to the barrel diameter and a cone length of three times the barrel diameter.



.Fig 1 cyclone separator.

1.1 The effect of particle size on cyclone separation

The principal behind the cyclone separator is to use centrifugal force to separate phases of different densities. The fluid in the cyclone is forced to rotate rapidly so that the centrifugal acceleration causes the denser particles to migrate towards the outside of the cyclone where they are collected. The condition for effective separation is, therefore, that this migration speed is sufficiently rapid to separate the particles within the residence time of the fluid in the cyclone.

$$\frac{\pi}{6}(\rho - \rho_{air})d^3rw^3$$

where ρ and ρ_{air} are the densities of the particles and air respectively, w is the angular velocity of the air in the cyclone and r is radial distance from the centre of the cyclone. As the particle density is much larger than that of the air, we may neglect ρ_{air} from this expression.

For small particles, the effect of fluid inertia on the lengthscale of the particle may be neglected, so that the drag force on the particle is $3\pi\mu\delta u' du$ where μ and u are the viscosity and particle velocity relative to the fluid respectively. Therefore, the radial drift velocity, u_d , of particles with respect to the fluid satisfies

$$\frac{\rho\pi d^3}{6} \dot{u}_d + 3\pi\mu \dot{u}_d = \frac{\rho\pi d^3}{6} r\dot{w}^2$$

where dot denotes differentiation with respect to time. Thus the maximum drift velocity U_d of a particle is given by

$$u_d = \frac{\rho d^2}{18\mu} R w^2$$

where R is the radius of the cyclone.

If the particles are to be removed from the airstream, their drift velocity must be sufficient for them to reach the outer part of the cyclone before the air exits the cyclone. If the airstream turns through an average angle of Q radians within the cyclone, the residence time in the cyclone will be α/w . The precise value of α depends upon the details of the flow within the cyclone, and important aspect of cyclone's design should be to make α as large as possible. In this time the particles must move radially by the width of the airstream. As this distance will scale with the size of the cyclone it is convenient to write this as βR . Again β will depend upon the design detail of the cyclone. The condition for particles to be removed is therefore

$$U \geq \frac{\beta}{\alpha} R\omega$$

and substituting from equation (2) we require that

$$\frac{\rho w d^2}{\mu} \geq 18 \frac{\beta}{\alpha}$$

From this condition we can estimate the minimum angular velocity required to separate particles of a given size. The particle density and air viscosity are approximately $2 \times 10^3 \text{ kg m}^{-3}$ and $2 \times 10^{-5} \text{ Pa s}$ respectively, and taking $18\beta/\alpha$ to be unity, we obtain the condition that

$$w \geq \frac{10^{-8}}{d^2} \text{ m}^2 \text{ s}^{-1}$$

Thus, for one micron diameter particles the angular velocity must exceed 104 radians per second (*i.e.* 10^5 r.p.m.), while 0.1 micron diameter particles require 10^6 radians

II. DESIGN ANALYSIS

The cyclone design procedure outlined in Cooper and Alley (1994), hereafter referred to as the classical cyclone design (CCD) process, was developed by Lapple in the early 1950s. The CCD process (the Lapple model) is perceived as a standard method and has been considered by some engineers to be acceptable. However, there are several problems associated with this design procedure. First of all, the CCD process does not consider the cyclone inlet velocity in developing cyclone dimensions. It was reported (Parnell, 1996) that there is an "ideal" inlet velocity for the different cyclone designs for optimum cyclone performance. Secondly, the CCD does not predict the correct number of turns for different type cyclones. The overall efficiency predicted by the CCD process is incorrect because of the inaccurate fractional efficiency curve generated by the CCD process (Kaspar et al. 1993).

In order to use the CCD process, it is assumed that the design engineer will have knowledge of (1) flow conditions, (2) particulate matter (PM) concentrations and particle size distribution (PSD) and (3) the type of cyclone to be designed (high efficiency, conventional, or high throughput). The PSD must be in the form of mass fraction versus aerodynamic equivalent diameter of the PM. The cyclone type will provide all principle dimensions as a function of the cyclone barrel diameter (D). With these given data, the CCD process is as follows:

1.1 The Number of Effective Turns (N_e)

The first step of CCD process is to calculate the number of effective turns. The number of effective turns in a cyclone is the number of revolutions the gas spins while passing through the cyclone outer vortex. A higher number of turns of the air stream result in a higher collection efficiency. The Lapple model for N_e calculation is as

follows:

$$N = \frac{1}{H} \left[L + \frac{Z}{2} \right] \text{ where}$$

N = number of turns inside the device (no units)

H = height of inlet duct (m or ft)

L = length of cyclone body (m or ft)

Z = length (vertical) of cyclone cone (m or ft).

1.2 Cut-Point (d_{50})

The second step of the CCD process is the calculation of the cut-point diameter. The cut-point of a cyclone is the aerodynamic equivalent diameter (AED) of the particle collected with 50% efficiency. As the cut-point diameter increases, the collection efficiency decreases. The Lapple cut-point model was developed based upon force balance theory. The Lapple model for cut-point (d_{50}) is as follows

$$d_p = \left[\frac{9\mu W}{\pi N V t (\rho_1 - \rho_2)} \right]^{\frac{1}{2}}$$

where

N = number of turns inside the device (no units)

W = width of inlet (m or ft).

Vt = terminal drift transverse velocity (m/s or ft/s)

d_p = diameter of the particle (m or ft)

ρ = density of the particle (kg/m^3)

ρ = air density (kg/m³)
 μ = air viscosity (kg/m.s)

1.3 Fractional Efficiency Curve (FEC - η)

The third step of CCD process is to determine the fractional efficiency. Based upon the cut-point, Lapple then developed an empirical model (equation 5) for the prediction of the collection efficiency for any particle size, which is also known as fractional efficiency curve:

$$\eta_j = \frac{1}{1 + (d_{pj}/d_{pc})^2}$$

where

j = collection efficiency of particles in the j th size range ($0 < n_j < 1$)

d_{pj} = characteristic diameter of the j th particle size range (in μm).

1.4 Overall Efficiency (η_o)

The overall efficiency, called performance, of the cyclone is a weighted average of the collection efficiencies for the various size ranges, namely

$$\eta = \sum \frac{\eta_j m_j}{M}$$

1.5 Pressure Drop (ΔP)

Cyclone pressure drop is another major parameter to be considered in the process of designing a cyclone system. Two steps are involved in the Lapple approach to estimation of cyclone pressure drop. The first step in this approach is to calculate the pressure drop in the number of inlet velocity heads (H_v) by first equation below. The second step in this approach is to convert the number of inlet velocity heads to a static pressure drop (ΔP) by the next equation.

$$H_v = K \frac{HW}{D_e^2}$$

Now becomes

$$\Delta p = \frac{1}{2} \rho g v^2 H_v$$

There is one problem associated with this approach. "The Lapple pressure drop equation does not consider any vertical dimensions as contributing to pressure drop" (Leith and Mehta, 1973). This is a misleading in that a tall cyclone would have the same pressure drop as a short one as long as cyclone inlets and outlets dimensions and inlet velocities are the same. It has been considered that cyclone efficiency increases with an increase of the vertical dimensions. With the misleading by Lapple pressure drop model one could conclude that the cyclone should be as long as possible since it would increase cyclone efficiency at no cost in pressure drop (Leith and Mehta, 1973). A new scientific approach is needed to predict cyclone pressure drop associated with the dimensions of a cyclone.

Texas cyclone design by Parnell (1996) addressed the problem of pressure drop and cyclone sizing as thus:

TCD process also provides an empirical model for cyclone pressure drop calculation. In this model, K is a dimensionless empirical constant :

$$\Delta p = K * (V_{pi} + V_{p\circ})$$

The TCD process is simpler by comparison with the CCD procedure and provides more accurate results for estimating pressure drop. But, the TCD process doesn't incorporate means for calculating the cyclone cut-point and fractional efficiency curve, so it cannot be used to estimate cyclone efficiency and emission concentration.

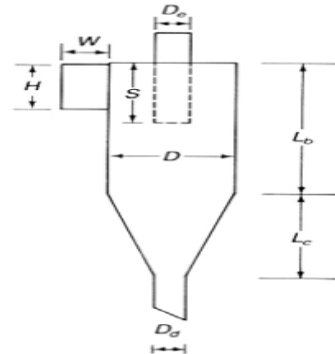
1.6 Cyclone sizing

Parnell (1996) addressed problems associated with the design of cyclones using the classical cyclone design (CCD) process and presented the Texas A&M cyclone design process (TCD) as an alternative. The TCD approach to design cyclones was to initially determine optimum inlet velocities (design velocities) for different cyclone designs. The design inlet velocities for 1D3D, 2D2D, and 1D2D cyclones are 16 m/s \pm 2 m/s (3200 ft/min \pm 400 ft/min), 15 m/s \pm 2 m/s (3000 ft/min \pm 400 ft/min), and 12 m/s \pm 2 m/s (2400 ft/min \pm 400 ft/min), respectively. This design process allows an engineer to design the cyclone using a cyclone inlet velocity specific to the type of cyclone desired. Knowing the design inlet velocities, a cyclone's dimensions could easily be determined by:

$$D_c = \sqrt{\frac{8Q}{V_i}}$$

Standard cyclone dimensions

	Cyclone Type					
	High Efficiency		Conventional	High Throughput		
	(1)	(2)	(3)	(4)	(5)	(6)
Body Diameter, D/D	1.0	1.0	1.0	1.0	1.0	1.0
Height of Inlet, H/D	0.5	0.44	0.5	0.5	0.75	0.8
Width of Inlet, W/D	0.2	0.21	0.25	0.25	0.375	0.35
Diameter of Gas Exit, D_g/D	0.5	0.4	0.5	0.5	0.75	0.75
Length of Vortex Finder, S/D	0.5	0.5	0.625	0.6	0.875	0.85
Length of Body, L_b/D	1.5	1.4	2.0	1.75	1.5	1.7
Length of Cone, L_c/D	2.5	2.5	2.0	2.0	2.5	2.0
Diameter of Dust Outlet, D_d/D	0.375	0.4	0.25	0.4	0.375	0.4



SOURCES:
Columns (1) and (5) = Stairmand, 1951; columns (2), (4) and (6) = Swift, 1969; column (3) and sketch = Lapple, 1951.

III. DISCUSSION AND CONCLUSION

For the purpose of design analysis the cyclone needs to be chosen for a given task. A target performance is imposed. And the designer should know the amount of air flow & characteristics of particles to determine the type of cyclone needed and the required size of the device. Cyclones have often been regarded as low-efficiency collectors, However, efficiency varies greatly with particle size and cyclone design. Advanced design work has greatly improved cyclone performance. Some cyclone manufacturers advertise cyclones that have efficiencies greater than 98% for particles larger than 5 microns, and others that routinely achieve efficiencies of 90% for particles larger than 15 – 20 microns.

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