RAW MATERIALS RESEARCH AND DEVELOPMENT COUNCIL MONOGRAPH SERIES

1. DESIGN OF GAS CYCLONES

**Ayoade Kuye, Daniel Ayo, Kenneth Okpala, Taofeek Folami,
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Foreword

Part of the mandate of the Raw Materials Research and Development Council (RMRDC) is to advise on adaptation of machinery and process for raw materials utilization as well as publicize research findings relevant to local sourcing of raw materials. In line with this mandate, the Council constituted a technical team for the development of process equipment design and process simulation software for industrial application. This is part of the CAD/CAM program of the Council. I am happy to note that the team has completed the work on the design, simulation and optimization of gas cyclones.

In this monograph, the authors have put relevant information on the design of cyclones in a concise and precise manner. Also included is a detailed algorithm that can easily be implemented on a computer. Apart from design, the text can also be used for evaluating the performance of cyclones.

I commend the authors for putting together this monograph. I have no doubt that it will be useful for researchers, equipment designers, fabricators, students of higher institutions and others who are interested in industrial development of the country.

Engr (Prof) A. P. Onwualu
Director General,
Raw Materials Research and Development Council

Preface

Gas cyclones are used to collect dust or particulate matter entrained in a gas stream. They are usually used downstream of another unit such as flash dryers and reactors. Cyclones come in different sizes and configurations. The most important parameters are its collection efficiency and pressure drop. We have tried in this monograph to present available information that would enable the reader to design and/or evaluate the performance of a gas cyclone. The information contained in this monograph was obtained from a wide variety of sources. Consequently, the equations are left in their original forms in order to ensure their accuracy.

We begin the monograph with a general overview on cyclone design and selection. Chapter two discusses the various factors that affect the performance of a cyclone. Also equations for calculating collection efficiency and pressure drop are presented. In Chapter three, cyclone optimization is discussed while Chapter four is devoted to the algorithms that can be used for computer-aided design of cyclones. Finally in Chapter five, some case studies are used to illustrate the appropriateness of the equations given in the previous chapters.

We acknowledge with gratitude the contributions from the in-house members of the CAPED (computer–aided process engineering design) group within the Raw Materials Research and Development Council. They are Mrs I.O Ejuya, I. I. Ismail, M. O. Ayoola, C. Hamilton, A. I. Okereke and U. M. Mansur. They provided both the logistic and technical support that were necessary to get this monograph to its present form.

Our special thanks go to the Director General, Raw Materials Research and Development Council for sponsoring the project. The project started during the tenure of Alhaji Dr Abubakar Abdullahi and reached this stage during the tenure of Engr (Prof) A. P. Onwualu. We appreciate the tremendous support and encouragement of the two Chief Executive Officers. To Engr. G. Ladan, Deputy Director. Machinery and Equipment Development Division, we appreciate the infrastructural support given. We also acknowledge the various contributions of other staff of the Council.

Contents

1/ Introduction

1.1 OVERVIEW

Cyclones are robust devices used for sizing, classification and screening of particulate materials in mixture with fluids (gases or liquids). Cyclones come in many sizes and shapes and have no moving parts. They operate on the principle that particles enter the device with the flowing fluid and swirl round the cylindrical parts of the device. The particles have too much momentum and cannot turn with the fluid. They impact the cyclone walls, fall down the cyclone walls (by gravitational action) and are collected in a hopper.

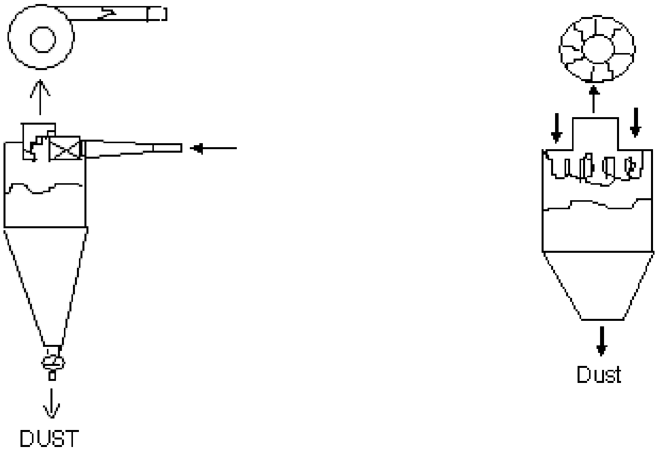
Cyclones are probably the most widely used dust or particulate matter collectors in the industry. Some of the reasons for the wide variety of applications of cyclones include:

- they are easy to build, inspect and maintain.
- they have low capital cost, relatively economical to operate and can be adapted to a wide range of operational conditions.

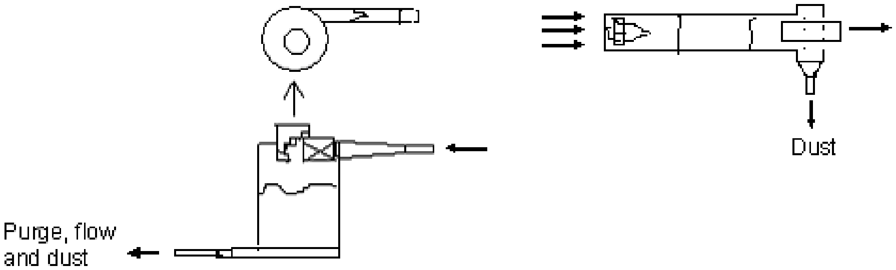
However, cyclones are prone to low efficiencies and high operating costs due to high pressure drop as well as internal erosion/corrosion. Cyclones have been employed in the cement industry for dust/particulate removal, in fluidized-bed reactors as well as in the processing industry for the recovery of spray-dried products. Cyclones are also used for classification as for example, in the degritting of kaolin clay where sand is removed from the crude clay suspension. Cyclones are usually used downstream of a unit (reactor, dryer, etc.) to collect the solid particles entrained by the gas.

1.2 OPERATING PRINCIPLES OF CYCLONE SEPARATORS

Cyclone separators can be classified according to either their geometrical configuration or their efficiency. Typical configurations include tangential inlet-axial discharge; tangential inlet peripheral discharge, axial inlet and discharge, and axial inlet-peripheral discharge (see Fig 1.1). Cyclone efficiencies are classified as high efficiency (98-99%), moderate efficiency (70-80%) and low efficiency (50%).



(a) Tangential inlet, axial discharge (b) Axial inlet, axial discharge



(c) Tangential inlet, peripheral discharge (d) Axial inlet, peripheral discharge

Fig 1.1: Most Commonly Used Cyclone Types

In the conventional cyclone (Fig 1.1a), the gas enters the cylinder tangentially, and it spins in a vortex as it proceeds down the cylinder. The cone section causes the vortex diameter to decrease until the gas reverses on itself and spins up the center to the outlet pipe or vortex finder. Dust particles are centrifuged toward the wall and collected by inertial impingement. The collected dust flows down in the gas boundary layer to the cone apex where it is discharged through an air lock or into a dust hopper serving one or more parallel cyclones. Although conventional cyclones can be built to larger diameter, they are commonly 600 to 915 mm in diameter.

In axial inlet and discharge cyclones, the operating principles are similar to those of the conventional cyclone and differs only in terms of smaller diameter (25 to 305 mm). Because of their smaller diameters, axial inlet and discharge cyclones have higher collection efficiency but low throughput. In the tangential inlet peripheral discharge and the axial inlet peripheral discharge cyclones, the dust is not completely removed from the gas stream but is concentrated into about 10% of the total flow. The collection efficiency is increased by removing the dust in airborne form and reducing its entrainment losses which occur at the cone apex. In the tangential inlet peripheral discharge cyclone, the gas reverses internally as in the conventional cyclone, but the axial inlet peripheral discharge provides straight through flow which is convenient for connecting to large volume sources where changes in gas direction could be inconvenient.

1.3 CONCEPTS IN CYCLONE DESIGN AND SELECTION

The most important parameters of a cyclone as a separating device are its collection efficiency and the pressure drop across the unit. The collection efficiency of a cyclone is defined as its ability to capture and retain dust particles whereas the pressure drop gives an indication of the amount of power that the unit needs to do so. These parameters are influenced by operational conditions, physical properties of the solid material fed and the geometry of the cyclone. In general,

- Reducing the cyclone diameter, the gas outlet diameter, the cone angle and/or increasing the cyclone body length would result in an increase in cyclone efficiency

- Increasing the cyclone diameter, inlet diameter, gas diameter and/or body length would result in increase in the cyclone capacity

- Increasing the pressure drop gives rise to
    - Increase in separation efficiency
    - Higher capacity
    - Decrease in the underflow to throughput ratio
    - More concentrated underflow, and
    - Cleaner overflow

Sizing: As can be seen from above the diameter of a cyclone strongly influences its collection efficiency. Smaller diameters (200 to 600mm) provide greater collection efficiency. The dust discharge opening should be as large as possible to forestall its clogging. The ratio between the discharge port diameter D_0 and the cyclone diameter normally ranges between 0.18 and 0.40 (Storch *et al*, 1979). The higher ratios are usually found on the large diameter cyclones intended for trapping coarser dusts. Cyclone overall height affects not only flow resistance but also collection efficiency. Increasing cyclone overall height will increase both its flow resistance and collecting efficiency. Overall heights of cyclones generally vary between 2D and 6D. The cone apex angle mostly lies between 10 and 20 degrees with the smaller angles being more usual on high efficiency units.

Selection of cyclone separators: Selecting a cyclone type for a given application seems to be based on only the collecting efficiency or performance of the cyclone. However, many other factors which tend to impair the performance of the cyclones or the quality of service one can get out of them include:

1. **Mechanical defects**: The mechanical defects in a cyclone are usually due to negligence or error in designs, manufacture or installation of the unit. These defects can cause the cyclone to fill up with trapped matter or the ingress of moisture which leads to clogging. Preventing the occurrence of such defects is preferable.

2. **Clogging:** It results from the chemistry of the dust and its physical properties. The chemistry of the dust can cause it to bond or cement. This type of clogging is prevented by improving thermal insulation, stricter observance of the specified operating conditions and meticulous maintenance of the equipment. The distribution of grain size can cause clogging which commonly occurs when high efficiency cyclones are used to deal with dust in the 10 to 15 micron range. Such clogging is very complicated to deal with and can lead to the replacement of the cyclone.

3. **Excessive Wear:** Excessive abrasion in a cyclone will ultimately wear a hole in the equipment. The critical zones where holes are commonly encountered are the cylinder part just beyond the tangential inlet opening and the conical part at its very bottom. With multi-cyclones any hole in the inlet chamber will affect the cyclone’s whole flow pattern and reduce collecting efficiency. Although it is impossible to prevent wearing, it can be limited by providing the critical zones of the cyclone with thicker walls or ceramic inserts.

4. **Gas velocity**: As the inlet velocity decreases, there is corresponding decrease in cyclone efficiency and pressure drop; the converse is also true up to a maximum level.

Experimental work using the same powder showed that cyclones with different geometrical proportions showed different efficiencies. It follows therefore, that optimization of a cyclone by the careful establishment of its operational conditions and/or its geometrical characteristics improves its performance and reduces the need for more sophisticated and expensive secondary gas cleaning devices. Cyclone optimization is discussed further in Chapter 3.

2/ Design of Cyclones

2.1 INTRODUCTION

Although the operation of a gas cyclone is relatively simple, it is however not completely understood, partly as a result of the complicated flow pattern within the cyclone. Despite that much work exists in the literature on how the cyclone dimensions and its operating conditions affect its performance, current design practice is based partly on theory and partly on empirical models. The design philosophy is based on a standard (or known) design cyclone, which is that cyclone that has the proper geometric relationship between the cyclone diameter, inlet area, vortex finder, apex orifice and sufficient length that provides adequate retention time for particle classification (Svarovsky, 1981). By selecting the standard design, a meaningful scale-up can be performed which leads to reasonably reliable design. There is a choice of several standard or optimum designs that have been developed and tested by different researchers as well as some well-documented commercial cyclones.

The most basic description of the data required for proper cyclone design must include all pertinent information about the gas and particulate that is entering the cyclone. It is important to remember that if total cyclone collection efficiency will be a requirement of the cyclone design, an inlet particle size distribution will be required. The following list gives the minimum information required for cyclone design.

- Gas flow rate (minimum, operating, and maximum)
- Gas density of each flow condition
- Gas viscosity of each flow condition
- Particulate specific gravity or particle density
- Particulate loading
- Aerodynamic particle size distribution

In addition to the above listed items, there are many attributes of any process that will affect the construction and design of the cyclone selected and to the extent possible, should be available to the cyclone designer prior to beginning the cyclone design. Some of these are

- Gas temperature (minimum, operating and maximum)
- Gas pressure (minimum, operating and maximum)
- Gas composition
- Particulate composition
- Known particulate characteristics (abrasiveness, friability, explosion characteristics, hygroscopic property (propensity for absorbing water), stickiness, etc).
- Corrosion characteristics

The remaining criteria required for cyclone selection and design include complete description of what are required of the cyclone. It is vital to completely describe:

1. The desired collection efficiency or fractional efficiency
2. The maximum allowable pressure drop

Aside from the inlet conditions, which are presumably a function of the process and are not controllable, collection efficiency and allowable pressure drop represent the two most significant design variables outside of cyclone geometry and arrangement. Great care must be given to balancing the desire for particle collection and that of energy consumption (pressure drop) so that the most economical final solution is obtained. A schematic diagram of a cyclone is shown in Fig. 2.1.

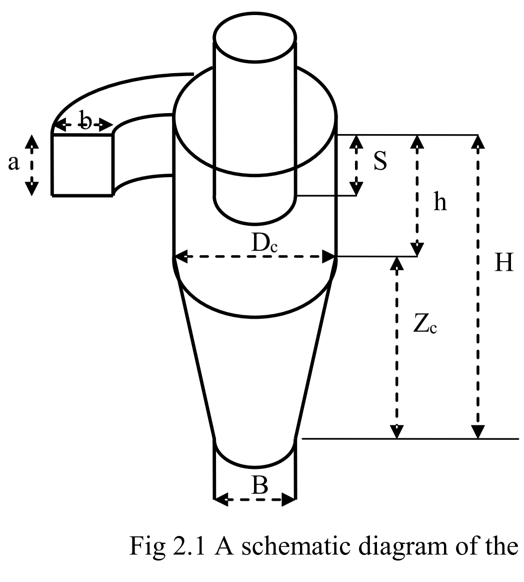


Fig 2.1 A schematic diagram of the cyclone

As mentioned earlier, the literature on gas cyclones is full of studies of the effect of the relative geometrical proportions on pressure drop or capacity and separation efficiency. In what follows we shall discuss how these factors affect the performance of a gas cyclone.

2.3 FACTORS THAT AFFECT CYCLONE DESIGN

Body Diameter

The cyclone body diameter is one of the most powerful tools in cyclone design. In fact other physical dimensions of a cyclone are usually quoted in geometric proportions to the body diameter. If all the other factors are the same, there will be less centrifugal force on particles traveling around a large-radius circle than a small-radius one. An increase in diameter decreases the centrifugal force on a particle, which in turn causes a decrease in the velocity with which a given particle moves toward the wall of a cyclone where it is theoretically captured. An opposite effect is noticed when the body diameter is decreased, Note that the effect of diameter on fractional efficiency curve is given by Equation 2.33.

From the foregoing, one can conclude that within a given family of cyclones, it is possible to achieve higher particulate collection efficiencies with multiple cyclones in parallel as against a single larger cyclone. However, such a conclusion cannot be reached when comparing cyclones of different geometry (different families). The practical use of cyclone laws as relating to body diameter provides a reliable and useful tool for shifting the fractional efficiency curve from a known efficiency curve to that of a different member (larger or smaller) of the same family.

Inlet velocity

In general, the higher the inlet velocity, the greater the centrifugal force on the particulate, which will subsequently move toward the wall of the cyclone at greater velocity. This effect of inlet velocity on the collection efficiency is described by the shift (increase) in the fractional efficiency curve, as higher velocity means higher flow rate, which increases the efficiency. However, the pressure drop (energy consumption) increases exponentially with increased inlet velocity. Moreover, when collecting abrasive particulate the rate of erosion will usually increase with increased inlet velocity. A frequent rule of thumb is that the rate of erosion will increase by a factor of 8 if the velocity doubles. In general care should be taken when inlet velocities exceed 100 to 120 ft/s (30 to 37m/s). An optimum value is about 15m/s, while the inlet velocity is usually restricted to between 15m/s and 30m/s.

However, according to Wang et al. (2002), there exist ideal inlet velocities (design velocities) for different cyclone design to optimize performance. The authors compiled a rather extensive table for different flow rates, different cyclone configurations and different number of cyclones in parallel. A small extract is shown in Table 2.1

Table 2.1 Typical design velocities for different configurations

Cyclone configuration	Design velocity, m/min
1D3D*	975 ± 122
2D2D	914 ± 122
1D2D	732 ± 122

* Cyclones are expressed in terms of the diameter of the cyclone. Thus ID3D means that the height of the cylindrical portion is 1xD and the height of the conical protion is 3xD.

Gas Viscosity

The viscosity of the feed gas is of great significance in cyclone design and operation. Since gas viscosity is a measure of the resistance of a gas or liquid to movement, viscosity relates directly to the drag forces placed on the object and the subsequent speed that the object will reach in moving through the gas under some driving force. This effect has been described by Stoke's law, from which it could be seen that the terminal velocity is inversely proportional to the gas viscosity. Since viscosity increases with temperature, there is a shift of the fractional efficiency curve toward lower collection efficiency at high temperatures. The converse is equally true at lower temperatures. Gas viscosity is a measured property and requires to be known for cyclone design.

Particle density

The density of the particulate directly affects the speed with which any given particle travels through a gas while being acted upon by some force. As the particle density increases, so does the velocity at which it travels through the gas, causing an increase in cyclone collection efficiency. A decrease in particle density also decreases the collection efficiency. As with gas viscosity, particle density is not a factor within the control of the designer.

Dust Loading

It has been well known that collection efficiency increases with increased dust loading. Although research in this area is ongoing, it seems one of the most significant mechanisms causing increased fractional efficiencies with increased dust loading is particle agglomeration. As dust loading increases, there is also increased probability of collision between particles and subsequent increase in particle agglomeration.

Cyclone Geometry

This is the greatest single variable that the designer can use to affect the final efficiency of the device. We have already discussed the effect of body diameter in the same cyclone family. There is an infinite number of geometries within each of several basic cyclone styles, and variations in cyclone geometry can provide for significant improvements in collection efficiency at equal or lower energy consumption. The different design geometries are described in Section 2.3. In general it can be concluded that the following guidelines apply to cyclone design.

- **H/D ratio**: The length-to-diameter ratio, H/D is the total cyclone height (cylinder length + cone vertical length) divided by the diameter of the cyclone body. Generally, with all other factors constant, cyclone performance improves with increased H/D ratios. Normally this ratio is between 3 and 6 for high efficiency cyclones, with 4 being the most common value. H/D value should rarely be below 2 if there is any concern whatsoever with cyclone performance. There is also minimal gain in using H/D ratios above 6.

- **Outlet Pipe Diameter**: The smaller the bottom end of the outlet pipe, the higher the cyclone pressure drop and collection efficiency. Holding all others factors constant, reducing the diameter of the outlet pipe, also reduces the axial (vertical) velocity components within the cyclone, and increases the residence time. Pressure drop will increase with increases in outlet velocity (decreases in outlet pipe diameter).

- **Outlet Pipe Length**: For any cyclone there is an optimum outlet pipe length. If the outlet pipe length is altered from its optimum, there will be an increased pressure drop and reduced collection efficiency. In general, the outlet pipe should extend below the bottom of the inlet by 10 to 60 percent of the inlet height. Significant losses of efficiency on both small and large diameter particles may occur by short circuiting of the gas flow if the outlet pipe does not extend below the inlet floor. Beyond the optimum length, collection efficiency will decrease while the pressure drop increases.

- **Cone Shape**: The cyclone cone serves the purpose of reducing the cyclone vortex at the material discharge making it possible to disengage the particulate to an area where it will not be substantially re-entrained. The smaller the cone discharge, the lower the turbulence beneath the cyclone and subsequent re-entrainment, and vice versa.

As a minimum, the discharge diameter of the cyclone underflow/or dipleg should be sized using

$$.B = 3.5\left(2450\frac{M}{\rho_g}\right)^{0.4} \qquad 2.1$$

where B = discharge pipe diameter of cone, (cm)
M = solids mass flow rate, (kg/s)
ρ_g = solid bulk density (kg/m^3)

Summary of Effects
The effect of the variation of the above parameters on cyclone efficiency is summarized in Table 2.2.

Table 2.2 The Effect Of Variation Of Various Parameters On Cyclone Efficiency

Parameter	Change	Effect	Reason
Vortex finder diameter	Increase	Decrease Efficiency	More likely to suck particles up
Pressure drop	Increase	Increase efficiency	Flow rate increases
Particle size	Increase	Increase efficiency	More likely for particle to migrate to exterior wall
Dust outlet diameter	Increase	Prevents overload and in extreme cases decreases efficiency	Causes flushing of particle and gas
Gas viscosity	Increase	Decrease Efficiency	Harder for particles to settle
Cyclone diameter	Increase	Decrease Efficiency	Decrease gravitational forces
Particle concentration	Increase	Decrease Efficiency	Decrease gravitational forces
Feed inlet area	Increase	Decrease Efficiency	More feed enters at less pressure
Gas/Particle density difference	Increase in density	Increase efficiency	More likely for particles to migrate to opposing spirals in cyclone
Cyclone length	Increase	Increase efficiency	Residence time increase

2.4 CYCLONE DESIGN GEOMETRIES

There are several geometrical configurations of industrial air cyclones that exist and as many as seventeen configurations that have been reported in literature. The earlier standard designs are six in number and are grouped into three categories: high efficiency, conventional (or medium efficiency) and high throughput. The later designs are modifications of the earlier geometries to achieve higher performance and for more specific applications. The designs are listed chronologically by the name(s) of the designer(s) as follows:

1. Shepherd and Lapple conventional (2D2D)(1939)
2. Stairmand high efficiency (1951)
3. Stairmand high throughput (1951)
4. Swift high efficiency (1969)
5. Swift conventional (1969)
6. Swift high throughput (1969)
7. Peterson and Whitby high throughput
8. Parnell and Davies (1D3D) (1979)
9. Simpson and Parnell (1D2D)(1996)
10. Tullis et al (Barrel) (1997)
11. Kenny, Gussman and Meyer (Sharp-cut cyclone, SCC) (2000)
12. Kenny and Thorpe (Very sharp-cut cyclone, VSCC) (2000)
13. StorchT2/160
14. StorchT3/315
15. Tengbergen100-2.5/A370
16. Tengbergen50-2.5/B280
17. Musch D

Information on the date of development of the last five geometries was not available. The standard dimensions of the early designs are given in Table 2.3 while those for the newer designs are presented in Table 2.4. The most commonly used cyclone designs are the 2D2D (Shepherd and Lapple, 1939), the Stairmand high efficiency (1951) and the 1D3D (Parnell and Davies, 1979). Simpson and Parnell (1996) introduced the 1D2D design as a new low pressure cyclone, for the cotton ginning industry. Tullis *et al* (1997) also introduced the Barrel cyclone to address the problem of fine particulate matter that get diverted into the clean air stream and enable them to be collected, for exhausts containing a significant fraction of cotton lint fiber. In comparative terms 1D3D and 2D2D cyclones are best designs for fine dust, 1D2D cyclone is best design for lint fiber/fine dust gin trash while Barrel cyclone is best design for lint fiber/large trash.

Kenny, Gussman and Meyer (2000) developed the tangential round-entry Sharp-cut cyclone (SCC) to offer size selectivity; that is, for sharpness of selectivity curve. Kenny and Thorpe (2000) further modified the SCC design by enlarging the cyclone cone (longer cone, wider base) and decreasing the inlet and outlet tube diameters to obtain the Very Sharp-Cut Cyclone (VSCC). The VSCC body diameter is smaller than the corresponding SCC, to compensate for the effects of these changes in geometry on d_{50}. A value of d_{50} as low as 2.5µm at a flow rate of 16.67l/min was obtained.

Table 2.3: Standard dimensions of early cyclone designs

	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, a*/D*	0.5	0.44	0.5	0.5	0.75	0.8
Width of Inlet, b/D	0.2	0.21	0.25	0.25	0.375	0.35
Diameter of Gas Exit, D_e/D	0.5	0.4	0.5	0.5	0.75	0.75
Length of Vortex Finder, L*/D*	0.5	0.5	0.625	0.6	0.875	0.85
Length of Body, *h/D*	1.5	1.4	2.0	1.75	1.5	1.7
Length of Cone, Z_c/D	2.5	2.5	2.0	2.0	2.5	2.0
Diameter of Dust Outlet, B*/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; columns (3) =Shepherd & Lapple, 1939.

Table 2.4: Standard Dimensions of New Cyclone Designs.

	Peterson & Whitby	1D3D	1D2D	Storch T2/160	Storch T3/315	Tengbergen 100-2.5/A370	Tengbergen 50-2.5/B280	MuschD
D/D	1	1	1	1	1	1	1	1
D_e/D	0.5	0.5	0.5	0.48	0.559	0.405	0.536	0.333
L/D	0.583	0.625	0.625	1.063	1.048	0.568	1.07	0.81
h_d/D	1.33	1	2	2.06	2.17	0.649	1.554	0.734
Z_c/D	3.17	3	2	4.875	3.86	2.335	2.87	2.417
a/D	0.583	0.5	0.5	0.8375	0.783	0.486	0.857	0.523
b/D	0.208	0.25	0.25	0.0244	2.83	0.268	0.268	0.143
B/D	0.5	0.25	0.25	0.375	0.434	0.405	0.536	0.547

2.5 CYCLONE DESIGN EQUATIONS

A number of cyclone (equations) are available in the literature for calculating these parameters. Some of these models are presented in this section.

2.51 Pressure Drop

The energy consumed in a cyclone is most frequently expressed as the pressure drop across the cyclone. This pressure drop is the difference between the gas static pressures measured at the inlet and outlet of the cyclone. Many models have been developed to determine this pressure drop. Some of the commonly used equations to calculate pressure drop are:

(a) Koch and Licht Pressure Drop Equation.

Koch and Licht (1977) expressed the cyclone pressure drop as

$$\Delta P = 0.003 \rho_g v_i^2 N_H \tag{2.2}$$

where

ρ_g = gas density (lbm/ft^3)
v_i = inlet velocity (ft/s)
N_H = number of velocity heads (inches of water) and is expressed as

$$N_H = K\left(\frac{a.b}{De^2}\right) \tag{2.3}$$

K = 16 for no inlet vane
= 7.5 with neutral inlet vane
a, b = inlet height and width, respectively.

(b) Ogawa Equation

Another pressure drop equation is due to Ogawa (1984), which takes the form of

$$\Delta P = \frac{1}{2}\rho_g v_i^2 \, N_H \tag{2.4}$$

Using statistical analysis Casal and Martinez (1983) expressed N_H as

$$N_H = 11.3\left(\frac{ab}{D_e}\right)^2 + 3.33 \tag{2.5}$$

(c) Stairmand Pressure Drop Equation

The Stairmand expression for pressure drop in a cyclone is (Sinnot, 1999; Strauss,1966)

$$\Delta P = \frac{\rho_g}{203}\left\{v_1^2\left[1+2\varphi^2\left(\frac{2[D-b]}{De}-1\right)^{1}\right]+2v_2^2\right\} \tag{2.6}$$

where

ρ_g = gas density
v_1 = inlet velocity
b = inlet duct width
φ = friction factor
De = vortex finder diameter
v_2 = exit gas velocity and is given by

$$v_2 = \frac{4Q}{\pi De^2} \tag{2.7}$$

where Q is the inlet feed flow rate.

The friction factor φ is given by (Strauss, 1966)

$$\varphi = \frac{-\sqrt{\frac{De}{2(D-b)}} + \sqrt{\frac{De}{2(D-b)} + \frac{4GA}{ab}}}{2GA/ab} \qquad 2.8$$

where

G = friction constant (= 0.005 for gas cyclones)
a, b = cross sectional area of inlet duct (a >b)
A = surface area of cyclone exposed to gas

This surface area is given by

$$A = \pi D^2 (\alpha_1 + \alpha_2) \qquad 2.9$$

α_1 = length ratio (h/D) for cylindrical portion of cyclone
α_2 = length ratio ($(Z_c - h)/D$) for vertical cone portion of cyclone

2.52 Collection Efficiency Calculation

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

$$\eta = \frac{\sum \eta_j m_j}{M} \qquad 2.10$$

where η = overall collection efficiency
η_j = fractional efficiency for j^{th} particle size
m_j = mass of particles in the j^{th} particle size range,
M = total mass of particles

If the particle size distribution of the dust is given by g(d) and the fractional efficiency curve can be described as a mathematical function of the particle size f(d), then an alternative expression for calculating the total collection efficiency η is:

$$\eta = \sum_{d=0}^{d=\infty} \left\{ \left[g(d)_{N+1} - g(d)_N \right] f\left[\frac{(d)_N + (d)_{N+1}}{2} \right] \right\} .100 \qquad 2.11$$

Available methods for calculating fractional efficiency are presented below.

(a) Theoretical determination of fractional efficiency curves

There exists a vast array of literature concerning methods of predicting cyclone fractional efficiencies utilizing generalized methods. One of the best theoretical approaches was presented by Leith and Licht (1972), which also compared other previous methods of calculating fractional efficiencies. Their expression for cyclone fractional efficiency is

$$\eta_i = \exp\left\{-2\left[\frac{K'\tau_i Q}{D_c^3}(n+1)\right]^{\frac{1}{2(n+1)}}\right\} \qquad 2.12$$

where Q is the gas volumetric flow rate and τ_i is called relaxation time which is given by

$$\tau_i = \frac{\rho_p d_{pi}^2}{18\mu} \qquad 2.13$$

where d_{pi} and ρ_p are the particle diameter and density, respectively and μ the gas viscosity.

The exponent n, normally called the vortex index, can be estimated as a function of the cyclone diameter (in feet) and of gas temperature (in °F) by the following expression:

$$n = 1 - \left[1 - \frac{(12D_c)^{0.14}}{2.5}\right]\left[\frac{T + 460}{530}\right]^{0.3} \qquad 2.14$$

The effect of cyclone configuration on separation efficiency is considered using factor K', given by

$$K' = \frac{8K_c}{K_a^2 K_b^2} \qquad 2.15$$

where

$$K_a = \frac{a}{D_c} \qquad 2.16$$

$$K_b = \frac{b}{D_c} \tag{2.17}$$

$$K_c = \frac{\left(2V_s + V_{nl,H}\right)}{2D_c^3} \tag{2.18}$$

The annular volume above the exit duct up to the middle of the gas entrance duct, V_s, is given by

$$V_s = \frac{\left[\pi\left(l - \frac{a}{2}\right)\left(D_c^2 - D_e^2\right)\right]}{4} \tag{2.19}$$

The natural length of the vortex, l, can be estimated by (Alexander, 1949)

$$l = 2.3D_e\left(\frac{D_c^2}{ab}\right)^{\frac{1}{3}} \tag{2.20}$$

For $l < (H - S)$, volume V_{nl}, which is the volume of the region that includes the natural length of the vortex excluding the central core, can be estimated by

$$V_{nl} = \frac{\pi D_c^2}{4}\left(h - S\right) + \left(\frac{D_c^2}{4}\right)\left(\frac{l + S - h}{3}\right) - \left(1 + \frac{d_n}{D_c} + \frac{{d_n}^2}{D_c^2}\right) - \frac{\pi D_e^2 l}{4} \tag{2.21}$$

where the diameter of the central core, d_n is defined by

$$d_n = D_c - \left(D_c - S\right)\frac{l + 1 - h}{H - h} \tag{2.22}$$

For $l > (H - B)$, volume V_H, which is the volume of the gas below the gas exit duct excluding the core, can be calculated by

$$V_H = \frac{\pi D_c^2}{4}\left(h - l\right) + \left(\frac{D_c^2}{4}\right)\left(\frac{H - h}{3}\right)\left(1 + \frac{S}{D_c} + \frac{S^2}{D_c^2}\right) - \frac{\pi D_e^2\left(H - l\right)}{4} \tag{2.23}$$

The natural length, which is the length of the inner vortex core is also referred to as the effective length (Wang, et al. 2003). This length does not necessarily reach the bottom of the cyclone (Leith and Mehta, 1973). When the effective length is shorter than the cyclone physical length, the space between the bottom of the vortex and the bottom of the cyclone will not be used for particle collection. On the other hand, if the effective length is longer than the cyclone physical length, the vortex will extend beyond the bottom of the cyclone, and a dust re-entrainment problem will occur (Wang *et al*, 2003). According to Hoffman *et al* (1995), vortex length increases with an increase in gas velocity for a fixed cyclone geometry. Therefore, besides increasing the centrifugal force, an increase in gas velocity also increases the effective collection area in the cyclone and both effects result in an appreciable improvement in collection efficiency (Santana *et al*, 2001).

The use of Equation (2.12) to predict collection efficiency has been shown by (Santana et. al (2001) to be restricted to a narrow range of G, the configuration factor, and fails in the prediction of cyclone efficiency for large variations in cyclone configuration. They observed experimentally a decrease in G, in contrast to an inverse tendency predicted by the theoretical correlation.

Other models that are available to predict fractional efficiency include the Barth model, the Dietz model and the Mothes and Loffler model.

(b) Empirical Equations for Fractional Efficiency Curves.

In cases where experimental data are available, attempts have been made to fit the data into equations. Such is the case for Stairmand high efficiency (HE) and high throughput (HT) fractional efficiency curves. Equations for the two types of cyclones have been derived by Gerrard *et al* (1976) and take the following form:

Stairmand High Efficiency

$$\eta = 1 - \exp - (-d^{0.42}) \qquad 2.24$$

Stairmand High Throughput

$$\eta = 1 - \exp(-0.115\, d) \qquad 2.25$$

where d = particle size and η is the fractional efficiency.

The Licht Model

Licht also developed a model that was based on the assumption of turbulent flow with lateral mixing. The following equations apply:

$$d_{p50} = \left(\frac{0.693}{A}\right)^{n+1} \qquad 2.26$$

where n is vortex exponent and A is a pre-factor that is determined according to the following equation

$$A = 2\left(\frac{K'Q\rho_p(n+1)}{18\mu D^3}\right)^{\frac{1}{2(n+1)}} \qquad 2.27$$

where K' is a configuration factor, Q is air flow rate and D is cyclone body diameter. The fractional efficiency for other particle sizes can then be calculated as

$$\eta_i = 1 - \exp\left[-0.693\left(\frac{d_{pi}}{d_{p50}}\right)^{\frac{1}{n+1}}\right] \qquad 2.28$$

The configuration factor, K along with other parameters, is listed in Table 2.1 for some standard configurations.

Table 2.5: Parameters of some standard industrial cyclones

		High Efficiency		Medium Efficiency	General Purpose	
Symbol	Description	Stairmand	Swift	Shephard & Lapple	Swift	Peterson & Whitby
D	Body diameter	1	1	1	1	1
C	Inlet height	0.5	0.44	0.5	0.5	0.583
B	Inlet width	0.2	0.21	0.25	0.25	0.208
L	Outlet length	0.5	0.5	0.625	0.60.5	0.53
D_e	Gas outlet diameter	0.5	0.4	0.5	1.75	0.5
h	Cylinder height	1.5	1.4	2	3.75	1.33
H	Overall height	4	3.9	4	0.4	3.17
B	Dust outlet diameter	0.375	0.4	0.25	381.8	0.5
K	Configuration number	551.3	699.2	402.9	8	342.3
N_H	Inlet velocity head	6.4	9.24	8	3.65	7.76
Surf	Surface parameter	3.67	3.57	3.78	13.1	3.2
K/N_Hsurf		23.5	21.2	13.3		13.8

The Lapple Model

Lapple (1951) developed a semi-empirical relationship to calculate a '50% cut diameter' d_{pc} which is the diameter of particles collected with 50% efficiency. The expression is

$$d_{pc} = \left[\frac{9\mu b}{2\pi N_e v_i (\rho_p - \rho)} \right]^{\frac{1}{2}} \qquad 2.29$$

where d_{pc} is the diameter of the particle which will be separated with an efficiency of 50% and N_e is the number of revolutions in the cyclone outer vortex (Shepherd and Lapple,1939), which is given by

$$N_e = \frac{1}{a}\left[h + \frac{H - h}{2} \right] \qquad 2.30$$

2.53 Effect of gas flow rate, gas density and dust loading on cyclone performance

Gas flow rate

With all other conditions remaining constant, pressure drop will increase exponentially with the gas flow rate according to the equation

$$\Delta P_2 = \Delta P_1 \left(\frac{Q_2}{Q_1} \right)^{C_1} \qquad 2.31$$

where

ΔP_2 = new cyclone pressure drop
ΔP_1 = original cyclone pressure drop
Q_2 = new cyclone flow rate
Q_1 = original cyclone flow rate

For most cyclones, the exponent C_1 varies between 1.9 and 2.3 and is best determined by actual measurements on a cyclone from a given family. (Two cyclones are of the same family if they represent scaled versions of each other.) Thus as the flow rate (velocity) increases, so does the pressure drop.

Gas density

Pressure drop is directly proportional to gas density as shown below

$$\Delta P_2 = \Delta P_1 \left(\frac{Q_2}{Q_1}\right)^{C_1} \left(\frac{\rho_{g2}}{\rho_{g1}}\right) \qquad 2.32$$

where ρ_{g2} = new gas density
ρ_{g1} = original gas density

Effect of Diameter

Having determined the fractional efficiency curve for a given cyclone, the new fractional efficiency curve for any other member of that family of cyclones may be determined by applying the following equation

$$d_2 = K_s\, d_1 \qquad 2.33$$

where d_2 = new particle size
d_1 = original particle size
and K_s = fractional efficiency curve shift constant computed as

$$K_s = \left[\left(\frac{D_2}{D_1}\right)^3 \left(\frac{Q_1}{Q_2}\right)\left(\frac{\rho_1}{\rho_2}\right)\left(\frac{\mu_2}{\mu_1}\right)\right]^{0.5} \qquad 2.34$$

where
ρ = particle density
μ = viscosity of the fluid
and the subscripts 1 and 2 refer to original condition and new condition, respectively.

Dust loading

Cyclone pressure drop decreases with increased dust loading, and vice versa. Numerous empirical measurements have shown the dust loading effect to be

$$\Delta P_2 = \Delta P_1 C_2 \qquad 2.35$$

and $C_2 = 1$ if $W < 1.249$
$= \left[0.96 - 0.4722 \ln \frac{W}{2.288}\right]$ if $1.249 \le W \le 12220.06$
$= 0.55$ if $W > 12220.06$

where
ΔP_1 = pressure drop at $W = 0$
ΔP_2 = pressure drop at specified dust loads

W = dust loading [g/m^3]

The general equation for cyclone pressure drop incorporating all of the effects then becomes

$$\Delta P_2 = C_2 \Delta P_1 \left(\frac{Q_2}{Q_1} \right)^{C_1} \left(\frac{\rho_{g2}}{\rho_{g1}} \right) \qquad 2.36$$

As dust loading increases, so does collection efficiency. An empirical adjustment factor Z for dust loading should be applied to the fractional efficiency curve after the K_s coefficient has been used to shift the curve for all conditions except dust loading (Heumann, 1997). The generalized equation for applying Z is

$$\eta_2 = 100 - Z(100 - \eta_1) \qquad 2.37$$

where η_2 = new efficiency at particle size d_2
η_1 = original efficiency at particle side d_1

$$Z = 2.095 \left(\frac{W}{2.288} \right)^{0.0197} - 1.09 \qquad 2.38$$

2.5 DESIGN CALCULATIONS

A close look at the equations presented in Section 2.2 would reveal that the calculations required in the design of a cyclone depend on the input variables that are specified. The following parameters can be specified and calculated:

a. Volumetric flow rate.
b. Cyclone diameter.
c. Cut diameter.
d. Cyclone efficiency.
e. Pressure drop

Of the five variables listed above, it is required to specify two or three and the others can be calculated. The feasible combinations are shown in Table 2.6. Cases 1 and 2 are explained further below while the information flow diagrams for all the cases are shown in Figs 2.2 to 2.10.

Table 2.6. Feasible combinations of cyclone variables.

Case	Variable Combinations
1	Volumetric flow rate and cyclone diameter
2	Volumetric Flow rate and cut diameter
3	Volumetric Flow rate and Cyclone Efficiency
4	Volumetric Flow Rate and Pressure Drop
5	Cyclone Diameter and Cut Diameter
6	Cyclone Diameter and Efficiency
7	Flow Rate, Pressure Drop and Diameter
8	Cut Diameter and Pressure Drop
9	Flow Rate, Efficiency and Pressure Drop

Case 1. Volumetric flow rate and cyclone diameter specified.

This is a straightforward case as one has to first choose the configuration desired. Then the inlet velocity can be calculated from the following equation:

$$v = \frac{Q}{ab} \qquad 2.39$$

Next, the cut diameter is calculated as

$$\mathrm{dp}_{\min} = \left[\frac{9\mathrm{b}\mu}{\mathrm{N_e}\,(\rho_s - \rho)\pi\mathrm{v}}\right]^{0.5} \qquad 2.40$$

where N_e is the number of effective turns, given by Equation (2.30)

Note that recent procedures (Casal, 1995, Perry et al, 1997) have suggested using $\mathrm{dp}_{\min}$ as the cut diameter, dp_c.

At this point one can calculate the collection efficiency but it is necessary to know both the particle size distribution of the feed and the fractional efficiency curve of the particular cyclone. It is usually preferred if an experimental fractional efficiency is available otherwise any appropriate model-predicted fractional efficiency curve is used. Equation 2.11 can now be used to obtain the total collection efficiency.

Case 2. Volumetric Flow rate and cut diameter given.

First choose a configuration and calculate the cyclone diameter by using the following equation (Casal, 1995)

$$D_c = \left[\frac{d_{pmin}^{\ 2}\ (\rho_s - \rho)\pi N_e\, Q}{9 b_0^{\ 2}\ a_0\ \mu N} \right]^{\frac{1}{3}} \qquad 2.41$$

N_e is obtained using Equation (2.30) and N is the number of cyclones in parallel. A method for calculating N is given in Chapter 3. Alternatively, N can be guessed.

Next dp_{min} is calculated using Equation (2.40). The right guess of N gives the calculated dp_{min} equal to the one given. Then one proceeds with the calculation of the total efficiency as per Case 1.

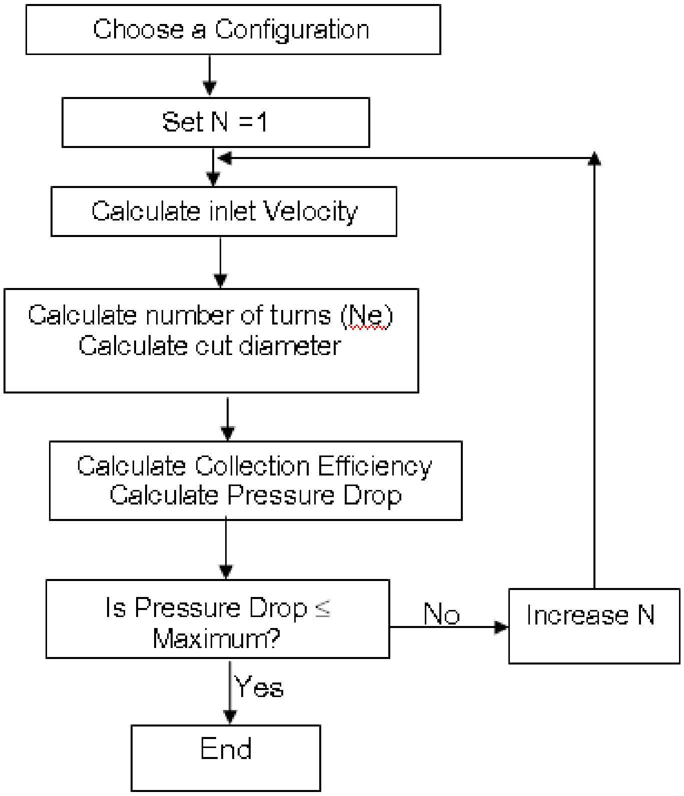


Fig 2.2: Information Flow for Case 1

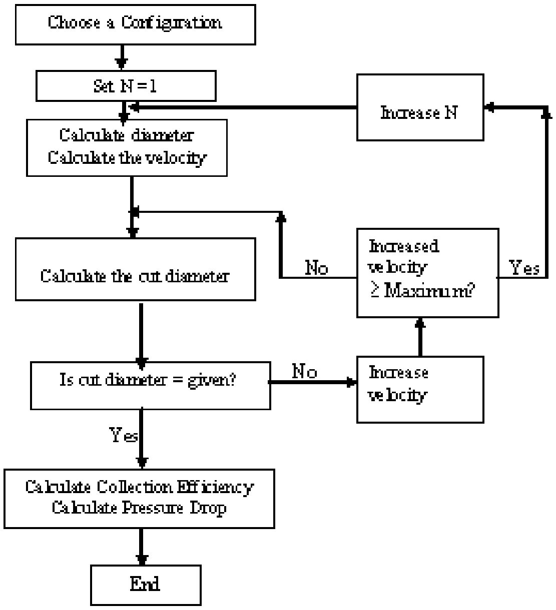


Fig 2.3: Information Flow for Case 2 (Q and d_{pc} specified)

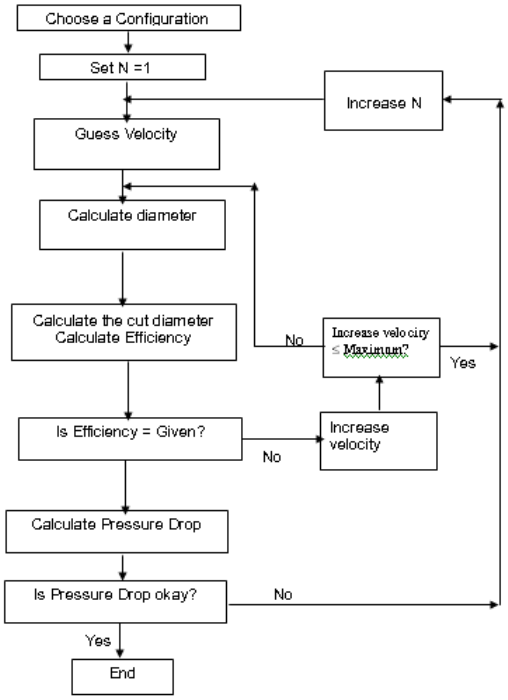


Fig 2.4 Information Flow for Case 3 (Q and Efficiency specified).

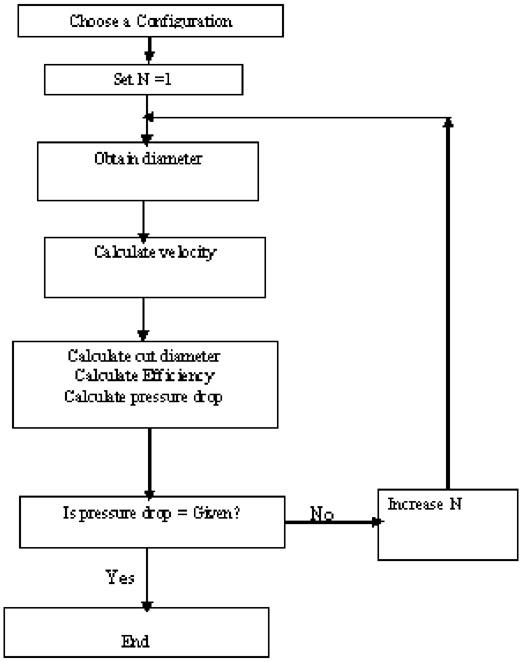


Fig 2.5 Information Flow for Case 4 (Q and ΔP specified)

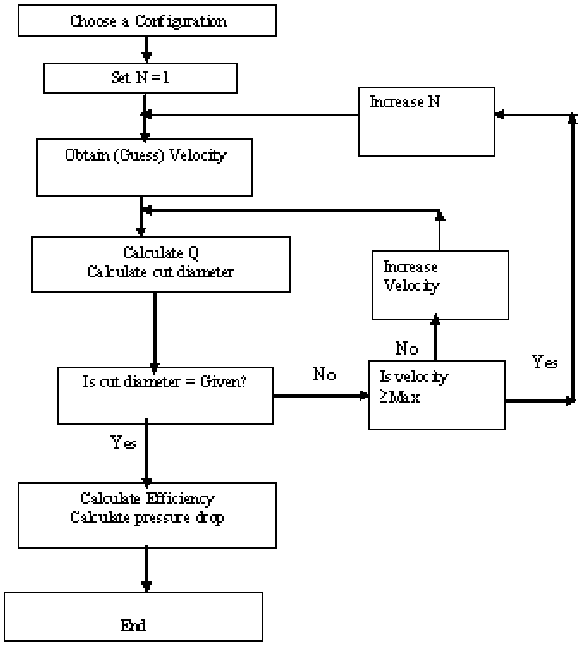


Fig 2.6 Information Flow for Case 5 (D and d_{50} specified).

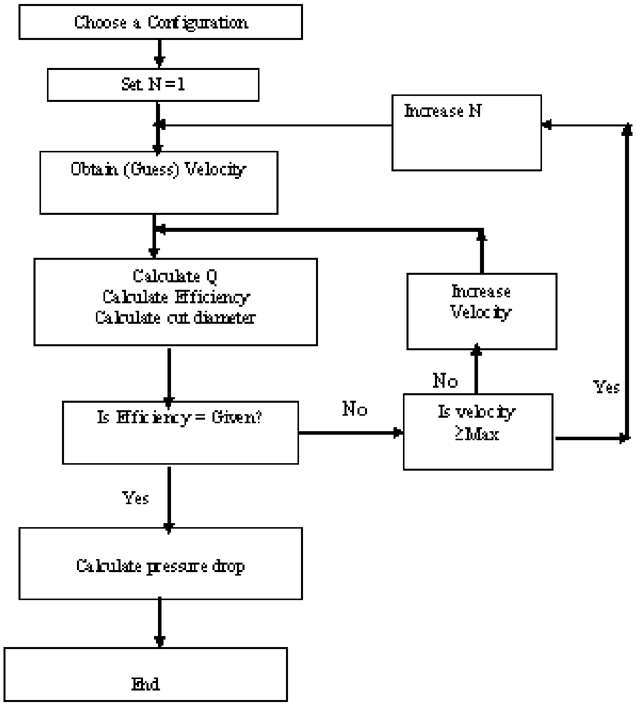


Fig 2.6 Information Flow for Case 6 (D and d_{50} specified)

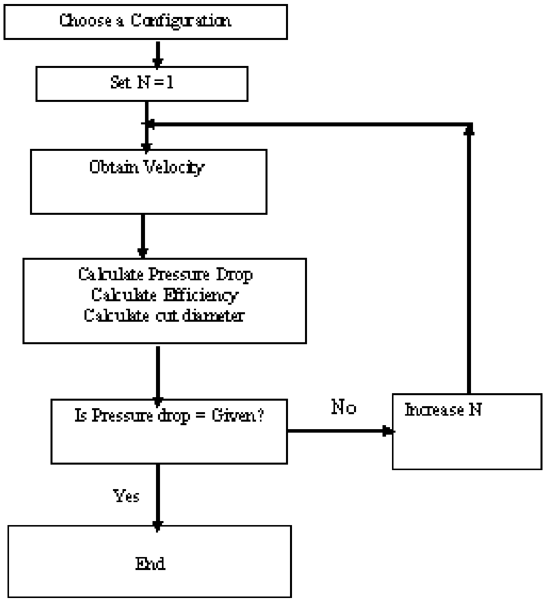


Fig 2.8 Information Flow for Case 7 (D , Q and ΔP specified).

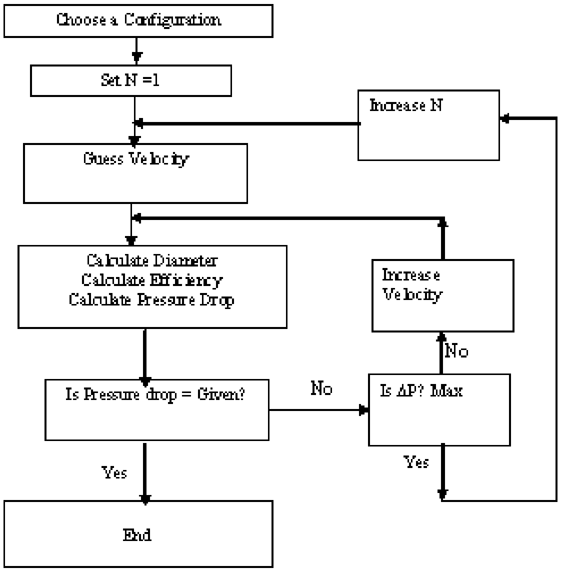


Fig 2.9 Information Flow for Case 8 (Cut Diameter and ΔP specified).

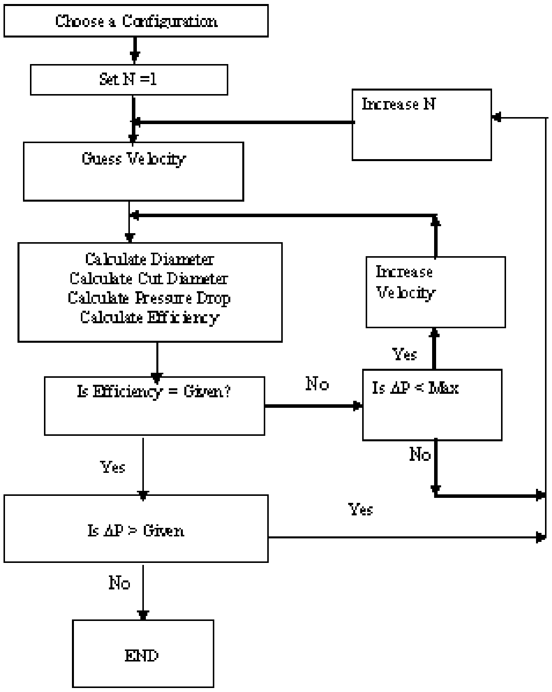


Fig 2.10 Information Flow for Case 8 (Flow Rate, Efficiency and ΔP specified).

3/ Cyclone Optimization

3.1 INTRODUCTION

As shown in Chapter 2, the design calculation involves mainly the computation of pressure drop and collection efficiency. In general, the higher the collection efficiency the higher the pressure drop required; the relationship is not linear. In fact it may be necessary to increase the number of cyclones in order to reduce the pressure drop and increase the overall collection efficiency. Reducing pressure drop means reduction in power consumption while increasing the number of cyclone would imply an increase is the capital cost. Fig. 3.1 shows the variation of the fixed cost as well as the power cost with the number of cyclones. As can be seen there is an optimum number of cyclones that would give a minimum total cost. A mathematical procedure for computing this optimum is presented in this Chapter.

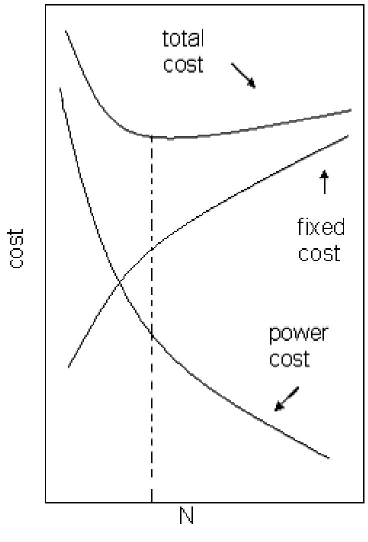


Fig 3.1: Optimization of Cyclone Number

3.2 OPTIMIZATION PROCEDURE

In general, the total cost per unit will be a function of the fixed cost of the cyclones, energy cost of operating the cyclones, and value of the lost participles, that is:

$$C_t = (\text{fixed cost}) + (\text{energy cost}) + (\text{value of lost particle}) \qquad 3.1$$

Assuming that the cost of a cyclone is dependent on its diameter, the fixed cost can be expressed as (Casal, 1995):

$$C_{fixed} = \frac{f}{YH} \text{ Ne } D_c^j \qquad 3.2$$

where f is an investment factor to allow for installation, fittings, piping, etc., H is the time worked per year, Y is the number of years. E and j are constants and can be calculated by using the prices of two cyclones of different diameters.,

The energy cost is given by

$$C_{energy} = Q \,\Delta\, P \,Ce \qquad 3.3$$

Where Ce is the cost per unit of energy. Neglecting the cost of lost particles equation 3.1 becomes

$$C_t = \frac{f}{YH} \text{ Ne } D_c^j + Q \Delta P \,Ce \qquad 3.4$$

The empirical equations given in section 2.5 for calculating pressure drop can be rewritten as

$$\Delta P = \frac{1}{2} \rho_f \; v_i^2 \xi = \frac{1}{2} \rho_f \left(\frac{Q}{ab\,N} \right)^2 \xi \qquad 3.5$$

Substituting Equation (3.5) and (2.41) into equation 3.4 gives

$$C_t = \frac{f\,N\,e}{YH} \left[\frac{d_{pc}^2 \left(\rho_s - \rho_f \right) \pi\, N_t\, N_E\, Q}{9\, b_0^2 \; a_0\, \mu N} \right]^{j/3} + \frac{\rho_f \xi\, Q^3}{2\, a_0^2 \; b_0^2\, N^2} \left[\frac{d_{pc}^2 \left(\rho_s - \rho_f \right) \pi\, N_t\, Q}{9\, b_0^2 \; a_0 \; \mu\, N} \right]^{-4/3} \qquad 3.6$$

$$= \frac{f\,e}{YH}\left[\frac{d_{pc}^{2}\left(\rho_s - \rho_f\right)\pi\, N\;\; Q}{9\, b_0^{2}\;\; a_0\, \mu}\right]^{j/3} N^{1-j/3} + \frac{\rho_f \xi\, Q^{3}}{2\, a_0^{2}\;\, b_0^{2}}\left[\frac{d_{pc}^{2}\left(\rho_s - \rho_f\right)\pi\, N_E\, Q}{9\, b_0^{2}\;\; a_0\, \mu\, N}\right]^{-4/3} N^{-2+4/3} \qquad 3.7$$

Differentating Equation 3.7 with respect to N and equating to zero yields an optimum value for N.

$$\frac{dC_t}{dN} = 0 = \frac{\left(1 - j/3\right)Ne}{YH}\left[\frac{d_{pc}^{2}\left(\rho_s - \rho_f\right)\pi\, N_E\, N_t Q}{9\, b_0^{2}\;\; a_0\, \mu}\right]^{j/3} N^{-j/3}$$

$$- \;\frac{\rho_f\;\; \xi\, Q_3}{3\, a_0^{2}\;\, b_0^{2}}\left[\frac{d_{pc}^{2}\left(p_s - p_f\right)\pi\, N_t\, Q}{9\, b_0^{2}\;\; a_0\, \mu}\right]^{-4j/3} N^{(j-5)/3}$$

$$\Rightarrow \frac{\left(1 - j/3\right)f\,e}{YH}\left[\frac{d_{pc}^{2}\left(\rho_s - \rho_f\right)\pi\, N_t Q}{9\, b_0^{2}\;\; a_0\, \mu}\right]^{j/3}$$

$$= \frac{P_f\;\xi Q^{3}}{3\, a_o^{2}\;\, b_0^{2}}\left[\frac{d_{pc}^{2}\left(\rho_s - \rho_f\right)\pi\, N_t\, Q}{9\, b_0^{2}\;\; a_0\, \mu}\right]^{-4/3} N^{\,(j-5)/3}$$

$$\Rightarrow\; N = \left\{\frac{3\left(1 - j/3\right)Ne\;\; a_0^{2}\;\, b_0^{2}}{p_f\;\xi Q_3\; YH}\left[\frac{d_{pc}^{2}\left(p_s - p_f\right)\pi\, N_t\, Q}{9\, b_0^{2}\;\; a_0\, \mu}\right]^{(4+j/3}\right\}^{3/(j-5)}$$

$$\text{i.e}\;\; N_{opt} = Q\left\{\frac{\left(3 - j\right)N_e\;\; a_0^{2}\;\, b_0^{2}}{P_f\;\; \xi YH}\left[\frac{d_{pc}^{2}\left(p_s - p_f\right)\pi\, N_t}{9\, b_0^{2}\;\; a_0\, \mu}\right]^{\frac{4+j}{3}}\right\}^{\frac{3}{j-5}} \qquad 3.8$$

Equation 3.8, when rounded off to the nearest integer, gives the optimum number of cyclones that would minimize the total cost per unit time.

For correct operation of a cyclone it is generally accepted that:

$$\Delta p \;\leq\; 2500\, \text{N/m}^{2} \qquad 3.9$$

$$15\text{m/s} \;\leq\; v_i \leq\; 30\, \text{m/s} \qquad 3.10$$

$$v_i < 1.35\, vs \qquad 3.11$$

Where v_s is the saltation velocity. Using equations (2.40) (3.9) to (3.11), Casal (1995) showed that the minimum and maximum values of number of cyclones are:

$$N_{\min} \approx \left(\frac{v^1}{15}\right)^3 \frac{1}{d^4_{p_{\min}}} \qquad 3.12$$

$$N_{\max} \approx \left(\frac{v^1}{v_{\max}}\right)^3 \frac{1}{d^4_{p_{\min}}} + 1 \qquad 3.13$$

$$\text{where } v^1 = \left[\frac{81\,Q\,bo\,N^2}{\pi^2\,a_0\,N_t^2\,(\rho_s - \rho_a)^2}\right]^{\frac{1}{3}} \qquad 3.14$$

$$V_{\max} = \sqrt{\frac{2 \text{ x } 2500}{\rho_g\ \xi}} \qquad 3.15$$

The procedure is to calculate Nopt. If Nopt is outside the range $N_{min} < N_{opt} < N_{max}$, then the actual value would be value closet to N_{min} or N_{max}.

4/ Computer Aided Design of Air Cyclone

4.1 INTRODUCTION

The computer aided design of air cyclone involves the following steps:

- Establishing the model equations
- Designing the database to store data
- Designing front-end modules and interfacing with database
- Establishing the design procedure for air cyclones
- Formulating the computational algorithm
- Database Development
- Front end modules development

Design Equations

The equations which are relevant in the computer aided design of cyclone are listed below. It should be noted that these equations have been discussed in Chapters 2 and 3.

Cyclone Natural Length, Distance below gas outlet where vortex turns

$$l = 2.3De\left(\frac{Dc^2}{ab}\right)^{\frac{1}{3}} \text{ natural length of the vortex, } l \qquad 4.1$$

Diameter of Central Core where vortex turns

$$dn = Dc-(Dc-B)\left(\frac{S+l-h}{H-h}\right) \qquad 4.2$$

No of Effective turns

$$N_t = \frac{1}{a}\left(h + \frac{Zc}{2}\right) \qquad 4.3$$

or

$$N_t = v_i\left(0.1079 - 0.00077v_i + 1.924x10^{-6}{v_i}^2\right) \qquad 4.4$$

Cyclone Volume at Natural length

If $l < H - S$, V_{nl}, which is the volume of the region that includes the natural length of the vortex excluding the central core is given by

$$V_{NL} = \frac{\pi Dc^2}{4}(h - S) + \frac{\pi Dc^2}{4}\left(\frac{l + S - h}{3}\right)\left(1 + \frac{d_n}{Dc} + \frac{{d_n}^2}{Dc^2}\right) - \frac{\pi De^2 l}{4} \qquad 4.5$$

where d_n is diameter of central core where vortex turns given by

$$d_n = Dc - (Dc - B)\left(\frac{S + l - h}{H - h}\right) \qquad 4.6$$

Cyclone Volume Below the exit duct
if l >H-B, V_H, which is the volume of gas below the gas exit duct excluding the core is given by

$$V_H = \frac{\pi Dc^2}{4}(h - S) + \frac{\pi Dc^2}{4}\left(\frac{H - h}{3}\right)\left(1 + \frac{B}{Dc} + \frac{B^2}{Dc^2}\right) - \frac{\pi De^2}{4}(H - S) \qquad 4.7$$

Relation between cut diameter, d_{pc}, and cyclone diameter Dc

$$Dc = \left[\frac{{d_{pc}}^2(\rho_p - \rho_f)\pi N_t Q}{9{b_o}^2 a_o \mu N}\right]^{\frac{1}{3}} \qquad 4.8$$

Vortex exponent

$$n = 1 - \left[1 - \frac{(12Dc)^{0.14}}{2.5}\right]\left[\frac{T + 460}{530}\right]^{0.3} \text{ vortex exponent, T in } {}^oF \qquad 4.9$$

Relaxation time for particle species i of diameter d_i

$$\tau_i = \frac{\rho_p {d_{p_i}}^2}{18\mu} \qquad 4.11$$

Cyclone Volume Constant

$$K_c = \frac{(2V_c + V_{NL,H})}{2Dc^3} \qquad 4.12$$

Cyclone Configuration factor

$$(\text{or } K) = \frac{8K_c}{{a_o}^2 {b_o}^2} \qquad 4.13$$

Where $K_c = \dfrac{(2V_c + V_{NL,H})}{2Dc^3}$, is cyclone volume constant 4.14

$V_c = \dfrac{\pi(S - a/2)(Dc^2 - De^2)}{2}$, is the annular volume above the exit duct up to the middle of the gas entrance duct

No of inlet velocity heads

$N_H = 16ab/De^2$	Shephard & Lapple (no inlet vane)
$N_H = 7.5ab/De^2$	Shephard & Lapple (with neutral inlet vane)
$N_H = 11.3(ab/De)^2 + 3.33$	Casal Martinez Equation

Gas Inlet velocity

$$V_i = \frac{Q}{ab} = \frac{Q}{a_o b_o Dc^2} \qquad 4.15$$

Gas Outlet Velocity

$$V_o = \frac{Q}{A_e} = \frac{4Q}{\pi {D_e}^2} \qquad 4.16$$

Cyclone pressure drop

$$\Delta P = \frac{1}{2}\rho {v_i}^2 N_H \qquad 4.17$$

Stairmand Pressure Drop Equation

$$\Delta P = \frac{\rho_f}{203}\left[v_i^{\ 2}\left[1+2\varphi^2\left[\frac{2(D-b)}{De}\right]-1\right]+2v_2^{\ 2}\right] \qquad 4.18$$

where v_i and v_2 are inlet and outlet velocities of gas given by

$$v_1 = \frac{Q}{ab} = \frac{Q}{a_o b_o D^2}$$

$$v_2 = \frac{Q}{A_e} = \frac{4Q}{\pi D_e^{\ 2}}$$

ρ_f is fluid (gas) density,
b inlet duct width,
De is diameter of vortex finder (for simplicity this is assumed as the gas outlet diameter),
D is the cyclone diameter
φ is the friction factor

$$\varphi = \frac{-\sqrt{\frac{De}{2(D-b)}}+\sqrt{\frac{De}{2(D-b)}+\frac{4GA}{ab}}}{2GA/ab} \qquad 4.19$$

where

G is friction constant (0.005 for gas cyclones)
a inlet duct height, b is inlet duct width
ab is cross sectional area if a>b
A is surface area exposed to gas given by $\pi D^2(\alpha_1+\alpha_2)$
where
α_1 is length factor for cylindrical portion of cyclone
α_2 is length factor for vertical cone portion of cyclone

Cyclone Friction loss

$$F = \Delta P + 1 - \left(\frac{4A_c}{\pi De^2}\right) \qquad 4.20$$

where Ac in cross sectional area of cyclone = $\frac{\pi Dc^2}{4}$

Saltation velocity, m/s

$$v_s = 4.91\left(\frac{4g\mu(\rho_p - \rho_f)}{3\rho_f^{\,2}}\right)^{\frac{1}{3}} \frac{b^{0.4}}{(1-b)^{\frac{1}{3}}} Dc^{0.067} v_i^{\frac{2}{3}} \qquad 4.21$$

Optimum Velocity ratio to determine efficiency & entrainment

Vel Ratio= v_i/v_s

Separation Factor

$$S_f = \frac{2v_i^{\,2}}{D_c g} \qquad 4.22$$

Collection Efficiency Model - Lapple

$$d_{p,critical} = \left[\frac{9\mu b}{\pi N_t v_i(\rho_p - \rho_f)}\right]^{\frac{1}{2}} \text{ Lapple Model} \qquad 4.23$$

$$d_{pc,} = \left[\frac{9\mu b}{2\pi N_t v_i(\rho_p - \rho_f)}\right]^{\frac{1}{2}} \qquad 4.24$$

$$\eta_j = \frac{1}{1+\left(\frac{d_{pc}}{d_{pj}}\right)^2} \text{ Lapple Collection efficiency model} \qquad 4.25$$

Collection Efficiency Model – Licht's Model

$$d_{pc,} = \left(\frac{0.693}{A}\right)^{n+1} \qquad 4.26$$

$$A = 2\left[\frac{KQ\rho_p(n+1)}{18\mu Dc^3}\right]^{\frac{1}{2(n+1)}} \qquad 4.27$$

where

K is Configuration factor, n is the vortex exponent

$$\eta_j = 1 - \exp\left[-0.693\left(\frac{d_{pj}}{d_{pc}}\right)^{\frac{1}{(n+1)}}\right] \qquad 4.28$$

Collection Efficiency Model :Leith and Licht Model

$$\eta_i = 1 - \exp\left[-2\left(\frac{G\tau_i Q}{Dc^3}(n+1)\right)^{\frac{1}{2(n+1)}}\right] \text{, grade efficiency} \qquad 4.29$$

where τ_i is called relaxation time for the i^th^ particle species, given by

$$\tau_i = \frac{\rho_p d_{p_i}{}^2}{18\mu} \qquad 4.30$$

Overall Collection efficiency

$$\eta_o = \frac{\sum \eta_j m_j}{M} \qquad 4.31$$

Air Density

$$\rho_g = 335.31T^{(-1.0029)} \text{ for T in range 100K – 3000K} \qquad 4.32$$

where
T is temperature in ^oK.
ρ_g is density in Kg/m^3

Air Viscosity (Dynamic)

$$\mu = \left(1.626263^{-7}T^3 - 4.670448^{-4}T^2 + 7.256015^{-1}T + 4.167699\right)10^{-7} \qquad 4.33$$

for Temperature range 100K - 1000K

$$\mu = \left(4.234403^{-9}T^3 - 2.596779^{-5}T^2 + 3.154121^{-1}T + 1.272374^2\right)10^{-7} \qquad 4.34$$

for Temperature range 1000K - 3000K

where
T is temperature in K. and
μ is dynamic viscosity in Ns/m^2

Particle Collection Probability Distribution Equation

The is given by the integral function

$$P(d) = \int_{d_{50}}^{\infty} \frac{1}{\sqrt{2\pi d}\,\ln(GSD)} \exp\left(- \frac{(\ln(d) - \ln(MMD))^2}{2(\ln(GSD))^2} \right) dd \qquad 4.35$$

where

P(d) is the particle collection probability at any point (P(r,z) in the outer vortex (r is radial point, z is axial point

d_{50} is the critical separation diameter with 50% collection probability at the point P(r,z)

d is the particle diameter

MMD is the mass median diameter of the inlet particle size distribution

GSD is the geometric standard deviation of the inlet particle size distribution.

To obtain the inlet particle size distribution and plot the values, we perform numerical integration on the above equation using a practical integration interval of d.

Optimum Number of Cyclones in Parallel

$$N_o = Q\left(\frac{fe(3-j)a_o^{\ 2}b_o^{\ 2}}{C_e YH\rho N_H} \left(\frac{d_{pc}^{\ 2}(\rho_p - \rho_f)\pi N_t}{9b_o^{\ 2}a_o\mu} \right)^{(4+j)/3} \right)^{3/j-5} \qquad (4.36)$$

Where

N_o = Optimum number of cyclones in parallel
f =investment factor
e =\$/m^j
j = capital cost exponent of cyclone diameter
Y =no of years over which depreciation occurs
H = time worked by cyclone per year, seconds/year

For our purposes we use j=2, f=2.5, 3900, Y=10, H=3.2x10^6

4.2 SOFTWARE DESIGN COMPUTATIONAL ALGORITHM

The computational algorithm implemented is described in this section.

Design parameters

Given the cyclone geometry and the operating conditions (operating temperature, operating pressure, particle density), there are 5 design parameters that can be specified for a design. These parameters are:

1. Feed Rate, Q
2. Cyclone Diameter, Dc
3. Set Cut Size, d_{pc}
4. Cyclone Efficiency, η
5. Cyclone Pressure Drop, ΔP

Of the five variables listed above, it is required to specify two or three and the others can be calculated. Depending on the design problem and available information, Table 2.6 indicates that there are 9 possible combinations of these design parameters. The 9 combinations are summarized in Table 4.1 and the details of the computations are shown below.

Table 4.1 Summary of design parameters

Case	**Design Parameters**	**Values to derive from parameters**
1	Q, Dc	Compute Vi from Q/(ab)
2	Q, d_{pc}	Compute Dc from dpc, Compute Vi from Q/(ab)
3	Q, η	Compute dpc from η, Dc from dpc, Vi from Q/(ab)
4	Q, ΔP	Compute Vi from ΔP, Dc from Q and Vi
5	Dc, dpc	Compute Q from dpc and Dc, Vi from Q/(ab)
6	Dc, η	Compute dpc from η, Q from dpc and Dc, Vi from Q/(ab)
7	Dc, Q, ΔP	Compute Vi from Q & Dc, Use ΔP as design validation
8	d_{pc}, ΔP	Compute Vi from ΔP, Dc from dpc and Vi (Q)
9	η, Q, ΔP	Compute dpc from η, Dc from dpc, Vi from Q/(ab)

- Note that ab is ($a_o b_o Dc^2$) where, a_o and b_o are inlet height and inlet width configuration ratios in the geometry.

4.21 Inputs

1. Select Unit Operation: i.e. Select Cyclone>Gas Cyclone
2. Selection of Cyclone Design Profiles
3. Operating Temperature, T
4. Operating Pressure, P
5. Cyclone Geometry
    - To retrieve cyclone dimensional ratios (De_o, h_o, H_o, a_o, b_o, B_o, S_o)
6. Efficiency Model Equations
7. Design Parameters

    - Design Check / Performance Calculation
    - Design Parameters combinations
    - Design Parameters
        - Feed Rate, Q
        - Cyclone Diameter, Dc
        - Set Cut Size, d_{pc}
        - Cyclone Efficiency, η
        - Cyclone Pressure Drop, ΔP

8. Dust/Particle Specification
    - Particle Density
    - Max Particle Size
    - Min Particle Size
    - Mass Median Diameter of dust particles
    - Geometric Standard Deviation of dust particles
    - Particle Size Distribution Data
9. No of cyclone in series or parallel

4.22 Outputs

- Cyclone Dimensions – Dc, De, h, H, a, b, B.
- D_o, diameter of central core where vortex turns
- Pressure Drop, ΔP
- Separation factor, S_f
- Velocity Ratio, v_i/v_s
- Collection Efficiency, %
- No of Cyclones
- Cyclones Arrangement (Series, Parallel)
- % removal of particles
- Overall Collection efficiency
- Outlet velocity
- Ratio Set cut size /d_{pc}

4.23 Design Constraints

- $\Delta P<10$ in H_2O ($<2490 N/m^2$)
- $a<S$
- $b<0.5(Dc-De)$
- $H>= S+1$
- $S<h$
- V_i range 9-27m/s
- $V_i/V_s <1.35$
- V_i/V_s @ 1.25
- Scss/d_{pc} : If > 1 separation is better than required.

4.24 Computational Algorithm

1. Select the geometric configuration for the Gas Cyclone design required
2. Select Efficiency Model
3. Get the cyclone dimensional ratios based on step 1.
4. Specify Operating Temperature
    a. Compute Fluid Density and Fluid Viscosity
5. Specify Operating Pressure.
6. Specify inlet feed rate Q.
7. Select Particles Category and extract particle density
8. Specify particle distribution (D_{min} and D_{max}).
9. Select design computation option, Design Check OR Performance Check
10. Specify Set Cut Size, scss
11. Specify Number of Cyclones in parallel (Feed to each = Q/No of Cyclones) Or Specify Number of Cyclones in series
12. If Design Check is selected, specify one of the design parameter combinations listed in Table 3.2
    a. Compute cyclone dimensions: De, a, b, h, H, S,B, Shift
13. If Performance Check Option is selected
    b. Specify Cyclone Diameter, Dc
    c. Compute cyclone dimensions: De, a, b, h, H, B, Shift
14. Compute the following in the order given
    d. Natural Lengths ()
    e. Diameter of Central Core at Vortex()
    f. Cyclone Volume At Natural Length()
    g. Cyclone Volume Below Exit Duct()
    h. Vortex Exponent()
    i. Relaxation Time()
    j. Cyclone Volume Constant()
    k. Cyclone Configuration Factor()
    l. Cyclone Grade Efficiency() based on model selected
    m. No Inlet Velocity Heads()
    n. Cyclone Surface Area()
    o. If Performance Check option, Compute Inlet Velocity()
    For each cyclone in series
    p. Pressure Drop()
    q. Friction Loss()
    r. Saltation Velocity()
    s. Velocity Ratio()
    t. Critical Particle Diameter()=Dp based on model selected

    u. CriticalParticleDiameterAt50PercentEfficiency()=D50 based on model selected()
    v. Ratio_scss_vs_Dp()
    w. Ratio_scss_vs_D50()
    x. Separation Factor()
    y. Collection Efficiency()
    z. Compute Overall Collection Efficiency() based on model selected
    aa. Compute Outlet Velocity()
    bb. Set inlet velocity to the outlet velocity
    Return to step r

15. If Overall Collection Efficiency not satisfactory Iterate from step 11.
16. Check Design through constraints.
17. If 13 not satisfied iterate from step 11.
18. **Save** the Design.

5/ *Case Studies*

The case studies presented in this Chapter are grouped into design calculations and performance evaluations. Three (3) cyclone configurations are evaluated and results analysed. The configurations are Stairmand HE, Stairmand HT and Shephard & Lapple ME configurations with the ratios given below.

Stairmand HE (High Efficiency)

Dimension	a	b	De	S	H	Zc	H	B
Ratio of Dc	0.5	0.2	0.5	0.5	1.5	2.5	4	0.375

Stairmand HT (High Throughput)

Dimension	a	b	De	S	h	Zc	H	B
Ratio of Dc	0.75	0.375	0.75	0.875	1.5	2.5	4	0.375

Shephard & Lapple ME (Medium Efficiency)

Dimension	a	b	De	S	h	Zc	H	B
Ratio of Dc	0.5	0.25	0.5	0.625	2.0	2.0	4	0.25

CASE STUDY 5.1 DESIGN CALCULATIONS

A cyclone is required to remove carbon dust particles from effluent air coming from a thermal power station at a rate of $5m^3/s$ at 65^oC. The dust particles are assumed to have normal size distribution with mass median diameter of 20µm and geometric standard deviation of 1.5µm. For energy cost considerations the pressure drop in the cyclone is required to be not more than $1000\ N/m^2$. The density of the dust particles is $2250Kg/m^3$ and cyclone operating at atmospheric pressure. What is the size, the efficiency and cut size of the cyclone that you recommend from the 3 configurations, Stairmand HE, Stairmand HT and Shephard & Lapple ME.

Solution: Note that the Lapple Efficiency model is used to estimate overall cyclone efficiency

S\N	**Configuration**	**D_c, m**	**d_{50} µm**	**Eff$_{overall}$, %**
1	Stairmand HE	1.586	6.137	90.43
2	Stairmand HT	0.841	6.668	89.00
3	Shephard & Lapple ME	1.445	6.386	89.76

From the results table the Stairmand HT configuration is recommended. It is much smaller in size in terms of diameter (i.e. cost of construction) and the efficiency\cut size is comparable with the other configurations. The output generated by the developed software is shown in Table 5.1

Table 5.1 Output generated by software for Case Study 5.1

Cyclone Configuration	Stairmand HE	Stairmand HT	Shephard and Lapple ME
Temp ^{o}C	65	65	65
Opt Pressure N/m^2	101325	101325	101325
Viscosity Ns/m^2	2.03859E-05	2.03859E-05	2.03859E-05
Density fluid kg/m^3	1.023705	1.023705	1.023705
Density particle kg/m^3	2250	2250	2250
Feed Rate SI per cyclone m^3/s	5	5	5
Feed Rate Total m^3/s	5	5	5
No of Cyclones in series	1	1	1
No of Cyclones in parallel	1	1	1
Set Cut size µm (microns)	0	0	0
Design Pressure N/m^2	1000	1000	1000
Design Efficiency %	0	0	0
MMD, µm (microns)	20	20	20
GSD µm (microns)	1.5	1.5	1.5
Gas	Air	Air	Air
Efficiency Model	Lapple	Lapple	Lapple
Cyclone Diameter ft	5.205	2.761	4.742
Cyclone Diameter m	1.586484	0.8415528	1.4453616
Cyclone Natural Length , l	12.89590745	7.269278854	10.9066
Diameter of Central Core where vortex turns, d_n	3.282273139	1.375086536	3.09711875
No of effective turns, N_t	3.2	2.25	4.25
Cyclone Volume at Natural Length, V_{NL}	152.7918482	5.168225545	120.7009904
Cyclone Volume at exit duct, V_H	153.726262	2.152424272	117.7706482
Vortex Exponent, n	0.713889243	0.653343656	0.70465267
Relaxation Time, τ s	0	0	0

Cyclone Volume Constant , Kc	0.689023466	0.294581498	0.786866853
Cyclone Configuration Factor G	551.2187727	29.79273622	402.8758289
No Inlet Velocity Heads (CasalMartinez Eqn) N_H	5.138	6.155	6.155
Cyclone Surface Area , ft^2	275.0930262	77.40534067	231.1305987
Inlet velocity ft/s	65.166	82.34	62.813
Inlet velocity m/s	19.86251113	25.09714554	19.14526492
No of Cyclones in series	1	1	1
Cyclone Model	1	1	1
DeltaP, ΔP N/m^2	1000.030641	1000.107213	1000.031457
Outlet velocity ft/s	33.19354531	52.42999025	39.99189735
Outlet velocity m/s	10.11739537	15.98066539	12.18953364
Friction Loss, F	-2669.322747	-523.2479861	-2735.351957
Saltation Velocity, vs	17.44909894	27.28903727	18.90256053
Velocity Ratio, vi/vs	1.138311565	0.919678671	1.012839763
Critical Particle Diameter, µm (microns)	8.678547967	9.430207976	9.031584844
Critical Particle Diameter at 50%, µm (microns)	6.136660119	6.668164008	6.386294888
Separation factor , S_f	50.67520547	152.5209293	51.6787079
Grade Efficiency, fractional	0.745964109	0.64436674	0.749352792
Overall Collection Efficiency %	90.43493859	89.00407959	89.76894458

CASE STUDY 5.2 PERFORMANCE EVALUATIONS

From 3 cyclone configurations (Stairmand HE, Stairmand HT and Shephard & Lapple ME) available, each with diameter of 1.25m, select the best one to use to remove alumina dust particles of density 3980 kg/m^3 from air coming at a throughput of 12m^3/s with normal size distribution of particles with mass median diameter of 25µm and geometric standard deviation of 2.0µm. The major economic factors for selection are the energy cost of pumping the gas through the cyclone (directly related to cyclone pressure drop) followed by the effectiveness of the cut (d_{50}). The fluid is delivered at 32 ^{o}C at atmospheric pressure.

Solution: Note that the Lapple Efficiency model is used to estimate overall cyclone efficiency

S\N	**Configuration**	**ΔP, N/m^2**	**d_{50} µm**	**Eff$_{overall}$, %**
1	Stairmand HE	15801.8	2.036	98.94
2	Stairmand HT	1251.275	8.107	93.41
3	Shephard & Lapple ME	10885.13	2.439	98.52

From the above table Stairmand HT configuration is the best since the pressure drop is lowest and within acceptable design limits. The cut size is however higher and hence low efficiency. The output generated by software for Case Study 5.2 is shown in Table 5.2.

Table 5.2 Output generated by software for Case Study 5.2

Cyclone Configuration	Stairmand HE	Stairmand HT	Shephard and Lapple ME
Temp ^{o}C	32	32	32
Opt Pressure N/m^2	101325	101325	101325
Viscosity Ns/m^2	1.95257E-05	1.95257E-05	1.95257E-05
Density fluid kg/m^3	1.081996	1.081996	1.081996
Density particle kg/m^3	3980	3980	3980
Feed Rate SI per cyclone m^3/s	12	12	12
Feed Rate Total m^3/s	12	12	12
No of Cyclones in series	1	1	1
No of Cyclones in parallel	1	1	1
Set Cut size µm (microns)	0	0	0
Design Pressure N/m^2	0	0	0
Design Efficiency %	0	0	0
MMD, µm (microns)	25	25	25
GSD µm (microns)	2	2	2
Gas	Air	Air	Air
Efficiency Model	Lapple	Lapple	Lapple
Cyclone Diameter ft	4.101	4.101	4.101
Cyclone Diameter m	1.2499848	1.2499848	1.2499848
Cyclone Natural Length , *l*	10.16063716	10.79728815	9.4323
Diameter of Central Core where vortex turns, d_n	2.586090709	2.042459212	2.678465625
No of effective turns, N_t	3.2	2.25	4.25
Cyclone Volume at Natural Length, V_{NL}	74.73211793	16.93602735	78.07203375
Cyclone Volume at exit duct, V_H	75.18914968	7.053391152	76.17662444
Vortex Exponent, n	0.693755243	0.693755243	0.693755243
Relaxation Time, τ s	0	0	0
Cyclone Volume Constant , Kc	0.689023466	0.294581498	0.786866853
Cyclone Configuration Factor G	551.2187727	29.79273622	402.8758289
No Inlet Velocity Heads (CasalMartinez Eqn) N_H	5.138	6.155	6.155

Cyclone Surface Area , ft^2	170.7723881	170.7723881	172.8677119
Inlet velocity ft/s	251.969	89.59	201.575
Inlet velocity m/s	76.8	27.307	61.44
No of Cyclones in series	1	1	1
Cyclone Model	1	1	1
DeltaP, ΔP N/m^2	15801.82121	1251.275272	10885.13074
Outlet velocity ft/s	128.3295914	57.03537395	128.3295914
Outlet velocity m/s	39.11487013	17.38438672	39.11487013
Friction Loss, F	-2609.877805	-522.239279	-2695.652763
Saltation Velocity, vs	48.60780094	34.06054969	46.79572837
Velocity Ratio, vi/vs	1.579993304	0.801719298	1.31294035
Critical Particle Diameter, µm (microns)	2.882481556	8.106933125	3.449709185
Critical Particle Diameter at 50%, µm (microns)	2.038222255	5.732467387	2.439312758
Separation factor , S_f	961.5648503	121.563565	615.400283
Grade Efficiency, fractional	0.743149794	0.652731547	0.747846743
Overall Collection Efficiency %	98.94249565	93.40069186	98.51885428

List Of Notations

a	Inlet height, m
a_o	Inlet height in ratio of Dc
A	Surface area of cyclone exposed to gas, m^2
Ac	Cross sectional area of cyclone, m^2
b	Inlet width, m
b_o	Inlet width, in ratio of Dc
B	Dust outlet diameter, m
B_o	Dust outlet diameter, in ratio of Dc
C_{fixed}	Fixed cost of cyclone
C_{power}	Power cost of running cyclone
d	Particle diameter, m
d_n	Diameter of core where vortex turns, m
d_{pc}	Cut size (critical diameter at 50% efficiency), microns (d_{50})
$d_{p,critical}$	Critical particle size diameter, microns
d_1	Original particle size, microns
d_2	New particle size, microns
Dc	Cyclone diameter, m (D)
De	Gas outlet diameter, m
De_o	Gas outlet diameter, in ratio of Dc
Do	Diameter of core where vortex turns, m
e	$/m^j$
E_{d1}	Original efficiency at particle size $d_{1,}$ %
E_{d2}	New efficiency at particle side $d_{2,}$ %
E_T	Total collection efficiency, %
f	Investment factor
G	Friction constant (0.005 for gas cyclones)
GSD	Geometric standard deviation of the inlet particle size distribution.
h	Cylindrical height of cyclone, m
h_o	Cylindrical height of cyclone, in ratio of Dc
H	Total height of cyclone (h+Zc), m
H’	Time worked by cyclone per year, seconds/year

H_o	Total height of cyclone (h+Zc), in ratio of Dc
Hpd	Hopper diameter, m
Hpd_o	Hopper diameter, in ratio of Dc
j	Capital cost exponent of cyclone diameter
K	Cyclone Configuration factor
K_c	Cyclone Volume Constant
K_s	Cyclone Shift Constant
l	Cyclone natural length, m
m_j	Mass of particle in j^{th} size range
M	Total mass of particle, kg
MMD	Mass median diameter of the inlet particle size distribution
n	Vortex exponent
N	No of cyclones in parallel
N_H	No of inlet velocity heads
N_o	Optimum number of cyclones in parallel
N_t	No of effective turns made by gas stream
P	Operating pressure, N/m^2
P(d)	Particle collection probability at any point (P(r,z)
PM	Particulate matters
P_1	Absolute pressure at cyclone inlet, N/m^2
P_2	Absolute pressure at cyclone outlet, N/m^2
Q	Feed rate, m^3/s
Q_1	Original cyclone flow rate, m^3/s
Q_2	New cyclone flow rate, m^3/s
r	Radial point
S	Gas outlet length or vortex finder, m
SCC	Sharp-cut cyclone
S_f	Separation factor
S_o	Gas outlet length, in ratio of Dc
T	Operating temperature, ^oC or ^oF
V_H	Volume of gas below the gas exit duct excluding the core, m^3
V_i, v_i	Inlet velocity, m/s
V_s, v_s	Saltation velocity, m/s
VSCC	Very sharp-cut cyclone
V_o, v_o	Outlet velocity, m/s
W	Dust loading, grain/acf [g/m^3]
Y	No of years over which depreciation occurs
z	Axial point
Zc	Conical height of cyclone, m
Zc_o	Conical height of cyclone, in ratio of Dc
z_o	Vortex length also known as the cyclone effective length, m
α_1	Length factor for cylindrical portion of cyclone

α_2	Length factor for vertical cone portion of cyclone
ΔP	Pressure drop, N/m^2
ΔP_1	Original cyclone pressure drop, N/m^2
ΔP_2	New cyclone pressure drop, N/m^2
ρ_f	Fluid density, kg/m^3
ρ_g	Gas density, kg/m^3
ρ_{g1}	Original gas density, kg/m^3
ρ_{g2}	New gas density, kg/m^3
ρ_p	Particle density, kg/m^3
μ_p	Fluid viscosity kg/ms
η	Collection efficiency, %
η_j	Collection efficiency of jth particle size range, %
η_o	Overall collection efficiency, %
φ	Friction factor
Dc	Cyclone diameter, m
a	Inlet height, m
b	Inlet Width, m
De	Gas Outlet Diameter, m
h	Cylindrical height of cyclone, m
Zc	Conical height of cyclone, m
H	Total height of cyclone (h+Zc), m
d_n	Diameter of core where vortex turns, m
Hpd	Hopper diameter, m
a_o	Inlet height in ratio of Dc
b_o	Inlet Width, in ratio of Dc
De_o	Gas Outlet Diameter, in ratio of Dc
S_o	Gas Outlet Length, in ratio of Dc
h_o	Cylindrical height of cyclone, in ratio of Dc
Zc_o	Conical height of cyclone, in ratio of Dc
H_o	Total height of cyclone (h+Zc), in ratio of Dc
B_o	Dust Outlet diameter, in ratio of Dc
Do	Diameter of core where vortex turns, m
P	Operating Pressure, N/m^2
Q	Feed rate, m^3/s
T	Operating Temperature, ^oC or ^oF
ρ_f	fluid density, kg/m^3
ρ_g	gas density, kg/m^3
ρ_p	particle density, kg/m^3
μ_p	fluid viscosity kg/ms
d_{pc}	cut size (critical diameter at 50% efficiency), microns (10^{-6} m=μm)
$d_{p,critical}$	Critical particle size diameter, microns (10^{-6} m= μm)
η	Collection efficiency, %

η_j	Collection efficiency of jth particle size range
η_o	Overall Collection efficiency
V_i, v_i	Inlet velocity, m/s
V_s, v_s	Saltation velocity, m/s
V_o, v_o	Outlet velocity, m/s
N_t	No of effective turns made by gas stream
N_H	No of inlet velocity heads
N	No of cyclones in parallel
L	Cyclone Natural length, m
m_j	mass of particle in j^{th} size range
M	total mass of particles
n	vortex exponent
S_f	separation factor

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