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Revision Memo

12/02 Corrections and minor updates. Added expansion angle criterion for cyclone design.



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SCOPE

This section discusses removal and collection of particulate matter from gases. Cyclones are the principal solid, gas separation devices described. References are given to descriptions of other solid, gas separation systems such as bag filters, scrubbers and electrostatic precipitators.

This section also describes the methods used to estimate solids losses in the gases from a fluid solids process by means of attrition, entrainment and loss through multistage cyclone systems.

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1. Design Practices, Section XVIII A-3, Cyclones.
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4. Danielson, A. M., *Improved Reactor Trickle Valve Design for Fluid Catalytic Cracking Units*, EE.13E.88 (February 1988).
5. Davuluri, R.P., Lathrop, B. H., Melfi, G., FCCU Primary Cyclone Design Criterion: Cold Flow Modeling of High Loading Cyclone, EE.71E.2001, (December 2001)

ADDITIONAL REFERENCE

1. Skouby, D. C., Rossetti, S. J., and Hoke, R. C., *Improved Cyclone Performance Correlation*, EE.76E.93 (November 1993).

CYCLONES

Cyclone design is also described in Design Practices [Section XVIII^{\(1\)}](#). A cyclone is a static device which separates solids from a gas (or from a liquid) by centrifugal force. A typical cyclone is shown in [Figure 1](#). Gas and suspended solids enter the cyclone at a relatively high velocity through a tangential inlet section. The tangential entry generates an inlet vortex as shown in [Figure 1](#). The centrifugal forces tend to drive the solids to the wall of the cyclone where they are separated from the vortex by impact with the wall. The solids then drop to the bottom of the conical section of the cyclone from where they are discharged through a solids outlet line. The cleaned gas forms a second (outlet) vortex which passes out through the gas outlet tube at the top of the cyclone.

The tangential inlet, axial dust outlet is the most common configuration used in Exxon installations. A variation of the standard tangential inlet design is the scroll or wrap-around inlet as shown in [Figure 2A](#). This variation is widely used in Exxon installations including most primary cyclones. Scroll inlets are discussed in more detail in a subsequent paragraph. In addition to cyclones with a tangential inlet and axial dust outlet, cyclones are also built with an axial inlet and outlet ([Figure 2B](#)). In this case, the vortex is generated by inlet vanes. Clusters of small axial inlet cyclones, called multiclones, are used in some installations.

CYCLONE APPLICATIONS

Cyclones should be given first consideration for particulate removal due to their low cost and compact size. However, cyclones have certain disadvantages, such as lower collection efficiency, compared to some other devices. Following is a listing of their advantages and disadvantages.

Advantages

- Compactness. Cyclones have a high capacity to size ratio. They are small enough to be placed inside process vessels and can be used for internal recycle of collected solids.
- Low installation and maintenance cost.
- Ease of staging. The above advantages permit staging of cyclones to improve collection efficiency.
- Operation at high inlet dust loading.
- Operation at high pressure and high temperature, limited only by materials considerations.
- Available in a wide range of efficiencies and gas handling capacities.
- Mechanical reliability.
- Flexibility. The outlet area can be decreased to increase efficiency at the price of increased pressure drop. The outlet area can be increased to increase capacity without increasing pressure drop or lowering efficiency.

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Disadvantages

- Low collection efficiency for particles less than 5 μm .
- High pressure drop (although not as high as certain wet scrubbers).
- Tendency to foul and plug when handling solids which are "sticky" or not free flowing.
- Dependence of performance on inlet velocity. Collection efficiency decreases at inlet velocities less than 40 ft/s (12 m/s) due to low centrifugal forces, and greater than 120 ft/s (35 m/s) due to re-entrainment of collected dust. In addition, cyclones are prone to erosion at higher inlet velocities and the upper acceptable inlet velocity is a function of the inlet dust loading and particle size. Particle attrition will also occur at higher velocities. These items are discussed further in subsequent paragraphs.

Multiclones

Multiclones, described previously and shown in [Figure 2B](#), have been used in a small number of Exxon installations. The primary advantage of multiclones compared to the standard tangential inlet cyclones is higher efficiency. This is due to the smaller diameter of the individual multiclones. The higher efficiency can also be traded for lower pressure drop at the same efficiency.

The main disadvantage of multiclones is more costly installation and maintenance. This is due to the need to use a much larger number of individual multiclone units for the same throughput. Smaller clearances in some models can also lead to plugging problems. The efficiency advantage may also be decreased by gas recirculation as noted later.

A proprietary small cyclone system developed by Polutrol in Europe, claims the advantages of small cyclones without all the disadvantages described above. It is currently used in some Non-Exxon FCC installations in place of conventional third stage cyclone systems. When used in conjunction with a turbo expander, Polutrol claims improved blade life and longer expander run lengths. One significant advantage of the Polutrol system is compactness. A smaller diameter tertiary cyclone vessel is possible and expansion can occur by increasing the vessel straight side instead of diameter.

TYPICAL CYCLONE INSTALLATIONS

Cyclones are currently used within Exxon, where they are installed inside process vessels to retain and return collected solids. They are also used in external tertiary collection systems, in solids transfer systems and in cleanup of incinerator stack gas.

[Figure 3](#) shows a typical two-stage cyclone system installed within a process vessel. The cyclones return solids back to the fluid bed through diplegs immersed in the fluid bed or a little above it.

[Figure 4](#) shows a cyclone installation used in a solids transfer system.

CYCLONE DESIGN CONSIDERATIONS

The design of a cyclone system consists in the specification of a number of design parameters. This includes gas inlet and outlet conditions, cyclone size and shape, the number of cyclones and number of stages. These parameters can be specified by the designer, within certain limitations. Specification guidelines are given below. The design is also influenced by certain fixed conditions such as gas and solid properties, required collection efficiency and possibly, required pressure drop. The fixed conditions are usually specified in the DBS. The effects of the fixed conditions on cyclone design are also described below. Subsequent paragraphs detail certain calculation procedures, and treat dipleg design and cyclone layout and placement.

Vendor contacts should be made early in the design of a cyclone system to allow inclusion of any desirable design features suggested by the vendor.

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DESIGN PARAMETERS

Certain key dimensions must be specified in designing a cyclone. Experience has indicated that the optimum cyclone geometry is fairly consistent. A generalized picture of the geometry can be given by relating the key dimensions to the cyclone diameter. This is shown in the following table:

CYCLONE GEOMETRY		
Inlet	width (w_i/d_b)	0.2 - 0.3
	height (h_i/d_b)	0.5 - 0.8
	area (A_i/d_b^2)	0.09 - 0.23
	height/width (h_i/w_i)	2/1 - 3/1
Outlet	Diameter (d_o/d_b)	0.4 - 0.6
	area (A_o/d_b^2)	0.13 - 0.25
Outlet/Inlet Area		0.5 - 1.5 ⁽¹⁾
Minimum Expansion Angle α (for FCC primary cyclones)		16°
Minimum Expansion Angle α (for FCC secondary cyclones)		1°
Length (ℓ/d_b)		3 - 5

Note:

(1) Lower ratios have been used, but are not common due to outlet velocity limitations.

where: d_b = The cyclone barrel diameter
 w_i = The inlet width
 h_i = The inlet height
 A_i = The inlet area
 d_o = The outlet tube diameter
 A_o = The outlet area
 α = Expansion Angle (see [Figure 1](#))
 ℓ = The cyclone length

Additional discussion of the specification of these dimensions is given in the following paragraphs. The exact dimensions are obtained from vendors' specifications modified as needed to conform to Exxon design practice. However, it is suggested that the vendors be guided by specifying cyclone efficiency, inlet area, length, diameter, and other basic dimensions in a request for bid, to assure that the cyclone designs provided by the vendors will meet performance requirements. Preliminary specifications for Ducon, Van Tongeren, Emtrol and General Electric cyclones are given in [Figures 5 through 8](#). Vendors should also be contacted to confirm that the preliminary specifications shown in the figures are up to date.

Inlet Conditions

Inlet conditions to be specified in the design include inlet velocity, area of the inlet section (height, width) and inlet configuration (tangential vs. scroll).

- **Inlet Velocity.** Increasing inlet velocity increases collection efficiency up to a maximum value. At higher velocities, efficiency decreases due to turbulence-induced re-entrainment. Erosion of the cyclone body will also occur at high velocity. The extent of erosion is also dependent on the inlet particulate size, hardness and loading and the internal configuration of the cyclone. The following table gives ranges of inlet velocities used in various applications. Consult process documents for specific acceptable ranges. The limits on the velocities have generally been set based on a balance between collection efficiency and erosion concerns.

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ALLOWABLE CYCLONE INLET VELOCITIES		
ft/s (m/s)		
PRIMARY STAGE	SECONDARY STAGE	TERTIARY STAGE
55 - 75 (17 - 23)	55 - 85 (17 - 26)	90 - 120 (27 - 37)

In special cases, lower inlet velocities can be used, but the outlet area must be decreased to maintain collection efficiency.

- **Inlet Shape.** The inlet to the cyclone has a rectangular cross section with a height to width ratio in the range of 2/1 to 3/1. This range of ratios minimizes the width, thereby minimizing the lateral distance particles must travel before impacting on the wall and being collected. The narrow width also minimizes the distance between the outlet gas tube OD and the cyclone wall needed to prevent impact of inlet solids on the outlet gas tube and subsequent outlet tube erosion. See [Figure 9](#).
- **Inlet Configuration.** Two types of inlet configurations, the tangential and scroll (or volute) are used depending on the size of the outlet tube diameter. The two types of inlet configurations are shown in [Figure 9](#). The scroll inlet prevents impact of inlet solids on the outlet gas tube in those cases where a large outlet tube diameter is required, for example, to reduce pressure drop through the cyclones.

Tangential inlet configurations are used when scroll inlets are not required.

Gas Outlet Conditions

The gas outlet conditions to be specified in the design are outlet tube diameter (or outlet to inlet area ratio) and outlet tube insertion length.

- **Gas Outlet Tube Diameter.** Decreasing the gas outlet tube diameter increases the collection efficiency but also increases the pressure drop through the cyclone. The increased efficiency is due primarily to a higher outlet vortex velocity. The outlet tube diameter is often specified by specifying the outlet to inlet area ratio, A_o/A_i . Outlet to inlet area ratios for various applications are given in the following table. Consult process documents for specific ratios.

GAS OUTLET TO INLET AREA RATIO (A_o/A_i)		
PRIMARY STAGE	SECONDARY STAGE	TERTIARY STAGE
0.85 - 1.5	0.5 - 1.0	0.5 - 0.7

Outlet tube diameter should be 24 in. (0.6 m) or more to permit inspection. Removable inserts have been used in some cases to reduce the diameter and still permit inspection. However, removal is difficult and some compromises are usually made during inspection to avoid insert removal. Removable inserts can also be used when expansion of the cyclone capacity is expected.

- **Outlet Tube Insertion.** The outlet tube should extend into the cyclone from 0.8 to 1.0 the inlet height (h_i). Shorter insertions result in bypassing from the inlet to outlet. Long insertions interfere with the vortex, increase pressure drop, and reduce collection efficiency.
- **Expansion Angle:** Cold flow testing shows that it is critical to keep a minimum expansion angle (see [Figure 1](#) for definition) of 16° (Reference 5) for FCC primary cyclones and 1° for FCC secondary cyclones. A maximum volute offset of 55% (see [Figure 1](#) for definition) could be used to meet the expansion angle criterion of 16° for the primaries. If volute offset greater than 55% is needed to meet the expansion angle criterion, outlet/inlet area ratio could be decreased provided it does not violate the pressure drop constraints.

Cyclone Size and Shape

- **Cyclone Diameter.** Increasing the diameter of geometrically similar cyclones decreases collection efficiency due to lower centrifugal forces and the effect of an increased inlet width. Since geometrically similar cyclones have the same ratio of inlet area to cyclone diameter, the larger cyclones will have increased throughput capacity. However, if inlet area and gas flow rate are held constant, increasing the cyclone diameter will increase collection efficiency. This is due to longer residence time in the cyclone.

Grouping of small [6 to 10 in. (150 to 250 mm) diameter] cyclones in multiclone clusters does not yield the entire theoretical advantage of their small size due to entrainment from the dust hopper. This is shown in [Figure 10](#). Increasing the fraction of the inlet gas, which passes down the dipleg (gas underflow) will decrease dust entrainment and increase efficiency. However, this will require more underflow gas to be handled along with the solids.

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Minimum cyclone diameters are usually set by maintenance requirements. The cyclone diameter should be large enough to permit internal inspection and repair. Since cyclone length increases with diameter, the maximum diameter is set by the overall length of the cyclone and its dipleg, which can be housed in the containing vessel, without excessively increasing the height of the vessel. Maximum diameter is also affected by collection efficiency, since efficiency decreases with diameter for geometrically similar cyclones. Cyclone diameters typically range from 42 to 100 in. (1.1 to 2.5 m).

Cyclone diameters less than the above have been used, but the small size may require early replacement due to maintenance difficulties. The smaller cyclones are more efficient, are shorter, thereby allowing shorter vessel straight side, and may permit increased capacity due to the ability to pack more of them into the top of the vessel. However, if greater efficiency is desired, decreasing the cyclone outlet pipe diameter can have a more significant effect than decreasing cyclone diameter, assuming the increased pressure drop can be tolerated.

- **Cyclone Length.** Cyclones should be long enough to contain the natural vortex length. This maximizes the residence time of the rotating gas and solids and increases collection efficiency. It also decreases erosion caused by the vortex. As the outlet tube diameter is decreased, the velocity of the outlet vortex increases. This requires lengthening the cyclone to prevent erosion caused by the higher vortex velocity. The relationship between outlet to inlet area and cyclone length to diameter ratio is shown in the following table.

CYCLONE LENGTH	
A_o/A_i	MINIMUM LENGTH TO DIAMETER
1.35 +	3.0
1.0 - 1.35	3.5
0.75 - 1.0	4.0
0.65 - 0.75	4.4
0.5 - 0.65	4.7
0.5 or below	5.0

The ratio of the length of the conical section to the total length of a cyclone is not a critical factor and is set by the vendor. Longer cones may be preferred in some cases to aid in drainage of the collected solids. The maximum included cone angle should be 40°.

- **Roof Configuration.** The flat roof design is preferred over the helical roof design. The benefits of the helical roof design, if any, do not justify the extra fabrication cost. Helical roofs may also be subject to higher erosion rates and poorer cyclone performance.

Number of Cyclones, Number of Stages

The number of cyclones per stage is determined by balancing the effects of diameter, length, velocity, erosion, efficiency and maintenance described above. Cyclone placement is another factor to consider.

The number of stages per installation depends on the required efficiency and pressure drop. In some installations, two stages are used with an external tertiary stage to provide additional particulate control if needed.

OTHER DESIGN FACTORS

Additional design factors such as gas and solids properties are usually fixed prior to the design. The collection efficiency (or solid losses) and cyclone pressure drop are factors which are determined in the course of the design.

Gas Properties

Gas density and viscosity influence design and performance. Increasing gas density increases pressure drop. Gas density has a negligible effect on collection efficiency except at high pressure where gas density becomes significantly large when compared to particle density. In this case, increasing gas density decreases collection efficiency. Increasing gas viscosity decreases collection efficiency.

Solid Properties

- **Particle Size.** Larger particles are collected more efficiently than smaller particles.
- **Particle Density.** Denser particles are collected more efficiently. The significant density parameter is particle density rather than bulk or skeletal density.
- **Dust Loading.** Increased dust loading increases collection efficiency.

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Collection Efficiency

The cyclone system must be chosen to meet the required collection efficiency (or solids losses). The primary factors affecting efficiency as described above are inlet velocity, outlet tube diameter, cyclone diameter and length, number of stages, gas properties, particle size distribution, density and loading. The efficiency (or solids losses) of the cyclone system should be calculated to assure that the specified efficiency is realistic. Comparison with available commercial experience is suggested to be sure that all factors affecting collection efficiency have been considered in the efficiency calculation. Calculation of efficiency is described in a subsequent paragraph.

Pressure Drop

Factors affecting pressure drop include many of the factors affecting efficiency. In many cases, increasing pressure drop also increases efficiency. When the pressure drop must be limited, the design must trade off pressure drop, efficiency and, possibly, maintenance considerations. If a higher pressure drop is available, high efficiency can be obtained for a given flow rate with large diameter cyclones by increasing inlet velocity, decreasing the outlet tube diameter or adding additional stages. If the pressure drop is limiting, high efficiency for a given flow rate can be obtained by using a larger number of small cyclones in parallel, but at the possible risk of making maintenance more difficult. Cyclones less than 42 in. (1.1 m) diameter may require disassembly for maintenance, adding to cost and turnaround time. In certain circumstances, pressure drop limitations can be removed by increasing the vessel straight side during turnaround, thereby permitting longer cyclone diplegs and higher allowable cyclone pressure drops. Calculation of pressure drop is described in subsequent paragraphs.

Flexibility

Cyclone systems should not be designed to tight limits. Sufficient flexibility should be included to allow for future changes in operations such as feed or catalyst changes, for pressure fluctuations, emergencies, etc.

CYCLONE CALCULATIONS

- ▶ A Computer Program within PEGASYS (cyclone module) can be used to calculate cyclone efficiency and pressure drop. This is a general purpose fluid solids program described in **Appendix A**, and is based on a h-Exxon program T-3575 "Fluidization and Particulate Emissions". The equations and correlations used to calculate cyclone performance in this program are described below. The equations and correlations can be used to make "hand" calculations of efficiency and pressure drop. Additional background is given in **References (2) and (3)**, the latter being the user's guide to T-3575.

CYCLONE COLLECTION EFFICIENCY

Cyclone collection efficiency is based on the use of a generalized grade efficiency curve shown in [Figure 11](#). In this figure, efficiency is given as a function of a relative particle size, d_p/d_c where d_p is the particle size and d_c is the critical particle size. The critical particle size is that size collected at 50% efficiency. It is given as:

$$d_c = 2.85 L_f \left[\frac{h_i}{\pi d_b} \right]^{0.25} \left[\frac{\mu w_i d_o}{\rho_p V \ell} \right]^{0.5} \left[\frac{0.52}{z} \right]^{0.33} V_f \quad (\text{ft}), (\text{m}) \quad \text{Eq. (1)}$$

where: d_c	=	The critical particle diameter (ft), (m)
L_f	=	A particle loading factor
h_i, w_i, d_b, d_p, d_o	=	As described above (ft), (m)
μ	=	The gas viscosity (lbs/ft/s), (kg/m/s)
ρ_p	=	The particle density (lbs/ft ³), (kg/m ³)
V	=	The inlet velocity (ft/s), (m/s)
ℓ	=	The effective cyclone length, defined below (ft), (m)
z	=	The Heywood shape factor (Table 1, Section VI-E)
L	=	Particle loading (lb/ft ³) (kg/m ³)
L_c	=	A corrected loading, $(120/\rho_p)L$ (lb/ft ³) $(1923/\rho_p)L$ (kg/m ³)
V_f	=	A velocity correction factor tabulated below for different values of L_c

▶ For conventional units [L_c in lb/ft³ and V in ft/s]

L_c (lb/ft ³)	V_f
$L_c \leq 0.1$	1
$0.1 < L_c < (1 + \log_{10} L_c) (0.032 V^{0.9}) - \log_{10} L_c$	



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1	
$L_c \geq 1$	$0.032 V^{0.9}$

For metric units [L_c in kg/m^3 and V in m/s],

$L_c (\text{kg/m}^3)$	V_f
$L_c \leq 1.6$	1
$1.6 < L_c < 16.02$	$(1 + \log_{10}(L_c/16.02))(0.093 V^{0.9}) - \log_{10}(L_c/16.02)$
$L_c \geq 16.02$	$0.093 V^{0.9}$

More efficient cyclones have lower values of d_c , i.e., the higher the efficiency, the smaller the particle size captured at 50% efficiency. Equation (1) illustrates the effects of design variables described previously. For example, for geometrically similar cyclones, where all dimensions remain in the same proportion to barrel diameter as barrel diameter changes, i.e., $h_i = k_1 d_b$, $w_i = k_2 d_b$, $\ell = k_3 d_b$, $d_o = k_4 d_b$, d_c is proportional to d_b . This indicates that efficiency decreases with increasing diameter for geometrically similar cyclones. However, as cyclone diameter increases at a constant inlet area and cyclone length, d_c decreases and efficiency increases. Cyclone length, ℓ , is the effective length, given as the smaller of:

$$\ell_1 = \left[\ell_b + \frac{\ell_c}{3} \right] \quad (\text{ft}), (\text{m}) \quad \text{Eq. (2)}$$

$$\ell_2 = \ell_b + \frac{1}{3} \left[2.3 d_o \left[\frac{d_b^2}{h_i w_i} \right]^{1/3} + \ell_o - \ell_b \right] \quad (\text{ft}), (\text{m}) \quad \text{Eq. (3)}$$

where: ℓ_b = The length of the barrel (ft), (m)
 ℓ_c = The length of the cone (ft), (m)
 ℓ_o = The length of the outlet tube insertion (ft), (m)

- ◆ The loading factor, L_f , is given in Figure 12 for solids with $\rho_p = 120 \text{ lbs/ft}^3$ (1923 kg/m^3). For other solids, the loading is corrected by multiplying by $120/\rho_p$ ($1923/\rho_p$ - metric) before using Figure 12.
- ◆ To calculate cyclone performance for a given set of inlet conditions, including inlet particle size distribution, the following procedure is used:
 1. Calculate d_c from Equations (1), (2) and (3) and Figure 12.
 2. Divide a log normal probability plot of inlet particle size vs. cumulative weight percent into n equal segments. Ten segments are suggested with midpoints of 5, 15, 25 - up to 95%.
 3. Calculate percentage of weight in each size bin: $W_{t_{in}}$.
 4. Divide the particle diameter, d , of the midpoint of each segment by d_c .
 5. From Figure 11, determine collection efficiency for each value of d/d_c . Plot efficiency vs. d to obtain the grade efficiency curve, if desired.
 6. Calculate weight collected: $W_{t_c} = W_{t_{in}} \times \text{EFF}/100$. This represents the fraction of total inlet collected in each bin
 7. Calculate the overall efficiency by summing values of W_{t_c} for each segment:

$$\overline{\text{Eff}} = \sum W_{t_c}$$

8. Normalize the W_{t_c} column to obtain the PSD (frequency) of the collected material: $W_{t_c}^n = W_{t_c} / \sum W_{t_c} \times 100$
9. To calculate the cumulative PSD for the i^{th} bin, find $\sum W_{t_c}^n$ for all bins $\leq i^{\text{th}}$ bin.
10. Calculate the solids losses as:

$$(1 - \overline{\text{Eff}}) \times (\text{Inlet solids rate}) \quad \text{Eq. (4)}$$



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11. Calculate the particle size distribution of the material escaping the cyclone in a similar fashion. In this case, the fraction of inlet material escaping is given by $W_{t_{in}} \times (1 - \text{EFF})/100$. Follow steps similar to 7-9 to calculate the cumulative PSD of the escaping material.
12. See the sample calculation for further illustration of the calculation procedure.

CYCLONE PRESSURE DROP

The procedure used to calculate cyclone pressure drop in PEGASYS cyclone module is given below. If vendors' calculation procedures are available, they probably will give better estimates of pressure drop and should be used. Procedures recommended by three vendors are discussed in a subsequent section.

Calculation Procedure

The pressure drop from the inlet of a primary cyclone to the gas outlet of the same cyclone is given by:

$$\Delta P_1 = \frac{1}{144 (2g_c)} V_1^2 (K_1' \rho_f + K_2' K_4 \rho_g) \quad (\text{psi}) \quad \text{Eq. (5c)}$$

$$\Delta P_1 = \frac{10^{-3}}{2} V_1^2 (K_1' \rho_f + K_2' K_4 \rho_g) \quad (\text{kPa}) \quad \text{Eq. (5m)}$$

where: ΔP_1 = The pressure drop (psi), (kPa)
 V_1 = The inlet gas velocity (ft/s), (m/s)
 K_1' = A velocity function equal to 1.1⁽¹⁾
 ρ_f = The density of gas/solids stream entering the cyclone (lbs/ft³), (kg/m³)
 K_2' = The number of velocity heads on the gas side
 K_4 = A dust loading factor given in [Figure 15](#)
 ρ_g = The gas density (lbs/ft³), (kg/m³)
 g_c = The gravitational conversion factor (32.2 ft lb mass/s² lb force)

K_2' can be calculated by:

$$K_2' = 4.62 \left(\frac{A_i}{d_b d_o} \right) \left[\frac{1-n}{n} \left(\left[\frac{d_b}{d_o} \right]^{2n} - 1 \right) + f \left(\frac{d_b}{d_o} \right)^{2n} \right] \quad \text{Eq. (6)}$$

where: n = A function of cyclone diameter and temperature given by:

$$n = 1 - \left[(T/520)^{0.3} \left[1 - \frac{(d_b)^{0.14}}{1.77} \right] \right] \quad \text{Eq. (7c)}$$

$$n = 1 - \left[(T/290)^{0.3} \left[1 - \frac{(d_b)^{0.14}}{1.5} \right] \right] \quad \text{Eq. (7m)}$$

where: T = Cyclone operating temperature (°R), (K)⁽²⁾
 f = A function of n given by:

$$f = 0.88 n + 1.7 \quad \text{Eq. (8)}$$

The pressure drop from the inlet of a primary cyclone to the gas outlet of a secondary cyclone is given by:

$$\Delta P_{1+2} = \frac{1}{144 (2g_c)} \left[V_1^2 (K_1' \rho_f + K_2' K_4 \rho_g) + V_2^2 K_2'' \rho_g \right] \quad (\text{psi}) \quad \text{Eq. (9c)}$$

$$\Delta P_{1+2} = \frac{10^{-3}}{2} \left[V_1^2 (K_1' \rho_f + K_2' K_4 \rho_g) + V_2^2 K_2'' \rho_g \right] \quad (\text{kPa}) \quad \text{Eq. (9m)}$$

where: V_2 = Inlet velocity to the secondary cyclone (ft/s), (m/s)
 K_2'' = The number of velocity heads on the gas side of the secondary cyclone.

Notes:

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- (1) This is the factor which will give the pressure drop required to accelerate the gas solids to the primary cyclone inlet velocity.
- (2) For FCC reactor conditions, use T as the temperature at which the viscosity of air equals the viscosity of the reactor gases. This will increase the calculated pressure drop by about 20%.

K_2'' can also be obtained from [Equation \(6\)](#).

In a similar fashion, the pressure drop from the inlet of a primary cyclone to the gas outlet of a tertiary cyclone is given by:

$$\Delta P_{1+2+3} = \frac{1}{144 (2g_c)} \left[V_1^2 (K_1' \rho_f + K_2' K_4 \rho_g) + V_2^2 K_2'' \rho_g + V_3^2 K_2''' \rho_g \right] \text{ (psi) Eq. (10c)}$$

$$\Delta P_{1+2+3} = \frac{10^{-3}}{2} \left[V_1^2 (K_1' \rho_f + K_2' K_4 \rho_g) + V_2^2 K_2'' \rho_g + V_3^2 K_2''' \rho_g \right] \text{ (kPa) Eq. (10m)}$$

where: K_2'' = The number of velocity heads on the gas side of the tertiary cyclone.

K_2'' can also be obtained from [Equation \(6\)](#).

Pressure drop from the primary cyclone inlet to the top of the primary, secondary or tertiary cyclone diplegs (solids outlet) can be calculated from the above equations by making the following substitutions:

Primary cyclone:	Use K_3' in place of K_2' in Eq. (5)
Primary + secondary cyclones:	Use K_3'' in place of K_2'' in Eq. (9)
Primary + secondary + Tertiary cyclones:	Use K_3''' in place of K_2''' in Eq. (10)

where: K_3' , K_3'' , K_3''' = Velocity heads on the solids sides of the primary, secondary and tertiary cyclones respectively. These constants can be calculated from:

$$4.62 \left(\frac{A_i}{d_b d_o n} \right) \left[\left(\frac{d_b}{d_d} \right)^{2n} - 1 \right] \text{ Eq. (11)}$$

where: d_d = The effective dipleg diameter (ft), (m) equal to the diameter of the bottom of the main cyclone cone or dust pot at the elevation of the apex of the projected cone, whichever is smaller. See [Reference \(10\)](#).

Vendor Procedures

Information obtained from Ducon, Emtrol and General Electric (formerly Buell) allows calculation of pressure drops using methods suggested by the vendors. The procedures used by Ducon and General Electric are similar to those given previously but use different values for the number of velocity heads. Emtrol uses an empirical approach as discussed below.

- **Ducon.** For Model 810 cyclones, use [Equations \(5\), \(9\), and \(10\)](#).

Use [Figure 13A](#) for K_2' , K_2'' , and K_2''' for the gas side pressure drop (gas inlet to gas outlet). Use [Figure 13B](#) for K_3' , K_3'' , and K_3''' for solids side pressure drop (gas inlet to solids outlet). For Model 800 cyclones ($L/D = 5$), Ducon recommends the following equation for gas side pressure drop for a primary cyclone:

$$\Delta P_1 = \frac{1}{144 (2g_c)} V_1^2 (K_1' \rho_f + K_5' \rho_g) \text{ (psi) Eq. (12c)}$$

$$\Delta P_1 = \frac{10^{-3}}{2} V_1^2 (K_1' \rho_f + K_5' \rho_g) \text{ (kPa) Eq. (12m)}$$

[Equation \(12\)](#) can be modified to calculate the gas side pressure drop from the inlet of a primary cyclone to the gas outlet of a secondary cyclone by adding a term for the secondary cyclone pressure drop:

$$\Delta P_{1+2} = \frac{1}{144 (2g_c)} \left[V_1^2 (K_1' \rho_f + K_5' \rho_g) + V_2^2 K_5'' \rho_g \right] \text{ (psi) Eq. (13c)}$$

$$\Delta P_{1+2} = \frac{10^{-3}}{2} \left[V_1^2 (K_1' \rho_f + K_5' \rho_g) + V_2^2 K_5'' \rho_g \right] \text{ (kPa) Eq. (13m)}$$

The equation can be modified further to include a tertiary cyclone:



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$$\Delta P_{1+2+3} = \frac{1}{144 (2g_c)} \left[V_1^2 (K_1' \rho_f + K_5' \rho_g) + V_2^2 K_5'' \rho_g + V_3^2 K_5''' \rho_g \right] \text{ (psi)} \quad \text{Eq. (14c)}$$

$$\Delta P_{1+2+3} = \frac{10^{-3}}{2} \left[V_1^2 (K_1' \rho_f + K_5' \rho_g) + V_2^2 K_5'' \rho_g + V_3^2 K_5''' \rho_g \right] \text{ (kPa)} \quad \text{Eq. (14m)}$$

Velocity head factors K_5' , K_5'' , and K_5''' are obtained from [Figure 13C](#). Ducon does not recommend use of a dust loading factor in [Equations \(12\)](#), [\(13\)](#), and [\(14\)](#).

For the solids side pressure drop for Model 800 cyclones, Ducon recommends the following equation for a primary cyclone:

$$\Delta P_1 = \frac{1}{144 (2g_c)} \left[V_1^2 (K_1' \rho_f + 0.92 K_6' \rho_g) \right] \text{ (psi)} \quad \text{Eq. (15c)}$$

$$\Delta P_1 = \frac{10^{-3}}{2} \left[V_1^2 (K_1' \rho_f + 0.92 K_6' \rho_g) \right] \text{ (kPa)} \quad \text{Eq. (15m)}$$

The pressure drop from the gas inlet of a primary to solids outlet of a secondary cyclone is:

$$\Delta P_{1+2} = \frac{1}{144 (2g_c)} \left[V_1^2 (K_1' \rho_f + K_5' \rho_g) + 0.92 V_2^2 K_6'' \rho_g \right] \text{ (psi)} \quad \text{Eq. (16c)}$$

$$\Delta P_{1+2} = \frac{10^{-3}}{2} \left[V_1^2 (K_1' \rho_f + K_5' \rho_g) + 0.92 V_2^2 K_6'' \rho_g \right] \text{ (kPa)} \quad \text{Eq. (16m)}$$

Pressure drop from the gas inlet of a primary to solids outlet of a tertiary cyclone is:

$$\Delta P_{1+2+3} = \frac{1}{144 (2g_c)} \left[V_1^2 (K_1' \rho_f + K_5' \rho_g) + V_2^2 K_5'' \rho_g + 0.92 V_3^2 K_6''' \rho_g \right] \text{ (psi)} \quad \text{Eq. (17c)}$$

$$\Delta P_{1+2+3} = \frac{10^{-3}}{2} \left[V_1^2 (K_1' \rho_f + K_5' \rho_g) + V_2^2 K_5'' \rho_g + 0.92 V_3^2 K_6''' \rho_g \right] \text{ (kPa)} \quad \text{Eq. (17m)}$$

[Figure 13D](#) gives K_6' , K_6'' , or K_6''' for Ducon Model 800 cyclones.

- **Entrol.** Entrol uses the empirical relationship shown in [Figure 14A](#) for gas side pressure drop. In this figure, the ratio of the gas side pressure drop to gas density is given as a function of:

$$\frac{(V_i)^2}{M (d_o / d_b)^{2.3}}$$

for various values of solids entrainment, e.

where: V_i = The inlet gas velocity (ft/s)
 M = The cyclone model number, e.g., 800 or 1550 [also equal to the ratio d_b^2 (in.²)/ A_i (ft²)]
 d_o = The gas outlet tube diameter (in.)
 d_b = The barrel diameter (in.)

Pressure drop due to acceleration of the solids at the inlet to a primary cyclone, ΔP_a , is taken as one velocity head, or

$$\Delta P_a = \frac{1}{144 (2g_c)} V_1^2 \rho_f \text{ (psi)} \quad \text{Eq. (18c)}$$

$$\Delta P_a = \frac{10^{-3}}{2} V_1^2 \rho_f \text{ (kPa)} \quad \text{Eq. (18m)}$$

For secondary and tertiary cyclones, the entrainment used in [Figure 14A](#) is 0. The total gas side pressure drop through a series of cyclones, e.g., a tertiary set, then consists of acceleration loss into the primary, ΔP in the primary plus ΔP in the secondary plus ΔP in the tertiary cyclones.

For solid side pressure loss, [Figure 14B](#) is used. In this figure, $\Delta P/\rho_g$ is given as a function of $(V_i)^2/Y$ for various values of entrainment, e.

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where: $Y = (M)^{0.6} (d_o L / d_b^2)^{0.74}$

L = The cyclone length from roof to the projected cone apex (in.)

For primary cyclones, inlet acceleration loss must be included as given in [Equation \(18\)](#). Entrainment is taken as 0 for secondary and tertiary cyclones. Solid side pressure drop through a series of cyclones is calculated as shown previously. This is summarized as follows:

$$\Delta P_1 = \Delta P_a + \Delta P_{1(ss)} \quad (\text{psi}), \quad (\text{kPa}) \quad \text{Eq. (19)}$$

$$\Delta P_{1+2} = \Delta P_a + \Delta P_{1(gs)} + \Delta P_{2(ss)} \quad (\text{psi}), \quad (\text{kPa}) \quad \text{Eq. (20)}$$

$$\Delta P_{1+2+3} = \Delta P_a + \Delta P_{1(gs)} + \Delta P_{2(gs)} + \Delta P_{3(ss)} \quad (\text{psi}), \quad (\text{kPa}) \quad \text{Eq. (21)}$$

where: 1, 2 and 3 refer to primary, secondary and tertiary cyclones

ΔP_a is given by [Equation \(18\)](#)

subscripts gs refer to gas side (gas inlet to gas outlet)

subscripts ss refer to solid side (gas inlet to solids outlet)

- **General Electric.** The method used by General Electric is similar to that used in Program 3575 and by Ducon. Pressure loss due to solids acceleration at the primary cyclone inlet is taken as 1 velocity head [Equation \(18\)](#). For Model CG-435 S and CG-375 S cyclones, gas side pressure drop is given as:

$$\Delta P = \frac{6.6}{144 (2g_c)} V_i^2 \rho_g \quad (\text{psi}) \quad \text{Eq. (22c)}$$

$$\Delta P = \frac{6.6 \times 10^{-3}}{2} V_i^2 \rho_g \quad (\text{kPa}) \quad \text{Eq. (22m)}$$

Gas side pressure drop through a tertiary cyclone system is obtained as before by summing the acceleration loss into the primary cyclone, primary cyclone gas side ΔP , secondary cyclone gas side ΔP , and tertiary cyclone gas side ΔP .

Solid side pressure drop for CG-4355 cyclones is given as:

$$\Delta P = \frac{7.6}{144 (2g_c)} V_i^2 \rho_g \quad (\text{psi}) \quad \text{Eq. (23c)}$$

$$\Delta P = \frac{7.6 \times 10^{-3}}{2} V_i^2 \rho_g \quad (\text{kPa}) \quad \text{Eq. (23m)}$$

For CG-3755 cyclones, the equation is:

$$\Delta P = \frac{9.3}{144 (2g_c)} V_i^2 \rho_g \quad (\text{psi}) \quad \text{Eq. (24c)}$$

$$\Delta P = \frac{9.3 \times 10^{-3}}{2} V_i^2 \rho_g \quad (\text{kPa}) \quad \text{Eq. (24m)}$$

Solid side pressure loss through a series of cyclones is as given in [Equations \(19\), \(20\), and \(21\)](#).

RELIABILITY OF CYCLONE CALCULATION METHODS

- ♦ The reliability of the predicted efficiency and solids losses using the PEGASYS cyclone module depends on how accurately the solids size distribution and concentration entering the cyclones are known. In many cases, these solids inlet conditions are calculated using the entrainment portion of the PEGASYS cyclone module. The reliability of the entrainment calculations, in turn, depends on how well the fines portion of the solids size distribution in the bed is known. Obtaining a good measure of fines distribution is very difficult due to measurement technique limitations. Before the use of the newer catalysts, the FCC bed fines content could be fairly well estimated by extrapolating a measured log-normal size distribution of the bed catalyst. In those cases, the PEGASYS cyclone module gave reasonably good estimates of catalyst losses. For example, calculated losses from two stage regenerator cyclone systems gave a standard error of about $\pm 30\%$ when compared to measured losses. These comparisons were based on the results of nine plant tests conducted over a period from 1970 to 1979. However, since the advent of the newer FCC catalysts, the fines size distribution can no longer be obtained by extrapolating the bed size distribution. Fines



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from the new catalysts tend to be smaller in size, showing bimodal distributions. Calculations using the PEGASYS cyclone module based on the measured bed solids size distribution, or even worse, on the fresh catalyst size distribution of the new FCC catalysts can be very inaccurate. Some adjustments to the inlet size distribution can be made which will give better estimates of losses if operating data are available upon which such adjustments could be based (12). However, solids losses for these situations can be better estimated using the DYNAMOD program described later.

Calculated losses from tertiary cyclone systems are subject to the limitations described above to an even greater degree. Most of the solids captured in a tertiary cyclone are finer than the smallest size normally reported in size distributions of bed solids. The uncertainty in the losses calculated from a tertiary cyclone is compounded by uncertainties in the starting bed size, entrainment, and primary and secondary cyclone efficiency calculations.

Calculations of cyclone pressure drop agree well with measured results.

DIPLEG DESIGN

Dipleg diameter, length and sealing method must be specified. Diameter is based on solids flow rate, size and density. Length is determined by the static head needed to allow the solids to flow from the dipleg. It is calculated from a pressure balance. Sealing methods must assure that excessive gas does not flow up the dipleg and affect cyclone performance. Each of these is described below.

DIPLEG DIAMETER

The diameter of a primary cyclone dipleg can be calculated from:

$$d_d = 0.623 [W / \rho_d]^{0.4} + 1.5 d_p \quad (\text{ft}) \quad \text{Eq. (25c)}$$

$$d_d = 0.790 [W / \rho_d]^{0.4} + 1.5 d_p \quad (\text{m}) \quad \text{Eq. (25m)}$$

where: d_d = The dipleg diameter (ft), (m)
 W = The solids flow rate (equal to inlet solids rate) (lbs/s), (kg/s)
 d_p = The weight mean particle size in the dipleg (ft), (m)
 ρ_d = The density of the material in the dipleg (lbs/ft³), (kg/m³)

For most applications, the second term in [Equation \(25\)](#) can be dropped.

Mass velocities in diplegs on primary cyclones are in the range of 100 - 150 lbs/ft²s (490 to 730 kg/m²s). Diplegs on secondary cyclones are usually 8 in. (200 mm). Tertiary cyclone diplegs are usually 6 in. (150 mm). Minimum diameter for all diplegs on commercial units is 6 in. (150 mm). For close coupled reactor cyclones, catalyst maldistribution often occurs and must be taken into account in sizing diplegs.

DIPLEG LENGTH

In order for solids captured by an internal cyclone to flow down the dipleg back into the vessel, the dipleg must be long enough to build the required static head. The static head must be sufficient to overcome the cyclone solids side pressure drop, the dilute phase and dense bed pressure drops and the trickle valve pressure drop (if used). Therefore, for a primary cyclone:

$$\frac{L \rho_d g}{144 g_c} = \text{Cyclone solids side } \Delta P + \text{dilute phase } \Delta P + \text{dense bed } \Delta P + \text{trickle valve } \Delta P \quad (\text{psi}) \quad \text{Eq. (26c)}$$

$$10^{-3} g L \rho_d = \text{Cyclone solids side } \Delta P + \text{dilute phase } \Delta P + \text{dense bed } \Delta P + \text{trickle valve } \Delta P \quad (\text{kPa}) \quad \text{Eq. (26m)}$$

where: L = The minimum dipleg length (ft), (m)
 ρ_d = The density of solids in the dipleg (lbs/ft³), (kg/m³)
 g = The acceleration due to gravity (32.2 ft/s²) (9.81 m/s²)
 g_c = The gravitational conversion factor (32.2 ft lb mass/s² lb force)

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Cyclone solids side ΔP is obtained at maximum operating cyclone velocity from [Equation \(5\)](#) using K_3' in place of K_2'

$$\begin{aligned}
 \text{Dilute phase } \Delta P &= \text{Dilute phase holdup (lbs)/dilute phase area (in.}^2\text{)} \\
 &= \text{Dilute phase holdup (kg) } \times 10^{-3} \text{g/dilute phase area (m}^2\text{)} \\
 \text{Dense bed } \Delta P &= \text{Height of dense bed above dipleg outlet (ft) } \times \rho_B / 144 \text{ (lb/ft}^3\text{)} \\
 &= \text{Height of dense bed above dipleg (m) } \times \rho_B \text{ (kg/m}^3\text{) } \times 10^{-3} \text{g} \\
 \rho_B &= \text{The dense bed density (lbs/ft}^3\text{), (kg/m}^3\text{)} \\
 \text{Trickle valve } \Delta P &= 0.05 \text{ psi (0.3 kPa)}
 \end{aligned}$$

For a secondary cyclone, the solids side ΔP in [Equation \(26\)](#) is replaced by the ΔP from the primary cyclone inlet to the top of the secondary dipleg. Use [Equation \(9\)](#) for the ΔP calculation, replacing K_2'' by K_3'' . The dense bed ΔP is calculated based on the height of the dense bed above the secondary cyclone dipleg outlet.

The dipleg design length is obtained by adding 3 ft (0.9 m) or an additional 35%, whichever is greater, to the minimum dipleg length. The added length will allow for variations in operating conditions. The minimum length for tertiary cyclone diplegs is 4 ft (1.2 m). Considerations should also be given to allowing a greater length to accommodate future expansions or bed level variations during startup or upset conditions.

Density of the solids in the dipleg used in the pressure balance should be based on measured densities. If such data are not available from design notes, the following ratios of dipleg solids density to density at minimum fluidization should be used.

PRIMARY CYCLONE DIPLEG - ρ_d/ρ_{mf}	SECONDARY, TERTIARY, CYCLONE DIPLEG - ρ_d/ρ_{mf}
0.70	0.55

DIPLEG SEALING

Diplegs must be sealed to prevent the backflow of gas up the diplegs, which will adversely affect performance. This is done by the use of trickle valves ([Figures 16](#) and [17](#)) or by assuring that the dipleg terminates below the level of the dense bed. If trickle valves are not used, the dipleg should terminate in a 90° elbow cut at a slant or a splash plate. Trickle valves are flapper valves which seal the dipleg until the static head is sufficient to force the trickle valve open and allow some solids to flow out. For dilute phase operation, a modified trickle valve design ([Figure 18](#)) should be used. This design minimizes flapper plate erosion and also improves the process performance by providing a more stable (less turbulent) dipleg solids level, particularly in the secondary dipleg operating range. The design incorporates a 1/2 in. (12 mm) thick steel flapper with hexmesh and erosion resistant refractory on both faces installed on an "elbow" type valve body. The refractory lined flapper minimizes thermal distortion as well as providing improved erosion resistance. "Elbow" type configurations provide more uniform solids discharge and less gas upflow compared to conventional miter body trickle valves. See [Reference \(4\)](#) for further details. Diplegs, which are immersed in a bed, should terminate 2 ft (0.6 m) below the bed level and 5 ft (1.5 m) above grids to prevent erosion and to minimize the chance for gas backflow. If this is not possible, the grid holes below the dipleg should be blanked. Diplegs should also be located away from other potential sources of erosion. It may be necessary to slope diplegs for process reasons. If so, the maximum slope is 20° from the vertical. This slope should be minimized.

CYCLONE LAYOUT

The cyclones should be arranged in a symmetrical fashion with primary cyclone inlets drawing gas as evenly as possible over the vessel cross section. The cyclones are usually arranged in a circle (looking at a top plan view of the vessel). In larger vessels, the cyclone sets are arranged in two concentric circles with the smaller circle of cyclones occupying the center portion of the vessel. The rotation of the gas in all the cyclones in a vessel should be in the same direction, all clockwise or all counter clockwise.

TERTIARY CYCLONE SYSTEMS

Tertiary cyclones are often used to protect flue gas expander turbines or to meet environmental limits. Tertiary cyclones are installed external to the process vessels to prevent recycling the captured fines back to the process. This arrangement requires a vessel to contain the cyclones, a fines hopper and cyclone to handle the fines prior to disposal, and a fines transport system connecting the tertiary cyclone vessel and the fines hopper. This arrangement is shown in [Design Practice Section XVIII-A3](#).

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INSTRUMENTATION

Differential pressure instruments to determine primary and secondary cyclone dipleg density, level and cyclone pressure drop should be considered for inclusion in the design, especially in a new service in which cyclone performance and solids properties such as dipleg density have not been characterized. It is sufficient to instrument only one cyclone in a set.

OTHER GAS, SOLIDS SEPARATION SYSTEMS

Other gas, solid separation systems may be used in conjunction with cyclones to meet particulate removal requirements in effect at the site of a fluid solids unit. If needed, systems would be installed downstream of the cyclones at lower temperatures and pressures. Bag filters, wet scrubbers and electrostatic precipitators can be used for this service. The design bases for these are described in [Design Practices Sections XVIII-A4, A5, and A6](#).

SOLIDS LOSSES

Loss of solids from a fluid solids process is given by:

$$\text{Loss} = \text{Entrainment} \times \text{Gas Rate} \times \left(1 - \frac{\text{Collector Efficiency}}{100} \right)$$

where the loss is given in lbs/hr (kg/hr), entrainment in lbs/ft³ (kg/m³) gas, gas rate in ft³/hr (m³/hr), and collector efficiency in percent. If the particle size distribution in the fluid bed is known, the losses can be calculated by direct application of the PEGASYS cyclone module. However, in many cases, the equilibrium bed particle size distribution is not sufficiently defined, especially in the -20 µm size range. In those cases, bed equilibrium particle size distribution, entrainment and fines losses can be calculated using DYNAMOD, a particle population balance model. Application of DYNAMOD requires information on the attrition rate and particle breakage pattern for the bed solids. This information can be obtained through jet and impact attrition tests described in [Section VI-E](#), as well as from other pilot plant or commercial plant operations. DYNAMOD calculates the bed particle size distribution over a series of time intervals as a result of particle attrition, reaction, entrainment and solids feeding and withdrawal. Entrainment rates, particle collection rates, and overhead solids recycle rates and size distributions are then calculated for each time interval based on the bed particle size distributions. The calculation is repeated for a number of cycles until the change in particle size distributions and solid stream rates with succeeding cycles is less than an acceptable level. In this way, a steady state estimate for the system is calculated. DYNAMOD may also be used to analyze transient as well as steady state results, as for example, from batch attrition tests.

DYNAMOD has the capability of including the effect of chemical reaction on the solids balance for reacting solids such as in char gasification or oil shale retorting. DYNAMOD has been applied to a number of fluid solids processes, including those under development. It permits estimates of the performance of integrated fluid solids processes based on small scale measurements of fundamental particle properties. It has been successfully applied to a few specific commercial operations, primarily FCC units.

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SAMPLE CALCULATIONS

CYCLONE EFFICIENCY, PARTICLE SIZE DISTRIBUTIONS

- Calculate overall collection efficiency, size distribution of collected and escaping material

Given: Cyclone dimensions

$$d_b = 3.0 \text{ ft}$$

$$w_i = 0.75 \text{ ft}$$

$$h_i = 1.5 \text{ ft}$$

$$d_o = 0.75 \text{ ft}$$

$$\ell_b = 2.0 \text{ ft}$$

$$\ell_c = 3.0 \text{ ft}$$

$$\ell_o = 1.5 \text{ ft}$$

Operating conditions

$$v = 67 \text{ ft/s}$$

$$\mu = 1.21 \times 10^{-5} \text{ lbs/ft/s}$$

$$\rho_p = 120 \text{ lbs/ft}^3$$

$$z = 0.52$$

$$\text{dustloading} = 3.2 \times 10^{-2} \text{ lbs/ft}^3 \text{ gas}$$

inlet solids size distribution - see [Figure 19](#)

$$\text{inlet gas rate} = 4500 \text{ ACFM}$$

- Calculate effective cyclone length, ℓ , using [Equations \(2\) and \(3\)](#).

$$\ell_1 = \left[\ell_b + \frac{\ell_c}{3} \right]$$

$$= 2.0 + \frac{3.0}{3}$$

$$= 3 \text{ ft}$$

$$\ell_2 = \ell_b + \frac{1}{3} \left[2.3 d_o \left[\frac{d_b^2}{h_i w_i} \right]^{1/3} + \ell_o - \ell_b \right]$$

$$\ell_2 = 2.0 + \frac{1}{3} \left[2.3 (0.75) \left[\frac{3^2}{1.5 \times 0.75} \right]^{1/3} + 1.5 - 2.0 \right]$$

$$= 2.98 \text{ ft}$$

$$\ell = \text{lesser of } \ell_1, \ell_2$$

$$= 2.98 \text{ ft}$$

- Determine dust loading factor, L_f , using [Figure 12](#).

$$\text{Log dust loading} = \log (3.2 \times 10^{-2})$$

$$= -2.50$$

$$L_f = 0.28 \text{ (Figure 12)}$$



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3. Calculate critical particle diameter, d_c , using Equation (1).

$$\begin{aligned}
 d_c &= 2.85 L_f \left[\frac{h_i}{\pi d_b} \right]^{0.25} \left[\frac{\mu w_i d_o}{\rho_p V \ell} \right]^{0.5} \left[\frac{0.52}{z} \right]^{0.33} \cdot V_f \\
 &= 2.85 \times 0.28 \left[\frac{1.5}{\pi \times 3.0} \right]^{0.25} \left[\frac{1.21 \times 10^{-5} \times 0.75 \times 0.75}{120 \times 67 \times 2.98} \right]^{0.5} \left[\frac{0.52}{0.52} \right]^{0.33} \cdot 1 \\
 &= 0.85 \times 10^{-5} \text{ ft (2.6 microns)}
 \end{aligned}$$

4. Divide log normal probability plot of inlet solids size distribution into 10 equal segments. Obtain particle diameters at midpoints of each segment. See Figure 19, Table 1.
5. Divide the midpoint diameter of each segment by d_c . See Table 1.
6. Obtain collection efficiency for each value of d/d_c using Figure 11. See Table 1. If desired, plot efficiency of each segment vs. d to obtain grade efficiency curve.
7. Determine percent wt in each bin ($W_{t_{in}}$), Table 1.
8. Calculate weight of particles collected in each bin ($W_{t_c} = W_{t_{in}} \times \text{EFF}$)
9. Calculate the overall efficiency by summing W_{t_c} for each segment. Overall efficiency = 96.35%. See Table 1.
10. Calculate the solids losses using Equation (4).

$$\begin{aligned}
 \text{Losses} &= (1 - \overline{\text{Eff}}) \times (\text{inlet solids rate}) \\
 &= 0.0365 \times 4500 \frac{\text{ft}^3}{\text{min}} \times 3.2 \times 10^{-2} \times \frac{\text{lbs}}{\text{ft}^3} \times 60 \frac{\text{min}}{\text{hr}} \\
 &= 316 \text{ lbs/hr}
 \end{aligned}$$

11. Calculate the ratio of $W_{t_c}/\Sigma W_{t_c} \times 100$ for each segment to obtain $W_{t_c}^n$. See Table 1. This gives the PSD of collected material.
12. Calculate the cumulative weight % for the collected solids by obtaining ($W_{t_c}^n/\Sigma W_{t_c}^n$) for Segment 1, ($W_{t_c}^n/\Sigma W_{t_c}^n + W_{t_c}^n/\Sigma W_{t_c}^n$) for Segment 2, etc. See Table 1. Plot cumulative weight % for each segment against the maximum particle size for each segment, e.g., 7.2 microns for Segment 1. See Figure 19.
13. Calculate $1 - \text{Eff}$ for each segment and obtain $W_{t_E} = W_{t_{in}}(1 - \text{Eff})/100$. See Table 1.
14. Calculate $W_{t_E}^n = (W_{t_E})/\Sigma(W_{t_E}) \times 100$ for each segment. See Table 1.
15. Calculate the cumulative weight % for the escaping solids by obtaining ($W_{t_E}^n/\Sigma W_{t_E}^n$) for Segment 1, $[(1 - \text{Eff}_1)/\Sigma(1 - \text{Eff}) + (1 - \text{Eff}_2)/\Sigma(1 - \text{Eff})]$ for Segment 2, etc. See Table 1. Plot cumulative weight % for each segment against the maximum particle size for each segment. See Figure 19.

CYCLONE PRESSURE DROP

- Calculate the pressure drop from the inlet to the gas outlet of a primary cyclone.

Given: Cyclone dimensions from previous sample calculation
 Operating conditions from previous sample calculation
 $\rho_g = 0.07 \text{ lb/ft}^3$ (flue gas)
 $T = 1760^\circ\text{R}$

1. Calculate ρ_f , the inlet mixture density as the sum of the gas density and dust loading.

$$\begin{aligned}
 \rho_f &= 0.07 + 0.0032 \\
 &= 0.0732 \text{ lbs/ft}^3
 \end{aligned}$$

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2. Calculate the number of velocity heads on the gas side, K_2' , using Equation (6).

$$K_2' = 4.62 \left[\left[\frac{A_i}{d_b d_o} \right] \left[\frac{1 - n}{n} \left[\frac{d_b}{d_o} \right]^{2n} - 1 \right] + f \left[\frac{d_b}{d_o} \right]^{2n} \right]$$

$$n = 1 - \left[(T/520)^{0.3} \left[1 - \frac{(d_b)^{0.14}}{1.77} \right] \right] \quad \text{Eq. (7)}$$

$$n = 1 - \left[\left[\frac{1760}{520} \right]^{0.3} \left[1 - \frac{(3)^{0.14}}{1.77} \right] \right]$$

$$= 0.51$$

$$f = 0.88 n + 1.7 \quad \text{Eq. (8)}$$

$$= 0.88 \times 0.51 + 1.7$$

$$= 2.15$$

$$K_2' = 4.62 \left[\left[\frac{0.75 \times 1.5}{3.0 \times 0.75} \right] \left[\frac{1 - 0.51}{0.51} \left[\frac{3.0}{0.75} \right]^{2 \times 0.51} - 1 \right] + 2.15 \left[\frac{3.0}{0.75} \right]^{2 \times 0.51} \right]$$

$$= 27.3$$

3. Obtain the dust loading factor, K_4 , from Figure 15.

$$K_4 = 0.9$$

4. Calculate the primary cyclone gas side pressure drop, ΔP_1 , using Equation (5).

$$\Delta P_1 = \frac{1}{144 (2g_c)} V_1^2 (K_1' \rho_f + K_2' K_4 \rho_g)$$

$$\Delta P_1 = \frac{1}{144 (2 \times 32.2)} (67)^2 (1.1 \times 0.073 + 27.3 \times 0.9 \times 0.07)$$

$$= 0.88 \text{ psi}$$

- Calculate the pressure drop from the inlet to the top of the cyclone dipleg of a primary cyclone.

Given: Cyclone dimensions from previous sample calculation

$$d_d = 1 \text{ ft}$$

Operating conditions from previous sample calculation

1. Calculate the number of velocity heads on the solids side, K_3' , using Equation (11).

$$K_3' = 4.62 \left[\frac{A_i}{d_b d_o n} \right] \left[\left[\frac{d_b}{d_d} \right]^{2n} - 1 \right]$$

$$= 4.62 \left[\frac{1.5 \times 0.75}{3.0 \times 0.75 \times 0.51} \right] \left[\left[\frac{3.0}{1.0} \right]^{1.02} - 1 \right]$$

$$= 9.36$$



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2. Calculate the primary cyclone solids side pressure drop, ΔP_1 , using Equation (5) with K_3' substituted for K_2' .

$$\begin{aligned}
 \Delta P_1 &= \frac{1}{144 (2g_c)} V_1^2 (K_1' \rho_f + K_3' K_4 \rho_g) \\
 \Delta P_1 &= \frac{1}{144 (2 \times 32.2)} (67)^2 (1.1 \times 0.073 + 9.36 \times 0.9 \times 0.07) \\
 &= 0.33 \text{ psi}
 \end{aligned}$$