CYCLONES

BACKGROUND

Cyclone Dust Collectors (Figure 1: Typical Cyclone) have been used in industry for over 100 years and are still the most commonly used gas cleaning device because of low capital and maintenance costs plus it can be constructed to with stand harsh operating conditions.

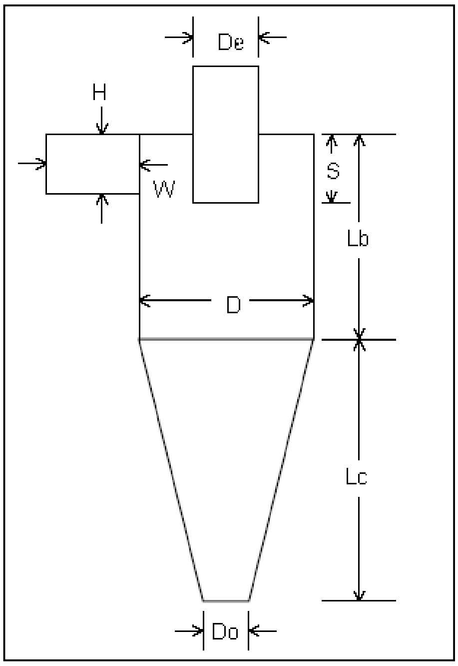

Figure 1: Typical Cyclone

Experience and theory have shown that there are certain relationships among cyclone dimensions that should be observed for efficient cyclone performance, and which are generally related to the cyclone diameter. Using the standard geometries of cyclones it is much easier to predict effects on variable changes and scale-up calculations. Such calculations may be carried out by means of dimensionless relationships. Selection and operation of cyclones can be described by the relationship between the pressure drop and the flow rate and the relationship between separation efficiency and flow rate.

The Euler Number is a pressure loss factor easily defined as the limit on the maximum characteristic velocity v.

$$Eu = \frac{2\Delta P}{\rho g_c v^2} \qquad \text{Equation - 1}$$

The Reynolds number defines flow characteristics of the system (cyclone). The characteristic dimension is the cyclone body diameter D_C

$$Re = \frac{D_C v \rho g}{D_P} \qquad \text{Equation - 2}$$

The relationship between separation efficiency and flow rate is not significantly influenced by operational variables, so it is commonly expressed in terms of cut size X50. The use of cut size to define efficiency of cyclones is of utmost importance since their performance is highly dependent on particle size. Since cut size implies the size of particles to be separated; it follows that the particles must be influenced by forces exercised on them while they are in suspension. The forces developed in a cyclone can be analyzed by sedimentation theory, and a dimensionless group thus derived the Stokes number Stk, will include the cut size. The Stokes number is a very useful theoretical tool

$$Stk_{50} = \frac{x50\rho_{sv}}{18\mu g D_C} \qquad \text{Equation - 3}$$

The cyclone inside diameter D_C has all the geometrical proportions related to it. In the case of scale-up, proportions must be maintained. The cyclone body velocity v is the characteristic velocity which can be defined in various ways, but the simplest one is based on the cross section of the cylindrical body so that

$$V = \frac{4\,Q}{\pi D_C^2} \qquad \text{Equation - 4}$$

Pressure drop and collection efficiency are the two major criteria used to evaluate cyclone performance. Both properties are functions of cyclone dimensions: inlet height (W), inlet width (H), gas outlet diameter (De), outlet duct length (S), Cyclinder height (Lb), cyclone height (Lc), and dust outlet diameter (Do). Since 1940 researchers have developed models to describe mathematically the operation of a cyclone. Obviously, a design method based on theory depends on the accurate prediction of efficiency and pressure drop especially when the designer’s goal is to obtain the greatest efficiency for a given pressure drop by adjusting the dimensions of the cyclone. Due to poor prediction of efficiency and pressure drop by some models, substantial improvements in performance was not shown by pilot scale cyclones designed according to the program. This problem was partially resolved by more accurate procedures which included doing a statistical analysis of 98 cyclone types. The net result of the analysis was three models were determined to be accurate - Dirgo and Leith (Pressure Drop); Iozia and Leith (Efficiency); with the model of Shepherd and Lapple which was the simplest method being judged to be the most accurate for a broad range of cyclone types. The Lapple method is the most frequently used efficiency model due to its simplicity. The other two methods appear to be more useful for design optimization.

DESIGN GUIDELINES

In a typical cyclone separator, the gas-dust mixture enters the top cylindrical section of the cyclone through a tangential opening. As particles must reach the wall of the cyclone before they can be recovered from the gas stream, it is best if the inlet shape is rectangular instead of circular.

When a rectangular inlet is used, it is recommended that the height of the inlet duct be greater than the width, to increase the tangential inlet surface.

For best efficiency the penetration of the outlet duct should be 1 to 1.2 times the height of the inlet duct to prevent the inlet particles from going directly out of the cyclone with the exiting gas stream. Increasing the penetration of the outlet duct beyond 1.2 is not economically feasible as the entire length of the cyclone would also have to be increased

The main areas of pressure loss in a cyclone are due to the contraction of the inlet and outlet ducts. If the ratio of outlet area to inlet area is less than one, an increased pressure drop is experienced and the cyclone must be lengthened to avoid dust reentrainment in the spiraling gas stream

DESIGN EQUATIONS

Lapple and Shepherd designed a simple model to describe mathematically the operation of a cyclone. In this model gas spins through a number of revolutions Ne in the outer vortex. Ne may be expressed numerically as –

$$Ne = (1/H)(Lb+Lc/2) \quad 5$$

Where

Ne	=	number of turns made outer vortex
H	=	height inlet duct
Lb	=	height of cyclone body
Lc	=	cyclone cone section height

To be collected a dust particle in the gas stream must strike the wall within the time that it travels in the outer vortex.

The *gas residence time* in the outer vortex is

$$\Delta t = \pi D N_e / V_i \quad 6$$

Where

ΔT	=	time spent by gas during spiraling descent (sec)
Dc	=	cyclone body diameter
Vi	=	volumetric flow to cyclone

e maximum radial distance that any particle will travel in the gas stream entering a cyclone is the width of the inlet duct (W).Centrifugal force accelerates the dust particles in the gas stream to its terminal velocity in a radial (outward) direction.

$$V_t = W / \Delta t \qquad 7$$

where V_t = particle terminal velocity in the radial direction (m/s or ft/s).

The particle's terminal velocity is a function of particle size and the above equation expresses that premises in terms of Stokes law (see next section). Substitutions of the two above equations being made equal to each other results in the following equation

$$V_t = \frac{(\rho_p - \rho_g) d_p^2 V_i^2}{9 \mu D} \qquad 8$$

where

V_t = terminal velocity (m/s or ft/s)
d_p = diameter of the particle (m or ft)
ρ_p = density of the particle (kg/m^3)
ρ_g = gas density (kg/m^3)
μ = gas viscosity (kg/m.s).

$$d_{pc} = \left[\frac{9 \mu W}{2\pi N_e V_i (\rho_p - \rho_g)} \right]^{1/2} \qquad 9$$

where d_{pc} = diameter of particle collected with 50% efficiency.

In theory the smallest diameter of particle collected with 100% efficiency is directly related to the gas viscosity, inlet duct Width (W), inversely related to number of effective turns, inlet gas velocity and density of gas and particle collected. There is a flaw however not all particles greater then dp will be collected. Lapple developed a 50% cut diameter which is a semi-empirical relationship given by dpc.
Lapple developed a general curve for standard conventional cyclones to predict collection efficiency for any particle size if the size distribution of particles is known. The collection efficiency of the "jth" particle is given by the following two equations

$$\eta_j = \frac{1}{1 + \left(d_{pc} / d_{pj} \right)^2} \qquad 10$$

where

η_j = collection efficiency of particles in the jth size range ($0 < \eta_j < 1$)
d_{pj} = characteristic diameter of the jth particle size range (in µm).

The overall collection efficiency of the cyclone is a weighted average of the collection efficiencies for the various size ranges as shown below

$$\eta = \frac{\sum \eta_j m_j}{M} \qquad 11$$

where

η = overall collection efficiency ($0 < \eta < 1$)
m_j = mass of particles in the jth size range
M = total mass of particles.

EFFICIENCY MODELLING

There is a general agreement that operating parameters of the system should be used to predict performance, and most theories account for the influence of particle diameter and density, and gas velocity and viscosity. There is less agreement on the effects of cyclone dimensions and geometry. Some theories consider all eight cyclone dimensions whle others include as few as three.

Separation of particles in the cyclone is due to the centrifugal force caused by the spinning gas stream; this force throws particles outward to the cyclone wall. Opposing this outward particle motion is an inward drag force caused by gas flowing toward the axis of the cyclone prior to discharge. All efficiency theories set up a balance between these opposing forces. By making different assumptions about gas flow through the cyclone, various terms in the force balance can be dismissed as insignificant. it is unlikely that any single set of assumptions will predict cyclone efficiency accurately for all applications.

Several methods for estimating cyclone efficiency have been developed. Most of these methods utilize a particle size term called a “50 % particle cut size”. The “d50” cut size corresponds to a size where 50% of particles smaller then d50 and 50% of particles larger then d50 will be collected (ie. 50 % collection efficiency). There are two common approaches to calculating efficiency and they are force balance theory (Lapple - see above) which assumes terminal velocity is achieved when opposing drag force(Stokes Law) equals the centrifugal force; and the Static Particle Approach (Barth) which considers a particle for which outward centrifugal force just balances inward drag force. Recent cyclone theories allow direct calculation of collection efficiency for particles of any size by cyclones of any design. Checking their equations (see below) there is a similarity of form for the equations. Later methods are basically refining the original two modelling typesans include determining the fractional efficiency curve without resorting to a generalized efficiency curve based on a critical diameter. Examples of this approach are the Leith-Licht (1972) theory and a newer theory by Dietz (1981). The Leith-Licht method assumes that gas turbulence mixes uncollected dust and calculated a residence time based on cyclone volume and gas flow to develop a theory to predict efficiency for particles of any size. Still newer theories are based on optimization of existing methods. One of these is the Iozia – Leith method which uses a logarithmic expression (logistic equation to calculate an "optimized cyclone efficiency)."

BASE EQUATIONS – EFFICIENCY MODELS AND PRESSURE DROP

EFFICIENCY MODELS

As discussed in the previous section there are two force models Lapple (Force Balance) and Barth (Static Particle) plus the Leith-Licht method(approximation of particulate turbulence, and back mixing in the cyclone and the Ioxia-Leith which predicts efficiency better then Lappel or Leich – Licht. It however has limited confirmation with Plant data . The base equations are listed below.

LAPPEL

Reference Equations 9 and 10

BARTH

Dpc = ((9*μ* Q) / (Π* ρ* Zc *vtmax^2))^0.5 -----12

Rc = 0.52*(Dc/2)*(WH/Dc^2)^-0.25*(De/Dc)^1.53 ------13

$$Zc = \frac{(L-S)*((L - Lb)*(2Rc)}{((Dc/De)-1)\ (De)} \quad \text{if } 2Rc > Do \qquad \text{--14}$$

Zc = (Lb - S) if 2Rc< Do ----15

Vtmax = 6.1*vi* ((WH/Dc^2)^0.61*(Dc/De)^-0.74*(L/Dc)^-0.33 -------16

LEITH-LICHT

Nt = (Q/WH)*(0.1079 - 0.00077*(Q/WH) + 1.906E-6*(Q/WH)^2) ------17

Dpc = ((9*μ*Q)/(π*ρ*Zc* vtmax^2))^.5 -------18

IOXIA-LEITH

η = (1/((1 + (**dc/d)**^β)) **--------19**

ln(β) = 0.62 – 0.87*ln(dpc)+5.21*ln(W*H/Dc^2) + 1.95(lnv(W*H/Dc^2)) ------20

PRESSURE DROP EQUATIONS

DIRGO

ΔH = 19.7*(H*W/Dc^2)^.99*(S/Dc)^.35*(L/Dc)^-.34*(Lb/Dc)^-.35*(Do/Dc)^-.33 ------21

ΔP = ΔH*(0.5*ρ* vi^2) ---22

CASEL ET AL.

Nh = 11.3*(W*H/Dc^2)^2 + 3,3 ------23

LAPPEL

Nh = 16*((W*H)/De ----- 24

ΔP = 0.192ρ(gas)*vi^2/2gc ------25

USER GUIDE

1.1 This template has 3 visible worksheets. READMEFIRST IS PART OF THIS FILE
CALCULATION is the user's interface to enter data required for cyclone design
REPORT1&2 are preformatted pages linked to CALCULATION for your design report
To complete just add comments in DESIGN CONDITIONS & CONCLUSIONS

1.2 Before using the program please check the REPORT and CALCULATION sheets to familiarize yourself with their layout and contents. Make a special note of the instructions in green font in the CALCULATION sheet before you use it for the first time. ONLY MAKE DATA ENTRIES TO THE CALCULATION SHEET AND ONLY TO SAND COLOURED CELLS AND/OR YELLOW CELLS. Do not make entries to any other page or cell without ensuring you have a working backup just in case something goes wrong. ONLY INSTRUCTIONS ARE 'LOCKED' SO MAKE CHANGES TO THE PROGRAM IF YOU WISH BUT PLEASE BACK UP FIRST!

1.3 The Calculation sheet contains a chart with 10 different cyclone types to select from for your design. Select a cyclone enter its dimensional parameters into sand colored cells in 'the cyclone dimensional parameter input

Please note that we have left the method of entering a cyclone's dimensional data as a two step manual operation
This was done so that you can manually enter your own cyclone data if your cyclone does not match one on the chart.

PROCESS CONDITIONS

ENTER TOTAL GAS FLOW & # OF CYCLONES PLUS GAS TEMP AND PRESSURE
USE GAS BUTTON OR MANUAL ENTER GAS, VISCOSITY, DENSITY IN YELLOW CELLS
ENTER PARTICLE DENSITY AND PARTICLE SIZE DISTRIBUTION IF KNOWN (SEE 3.0 BELOW)
SIZE YOUR CYCLONE INPUT "D" IN CYCLONE PROPERTIES TABLE (SEE 2.1)
ENTER CYCLONEnumber (1-10) INTO PARAMETER INPUT TABLE (used in your Leith Licht design and calculations.

This template can be used for single or multi cyclones - the procedure for this follows in 4.0 below and is briefly described in the Calculation Sheet .

2.1 There are two modes for using this template - a Cyclone has been selected and you are checking its capabilities or no Cyclone has been selected and you are selecting one using the cyclone presizer to determine a best guess Collector for the initial calculations. To use the presizer enter gas flow rate Q plus H/D & W/D for cyclone selected and the presizer calculates the cyclone diameter D (size) for the cyclone you wish to evaluate. The presizer provides the D factor(see 1.3 above) to use calculate cyclone dimensions to use with process properties for the full test.

2.2 Included at the bottom of this page are two FISHER KLOSTERMAN CYCLONEs which were evaluated a SIZE 21 MODEL XQ120 & a MODEL XQ340. The first one was checked as follows:
The collection efficiency and pressure drop was calculated using the equations developed for this template. The pressure drop - velocity relationship showed good agreement with that calculated using the Manufacturers equipment specific methodology'. The efficiency was lower then the Manufacturers', however, by using a collector factor resulted in a reasonable agreement (95% collection efficiency vs 91%). Why use a factor? Per EPA (see below), efficiency varies greatly with cyclone design and increases with the number of turns (revolutions) the gas makes in the cyclone. Revolutions that the gas makes is a theoretical number(Ne) which has been calculated for generic collectors, and is a significant impactor upon efficiency. Adding a factor is reasonable based on using the factor with a second F-K cyclone (model XQ340) and evaluating it on the same basis. In both instances there was good agreement wiith MANUFACTURERS site data. for the calculation of Dpc which is tabulated below

F-K CYCLONE SIZE	F-K CYCLONE MODEL	Vi fps	Dpc EZZE	Dpc F-K
21	XQ120	57	2.33	2.177
21	XQ340	57	3.91	3.697

The F-K CYCLONE FACTOR is 2.0 . The CYCLONE FACTOR for generic and other cyclones is 1.0.

2.3 This method may be valid for fitting the generic theory to other Manufacturer's published performance claims. The ultimate test is confirming the equations with plant data. Until confirmed with field data this technique is only theoretical fitting equations to manufacturer performance claims. It does however provide a basis to do a preliminary evaluation of how his equipment(compare sizes, models, options) might perform in your process.

3 If you know the particle size distribution in the feed to the cyclone the program can estimate the efficiency for each of the fractions. This is done automatically just enter your data in the same format as the example. There are 8 micron ranges from 0 to 2; 2 to 4 .with weight %s for each range. The sum of 8 ranges is 100. The program is set for 8 ranges, However, if you only have say 6 ranges that is ok just make that the amount for the last two ranges are 0 and that your total wt % for the six fractions equals 100. You can enter micron ranges other then that currently o the calculation sheet just make sure te ranges listed are continuous from minimum (0 my example) to maximum (100 my exqmple) .

4 In some cases, due to capacity and/or space constraints it may be more practical to use a 'multi cyclone. The method for doing this is as follows. Consider the multiunit as a single unit for the exhaust from and inlet to the multiclone. Internally it is split up into a set of equal gas flows equal to the number of cyclones in the multiclone. Each of the cyclones work as if it were a single cyclone (gas+dust in, cyclonic forces=dust out dust exit and gas + less dust out the exhaust into the common exhaust. Each cyclone operates independently but additive in the overrall system

5 The results of your Cyclone investigation are automatically summarized on a report page which is setup for printing. Just add your comments and your report is ready to print!

7 In the program there are four calculation methods used for EFFICIENCY- plus a "future" method..The methods will be discussed in 8.0 (below). The first method (Lapple) is most common in printed literature, has been confirmed with published data and appears to be the most widely accepted by industry and government. The second method (Leith and Licht) takes into consideration back mixing of uncollected particles plus it is more responsive to changes in De and S. For this reason it has been found to be most useful as a check on the Lapple efficiency calculation and for efficiency comparisons if you are changing cyclone parameters from the standard ratios.

8 There is much research to develop the most accurate models to calculate efficiency and pressure drop but most are accurate for a limited number of cyclone types and/or operating conditions.///. Two procedures are presented which were developed by doing a statistical analysis of 98 cyclone types - Dirgo and Leith (Pressure Drop) + Iozia and Leith (Efficiency). An additional method (Barth) is also included because it is gives an alternate approach to the calculation of efficiency as noted below. The limitations for the models are presented in literature listed above and will be noted below. Also note that there are more pressure drop caculation procedures added which will also be discussed below.

9 There are two report pages to choose from. Just add your comments and print either or both. The calculation sheet is also setup to be printed if you wish.

NOMENCLATURE

Dc	Cyclone main body (cylinder) diameter	(L)
H	Height of gas inlet nozzle	(L)
W	Width of gas inlet nozzle	(L)
De	Diameter of gas outlet nozzle	(L)
S	Distance vortex finder extends into cyclone	(L)
Lb	Cyclone cylinder body length	(L)
Lc	Cyclone cone section length	(L)
Do	Diameter solids outlet nozzle	(L)
Vi	Inlet velocity to cyclone	(L/T)

Vs	Saltation velocity(velocity at which solids Start to settle out of gas stream)	(L/T)
Pd	Pressure drop through cyclone	(M/A)
Eu	Euler number	(-)
Re	Reynolds number	(-)
St	Stokes number	(-)
'k'	length of vortex below vortex finder	(L)
'd'	diameter of vortex distance k	(L)
Td	Gas residence time outer vortex	(T)
Ne	Number of turns for vortex	(#)
Nh	Number of velocity heads at inlet	(#)
Dpc	Diameter of particles collected 50% efficiency	(L)

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