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Integrated Design of Cyclone and Multi-Cones for Controlling Dust Emissions

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***Abstract*: Cyclone is a Structure without moving parts having Inlet velocity of gas stream transformed into a confined vortex or spiral flow downward between walls of gas discharge outlet and body of cyclone or main vortex where in centrifugal force created which tend to drive particles to the wall of cyclone. The industries generate and emit Dust Emissions from various processes either in the form of fugitive or channelized emissions. These dust particles are either coarser or fine in nature. The coarser particles can easily be controlled by Cyclones of standard design, but fine dust particles are required to be controlled by designing high efficiency Cyclones. An effort has been made in the present paper for integrated design of Cyclones and Multi-Cones which may be employed in the field to arrest Dust Emissions from industries.**

Cyclone design:
Principles:

- Works on centrifugal action
- Throws heavy particles to the side of Cyclone
- particles slide down into hopper bottom of Cyclone
- Operates with two vortexes
- High separation factor, ratio of radial velocity to the Stokes velocity

$V_s = \rho D^2 g / 18 \mu$

V_R = Radial velocity = $D^2 \rho V_T^2 / 18 R \mu$

Where,

V_T is tangential velocity

Thus,

$S = V_R / V_s = V_T^2 / R g$

For typical parameters of R = 6 inches and V_T = 50 ft / s,

Separation factor, $S = V_R / V_s = 2500 / 0.5 * 32 = 155$

In practice S ranges from 5 for large diameter, low resistance cyclones to 2500 for small diameter, high resistance devices.

Properties of the vortex:

The tangential velocity of gas in the vortex (V_t) increases as radius decreases from the radius of cyclone body (R_p)

In the main vortex,

$$\mathbf{V_t = V_{tp} (R_p / R)^n}$$

Where
V_t = tangential velocity at radius R, ft / s
V_{tp} = tangential velocity at body wall, ft / s
R_p = radius of cyclone body, ft
R = radius, ft
n = exponent, dimensionless, for ideal gas n = 1 , real values are between 0.5 to 1 , depending upon radius of cyclone body and gas temp.

- Vortex core is smaller in dia than gas outlet
- Radius of core is between 0.2 to 0.4 times the radius of gas outlet
- Radius of max. tangential velocity is 0.4 to 0.8 times gas outlet radius

Separation of the dust particles in the vortex:

- Particles are separated from gas by centrifugal force
- Drives the particles towards cyclone wall
- Radial force imparted to particle is

$$\mathbf{F_s = M_p V_p^2 / g R}$$

Where,

F_s = separating force, pounds
M_p = particle mass, pounds
V_p = particle tangential velocity, ft / s
G = gravitational constant, 32.2 ft / s / s
R = radius of rotation, ft

Assuming that particle velocity is same as gas velocity and introducing particle mass , the separating force becomes,

$$\mathbf{F_s = \beta \rho_p Dp V_{tp}^2 R_p^{2n} / g R^{(2n+1)}}$$

Where,

ρ_p = particle density , lb / ft^2
D_p = particle dia , ft
β= volume shape factor , dimensionless

Size of particle collected in cyclone

$$\mathbf{D_{cp} = \sqrt{9 \mu W_i / 2 \pi N_e V_i (\rho_p - \rho)}}$$

Where,

D_{cp} = cut size, that size which collected at 50 % efficiency
µ = gas viscosity , lb / ft-sec
W_i = inlet width , ft
N_e = effective no. of turns in cyclone (5 to 10 for typical cyclone)
V_i = gas inlet velocity , ft / sec
ρ_p = particle density , lb / ft ^{3}
ρ = gas density , lb / ft ^{3}

Cyclone efficiency:

Efficiency will increase with increase in :

- Dust particle size
- Particle density
- Gas inlet velocity
- Cyclone body or cone length
- Ratio of body diameter to gas outlet diameter

Efficiency will decrease with :

- Increase in gas viscosity or density
- Cyclone diameter
- Gas outlet diameter
- Inlet width or inlet area

Cyclones are generally divided into conventional and high efficiency. High efficiency cyclones have smaller dia upto about 9 inches, achieve greater separating force.

Pressure drop:

Cyclone resistance is assumed to be a function of gas inlet area and outlet area in the form of:

$$\Delta P_c = C\, H_i\, W_i / d_o^2$$

Where,

ΔP_c = Cyclone resistance, no. of inlet velocity heads
C = Proportionality constant
H_i = Inlet height, ft
W_i = Inlet width, ft
d_o = Gas outlet dia, ft

C can be determined from :

$$C = 4.62\, R_o / R_v \{[(R_p / R_o)^{2n} - 1] ((1- n) / n) + f (R_p / R_o)^{2n})) \}$$

Where,

R_o = Gas outlet radius, ft
R_p = Body radius, ft
f = Varies with n

n	**0**	**0.2**	**0.4**	**0.6**	**0.8**
f	**1.90**	**1.94**	**2.04**	**2.21**	**2.40**

Values of exponent n can be determined from graph

Design factors affecting efficiency and pressure drop

● Body diameter and dimension ratios:

- Cyclone of high efficiency and high pressure drop could be designed by :
- Increasing length of cyclone, minimum 8 times outlet dia.
- Decreasing inlet width
- Increasing ratio of body dia to outlet dia up to 3
- Smaller body dia.
- Ht of main vortex zone should be at least 5.5 times gas outlet diameter, preferably more, upto 12 times outlet dia.

● Cone design

- Apex cone dia should be greater than ¼ th the gas outlet dia to prevent vortex core from touching wall of cone and reentraining collected dust.

● Inlet design

- Cyclone inlet design is of critical importance to both efficiency and pressure drop. Tangential inlets are Standard type with expanding or nonexpanding vanes, Helical, and Involute types.
- Inlets should be such that incoming gas does not have interference with the mass of gas already rotating in the annulus and suppression of vortex.
- Most commercial Cyclones do not have helical type inlets.
- Involute inlet minimizes the interference between these gas streams. Use of multiple Involute inlets has advantage that for the same inlet area and height, inlet width is reduced.
- Tangential inlets with nonexpanding inlet vanes result in ½ pressure drop of the same cyclone without vanes whereas expanding vanes reduces pressure drop by ¼ th.
- Approach duct to common cyclone is usually round, and if a proper inlet height to width ratio is to be obtained, round duct is to gradually be transformed to rectangular inlet with maximum included angle of 15° or less.

● Dust discharge

- Where negative pressure exits at the bottom of cyclone, provide rotary valves, double set of valves, choke discharge screw conveyers, automatic flap valves
- Inflow of gas at the dust discharge is to be prevented by installing an auxiliary fan to maintain a positive gas flow outward – called " purge " flow. A purge flow of 10% of gas throughput may decrease dust emission by 20 – 28 %.

● Gas outlet design

- Eddy currents in annulus of cyclone require extension of gas outlet into body of cyclone to minimize loss of dust through gas outlet
- Length of gas outlet extension to be about 1 gas outlet dia. and slight below bottom of gas inlet
- Gas flowing out of gas outlet extension is in vortex flow and contains energy and separate dust from gas stream by centrifugal force. This energy and pressure needs to be recovered
- Most successful pressure recovery devices on the outlet are Involute scroll or outlet drum
- Involute scroll is designed as duct expansion wrapped around circle, receiving gases at high rotational velocity near the wall of gas outlet pipe and converting the kinetic energy into to static pressure by gradual expansion
- Outlet drum operates as a cyclone in reverse tending to convert vortex flow back into linear flow. Decreasing the pressure drop of cyclone by 5 to 10 % without affecting dust collection efficiency.
- Vortex in gas outlet pipe also concentrates dust near wall of outlet, thus installation of skimmers to shave of dust rich layer can further improve collection efficiency. Purge flow through such skimmers must be induced by a separate fan.

● Effect of internal roughness:

- Increased roughness may induce local eddy currents, reduces vortex intensity, reduce pressure drop and also collection efficiency.

Effect of operating variables on cyclone performance:

● Flow rate

- Pressure drop varies with the square of flow rate and therefore inlet velocity
- Efficiency increases with increasing flow rate up to some limiting velocity, above which internal turbulence increases more rapidly than separation,
- Thus causing decrease in efficiency with further increase in flow rate
- Variation of efficiency with flow rate over short ranges of flow may be estimated by :

$$100 - \eta a / 100 - \eta b = (Qb / Qa)^{0.5}$$

Where,

η_a = collection efficiency, wt percent at condition a
η_b = collection efficiency, wt percent at condition b
Q_b = flow ft^3 / minute at condition b
Q_a = flow ft^3 / minute at condition a

● Physical properties of the gas

- Pressure drop of cyclone is affected by temp., density and pressure of the gas as shown by :

$$h = K Q^2 P \rho_g / T$$

Where,

h = pressure drop, inches water gauge
K = proportionality constant
Q = flow rate, ft^3 / minute
P = absolute pressure, atmosphere
ρ_g = gas density, lb / ft^3
T = absolute temp., °R

- Viscosity of gas increases with increasing temp., efficiency will decrease

- **Relation between efficiency and gas viscosity at constant flow rate is :**

$$100 - \eta_a / 100 - \eta_b = (\mu_a / \mu_b)^{0.5}$$

Where,

μ = viscosity at conditions a and b in any consistent units

Relationship between efficiency and gas density is :

$$100 - \eta_a / 100 - \eta_a = ((\rho_p - \rho_{gb}) / (\rho_p - \rho_{ga}))^{0.5}$$

Where,

ρ_p = density dust particle, lb / ft^3
ρ_g = density of gas at condition a and b, lb / ft^3

- **Properties of the dust**

- Properties of dust to be collected represents most important variable in cyclone efficiency.
- Physical properties like particle size and density are important for cyclone efficiency whereas chemical properties will affect the cyclone operation.

- **Dust loading**

- Increased dust loading to cyclone causes pressure drop to be lower and efficiency to be increased
- Small dia. cyclones are seldom used for high dust loading due to erosion and plugging.
- Pressure drop at dust load of 75 – 100 grains /ft3 will be in the range of 75 – 85 % of clean air.

$$\Delta P_d = \Delta P_c / (0.013 \sqrt{C_1} + 1)$$

Where,

Δ_{Pd} = pressure drop with dust load
Δ_{Pc} = pressure drop with clean air
C_i = Inlet dust concentration, grains / ft^3

- **Relationship between dust loading and collection efficiency:**

$$100 - \eta_a / 100 - \eta_b = (C_{bi} / C_{ai})^{0.182}$$

Where,

η = efficiency at conditions a and b
C = inlet concentration at conditions a and b, gr./ft^3

- **Parallel Cyclone operation**

- Where high efficiency cyclones are used, they are put in parallel to achieve practical gas volume
- If number of cyclone in parallel is small, each cyclone should have its own inlet and dust bin
- If number of cyclone in parallel is large, the only practical arrangement is to use common inlet plenum chamber, a common dust bin, and common outlet plenum chanber.

- Equal distribution of gas and dust load is necessary in each cyclone to prevent backflow through individual cyclone, plugging of cyclones, and re-entrainment from the dust bin.
- Inlet, outlet plenums and dust bin should be designed so that pressure relationship between these three chambers is same at all portions of the housing.
- In order to minimize dust outlet plugging in parallel cyclone operation, provide a small purge out of the dust collection hopper through purge fan with a rate of about 5% of the total gas flow.

- **Series cyclone operation**

  - **Efficiency of two cyclone collectors operating in series is expressed by :**

$$\eta = \eta_p + \eta_s \,(100 - \eta_p)$$

Where,
η = efficiency combined cyclones
η_p = efficiency of primary cyclone
η_s = efficiency of secondary cyclone (based on inlet dust load to it)
Efficiency of second cyclone is less than primary cyclone, around 50 %.

- **Optimizing cyclone design and performance**

  - **The term C D2 / a b is defined to include all cyclone dimension ratios which are listed below :**

a / D
b / D
De / D
S / D
h / H
H / D
B / D

Where,

a = gas inlet height
b = gas inlet width
D = cyclone diameter
C = cyclone geometry coefficient
De = gas exit duct diameter
S = gas exit duct length
h = cylinder height
H = overall height
B = dust outlet diameter

Limitations

$a / D \leq S / D$
$S / D \leq h / D$

- **Relationship between velocity head and velocity yields**

$$P = g\, \rho_L\, D^4\, \Delta P / 8\, \rho_g\, Q_g^2$$

Where,

P = cyclone pressure drop coefficient
g = acceleration of gravity
ρ_L = density of gauge liquid
D = cyclone diameter
ΔP = pressure drop
ρ_g = density of gas
Q_g = gas throughput

  - **After considering length of vortex and other geometric relations and constraints, an equation is obtained :**

$$C^* D^2 / a^* b = \pi * P^2 * (D_e / D)^4 * \{ 2* [1 - (D_e / D)^2] * [H / D - 2.3*P^{1/3} * (D_e / D)^{5/3} - 1 / (P^* (D_e / D)^2 *(1 - D_e / D)))] + (1 / 3) * ((H - h) / D))*[1 + B / D + (B / D)^2] + [1 - (D_e / D)^2]* [2.3 *P^{1/3} * (D_e / D)^{5/3}] + h / D - H / D \}$$

Above equation holds good, if

H / D = 5

h / D = 3

Assuming a value for B / D (a most important ratio) as 0.375, and substituting values for H / D and h / D , an expression for $C D^2 / a b$ is obtained which depends only on D_e / D and P. Values of $C D^2 / a b$ may be maximized in terms of D_e / D for a range of values of P, and all other dimension ratios calculated as a function of D_e / D. The value of optimized C is then computed from :

$$C = \pi*D^2/a*b\{2*[1-(D_e/D)^2](S/D-a/2*D)+(1/3)*((S+l-h)/D)*[1+d/D+(d/D)^2]+h/D-(D_e/D)^2*l/D-S/D\}$$

Where,

$$l/D = 2.3*(D_e/D)*((D^2)/(a*b)^{1/3})$$

- **Standard cyclone proportions**

Diameter of cyclone = D_2
Length of cylinder = $L_1 = 2D_2$
Length of cone = $L_2 = 2D_2$
Diameter of exit = D_e = ½ D_2
Height of entrance = ½ D_2
Width of entrance = B = ¼ D_2
Dia of dust exit = Dd = ¼ D_2
Length of exit duct = L_3 = 1/8 D_2

- **Efficiency of cyclone for true cyclone flow is:**

$$\eta = 1 - \exp[-\rho_p*Q*d^2*\theta_1/18*\mu*W*r_2*(r_2-r_1)*\ln r_2/r_1]$$

$$\theta 1 =- 18*\mu*W*r2(r2-r1)*(\ln r2/r1)*\ln(1-\eta)/\rho p*Q*d2$$

- **For modified cyclone flow, eq. becomes :**

$$\eta = 1-\exp[-(1-n)*\rho_p*Q*d^2*\theta_1/18*\mu*W*(r_2^{\ 1-n}-r_1^{\ 1-n})*r_2^{\ n}(r_2-r_1)]$$

$$\theta_1 = - 18*\mu*W*(r_2^{\ 1-n}-r_1^{\ 1-n})*r_2^{\ n}*(r_2-r_1)\ln(1-\eta)/(1-n)*\rho_p*Q*d^2$$

The angle θ_1 is given as 2πN, where N is number of turns which the gas executes in traversing the length of cyclone

The value of W indicates ht of entry duct for tangential entry, helical, and involute entry. For axial entry:

$$W = 2*\pi*r_2*\cot\alpha_2$$

Where α_2 is the exit angle with respect to axial direction measured at the outer radius.

$$\theta_1 = 2\pi L/W$$

Tangential velocity = $V_t = Q/W(r_2-r_1)$

The value of n generally ranges from 0.5 to 0.7 for gas flows. Here, value of n is taken as 0.5, thus η and θ_1 becomes:

$$\eta = 1-\exp[-\rho_p*Q*d^2*\theta_1/36*\mu*W*(r_2-\sqrt{r_1*r_2})*(r_2-r_1)]$$

$$\theta_1 = 36*\mu*W*(r_2-\sqrt{r_1*r_2})*(r_2-r_1)*\ln(1-n)/\rho_p*Q*d^2$$

Tangential velocity can be computed as

$$V_t = Q/W*(r_2-r_1)$$

The collection efficiency expression is based on particle size for which collection efficiency is 0.5, expressed as $d_{0.5}$ and referred to as particle cut size. The eq. for $d_{0.5}$ for tangential, helical, involute velocity is :

$$d_{0.5} = \sqrt{9*\mu*B^{2*}H/\rho_p*Q*\theta_1}$$

The value θ in above eq. represents effective no. of turns which the gas makes in traversing the cyclone. Approximately, the value of θ_1 is given by:

$$\theta_1 = 2*\pi*(L_1+L_2/2)/H = \pi*(2*L_1+L_2)/H$$

Above eq. gives $\theta_1 = 12\pi$ for a cyclone of standard proportions

For axial entry, $d_{0.5}$ is

$$d_{0.5} = \sqrt{27*\pi*\mu*B^2/\rho_p*Q*\theta_1*\tan\alpha}$$

● Multiple cyclones

- Efficiency of cyclone increases as the dia of cyclone reduced even if tangential velocity remains constant
- Higher efficiency dictates use of smaller cyclones
- Pressure drop increases as tangential velocity increases
- If cyclone is made smaller while tangential velocity remains same, the flow which the cyclone can handle is reduced by square of cyclone dia. Thus, multi cyclones are used to take care of complete flow.

● Pressure drop and power requirement

Power required to overcome pressure is given by:

$$W = Q\,\Delta P$$

Pressure drop is given as:

$$\Delta P = C*B*H*\rho*V_t^2 / D_e^2*2$$

Equation in terms of flow is :

$$\Delta P = C*\rho*Q^2 / 2*D_e^2*B*H$$

Constant C is given by :

$$C = 4.62*D_e/D_2\{[\,(D_2/D_e)^{2n} -1\,]*((1-n)/(n)) + f*(D_2/D_e)^{2n}$$

Where f is given in terms of n as :

n	**0**	**0.2**	**0.4**	**0.6**	**0.8**
f	**1.90**	**1.94**	**2.04**	**2.21**	**2.40**

$$W = C*\rho*Q^3 / 2*D_e^2*B*H$$

For cyclone of standard proportions :

$$\Delta P = 16*C*\rho*Q^2 / D_2^4$$

$$W = 16*C*\rho*Q^3 / D_2^4$$

Conclusions: Design of Cyclones and Multi-Cones with proper integrated design having regard to various operating conditions and compatible input parameters can control Dust Emissions to the extent of more than 90 percent and can easily achieve the emission norms prescribed for different industries. Moreover, the Cyclones and Multi-Cones are easy to maintain or operate with cost-effectiveness on capital and recurring expenditure front.

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