Analysis of Cyclone Pressure Drop

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Abstract

A new method to analysis cyclone pressure drop is reported. The frictional pressure loss is the primary pressure loss in a cyclone. The air stream travel distance is a function of cyclone diameter. The frictional pressure loss is independent of a cyclone diameter, therefore cyclone total pressure loss is independent of cyclone diameter.

Introduction

Cyclone separators use centrifugal force to separate suspended particulate matter from the air stream. A cyclone consists of a cylindrical upper body with a conical lower section and a smaller center cylinder that extends from the top to just below the entrance through which the relatively clean air is discharged (Figure 1.). The dust-laden air stream enters tangentially at the top of the barrel portion of the cyclone and travels downward into the cone portion of the cyclone forming an outer vortex. The increasing air velocity in the outer vortex results in an increased centrifugal force on the particles separating them from the air stream. When the air reaches the bottom of the cone, an inner vortex is created reversing the air stream direction in the center of the cone. The air stream leaves the cyclone through the center cylinder at the top of the cyclone while the particulate falls into the dust collection hopper attached to the bottom of the cyclone.

The operation of a cyclone is relatively simple but not completely understood. Extensive work has been completed to determine how the cyclone dimensions and its operating conditions affect its performance. However, the engineering data associated with air and particle flow patterns in the cyclone are difficult to accurately measure. The current cyclone design theory is based partly on theoretical analysis and partly on empirical models. The goal of this work is to develop a sound science description of the operation of a cyclone that can be used to facilitate engineering design with a minimum of empirical data.

The three parameters used to evaluate the cyclone performance are emission concentrations, collection efficiency as a function of particle size and energy consumption (pressure drop) as a function of inlet velocity. Cyclone pressure drop associated with the operation of the cyclone is a major factor to be considered in the design of a cyclone collection system. Many models have been developed to determine drop such as Shepherd and Lapple equation (1939), Stairmand equation (1949, 1951), First equation (1950) and Stern equation (1977). However, the equations are either empirical models or involve variables and dimensionless parameters not easily accounted for in practical applications. It is known that cyclone pressure drop is dependent on the cyclone design and its operating parameters such as inlet velocity. The empirical models cannot be used for all the cyclone designs as new cyclone technology and new cyclone designs are developed. Further theoretical research is needed to scientifically evaluate the cyclone performance including predicting cyclone pressure drop.

Cyclone Theory

The air flow pattern in a cyclone rotational field is rather complex. It can be characterized by three velocity components such as tangential velocity, axial velocity and radial velocity. Ter Linden (1949) first measured the details of the flow field in a cyclone and described the air flow tangential velocity distribution and the pressure distribution in a cyclone as given by the Figure 2.

After the air stream enters the cyclone, it will spiral downward because of centrifugal and frictional forces. In the outer vortex, the total air flow velocity consists of tangential velocity, radial velocity and axial velocity. The tangential velocity is the dominant velocity component. It also determines the centrifugal force applied to the air stream. The tangential velocity can be described as follows:

$$V_t * r^n = C \qquad (1)$$

where:

V_t = tangential velocity,
r = rotational radius,
n = flow pattern factor,
n = 0.5~0.8 (in outer vortex)
n = 0 at the boundary of inner vortex and outer vortex
n = -1 in inner vortex
C = constant. (guangda Ma,1983)

The tangential velocity increases with the decreasing of the rotational radius in the outer vortex. It increases to the maximum at the boundary of the outer vortex and inner vortex. In the inner vortex the tangential velocity decreases as the rotational radius decrease. In the inner vortex, the relationship of the tangential velocity and the rotational radius can be modeled by the following equation:

$$\frac{V_t}{r} = \omega = C \qquad (2)$$

where:

V_t = tangential velocity,
ω = angular velocity,
C = constant.

The pressure distribution in a cyclone varies with different cyclone designs. The rotation of the air-flow establishes a pressure field. The highest pressure is located at the wall of the cyclone. The pressure decreases with the reduction of the rotational radius because of the increasing tangential velocity. In the radial direction, there is a significant pressure drop caused by the change of the tangential velocity, since the increasing of the tangential velocity causes a large radial acceleration. This pressure change in the radial direction can be expressed by the following equation:

$$\frac{dP}{dr} = \rho * \frac{V_t^2}{r} \qquad (3)$$

where:

dP = change of the pressure,
dr = change of the rotation radius,
V_t = tangential velocity,
R = rotational radius, and
ρ = air density.

The solution of the equation 3 is:

$$P = \rho * V_t * \ln(r) + C \quad (4)$$

This solution gives the pressure distribution in the cyclone flow field.

Analysis of the Cyclone Pressure Drop

The cyclone pressure drop is a function of the cyclone dimensions and its operating conditions. Shepherd and Lapple (1939, 1940) determined the optimum dimensions of cyclones based on the body diameter. Such general relationships have allowed for a simplified analysis. The definition of the cyclone dimensions is shown in the Figure 3.

The pressure drop over a cyclone is caused by the area changes, the wall friction, change of the flow direction and the dissipation in the vortex finder (outlet tube). Because of these effects, the cyclone pressure drop is mainly composed of the following parts:

(1) ΔP_1 --- the entry pressure loss in the tangential inlet duct.

(2) ΔP_2 --- the frictional loss along the total spiral travel distance in the outer vortex, caused by the wall friction.

(3) ΔP_3 --- the pressure loss caused the change of the air flow direction from the outer vortex to the inner vortex (approximately "U" turn).

(4) ΔP_4 --- the entry pressure loss from the point that air enters the inner vortex to the point that air leaves the outlet tube. To determine this part of pressure loss, an assumption is made that the inner vortex forms an imaginary solid cylinder whose outer surface is the boundary between the inner vortex and the outer vortex. This cylinder starts at the point that air enters the inner vortex and ends at the bottom of the outlet tube. The diameter of this inner vortex cylinder is 0.6 times the outlet tube diameter (Ter Linden, 1949, Guangda Ma, 1983).

Entry Pressure Loss in the Tangential Inlet Duct (ΔP_1)

In this part, the pressure loss is caused by the inlet duct area changes. It can be determined as follows:

$$\Delta P_1 = C * VP_i \quad (5)$$

where:

ΔP_1 = dynamic pressure loss in the inlet duct,
C = dynamic loss constant, and
VP_i= cyclone inlet velocity pressure

Frictional Pressure Loss (ΔP_2)

This part of pressure loss is the pressure loss in the cyclone outer vortex caused by the friction of the gas/surface wall. In the outer vortex, air stream flows in a downward spiral through the cyclone. It may be considered as the air stream travels in a imaginary spiral tube with diameter D_s and length L (the air stream travel distance in the outer vortex). It can be determined as follows:

$$\Delta P_2 = f * \frac{L}{D_s} * VP_{si} \quad (6)$$

where:

ΔP_2 = the frictional pressure loss,
f = friction factor, dimensionless ,
L = total travel distance,
D_s = the imaginary spiral tube diameter, and
VP_{si}= air stream inlet velocity pressure in the imaginary spiral tube.

The imaginary spiral tube diameter can be approximated by the following equation:

$$D_s = \left(\frac{D_c - D_e}{2}\right) \quad (7)$$

where:

D_s = the imaginary spiral tube diameter,
D_c = cyclone barrel diameter, and
D_e = cyclone outlet tube diameter.

The travel distance (L) consists of the travel distance in the zone Z_1 (L_1) plus the travel distance in the zone Z_2 (L_2).

<u>Travel distance in the barrel portion (zone Z_1) --- L_1</u>

The air-flow in the zone Z_1 only has two velocity components: tangential velocity (V_t) and the axial velocity (V_z) (see Figure 3.). The tangential velocity and axial velocity in this zone are constant. As a result, the travel distance in this zone can be determined by the following equation:

$$L_1 = \int_0^{t_1} \left|\vec{V}_{t1} + \vec{V}_{z1}\right| dt$$

$$= \int_0^{z_1} \sqrt{V_{t1}^2 + V_{z1}^2}\, \frac{dz}{V_{z1}} \quad (8)$$

where:

L_1 = travel distance in the zone Z_1,
t_1 = travel time in the zone Z_1,
Z_1 = the total height of the zone Z_1,
V_{t1} = tangential velocity in the zone Z_1 ($V_{t1} = V_i$),
and
V_{z1} = axial velocity in the zone Z_1.

Because the air flow rate (Q) in a cyclone is constant, the axial velocity can be calculated by the following equation:

$$V_{z1} = \frac{2V_i}{3\pi} \quad \text{(for } D_e{=}D_c/2 \text{ design)}$$

$$= \frac{32V_i}{39\pi} \quad \text{(for } D_e{=}D_c/1.6 \text{ design)} \quad (9)$$

The equations (8) and (9) can be used to calculate L_1 as follows:

$$L_1 = \frac{3 * \pi * Z_1}{2} * \sqrt{1 + \left(\frac{2}{3\pi}\right)^2} \quad \text{(for } D_e{=}D_c/2 \text{ design)}$$

$$= \frac{39 * \pi * Z_1}{32} * \sqrt{1 + \left(\frac{32}{39\pi}\right)^2} \quad \text{(for } D_e{=}D_c/1.6 \text{ design)} \quad (10)$$

<u>Travel distance in the cone portion (zone Z_2) --- L_2</u>

In the zone Z_2, the total velocity consists of three components (V_t , V_z , V_r) (see Figure 3). The travel distance in this zone is calculated based on those three velocity components.

$$L_2 = \int_0^{t_2} \left| \vec{V}_{t2} + \vec{V}_{z2} + \vec{V}_{r2} \right| dt$$

$$= \int_0^{z_2} \sqrt{V_t^2 + V_z^2 + V_r^2} \frac{dz}{V_z}$$

(11)

where:

L_2 = travel distance in the zone Z_2,
t_2 = travel time in the zone Z_2,
Z_2 = the total height of the zone Z_2,
V_t = tangential velocity in the zone Z_2,
V_z = axial velocity in the zone Z_2, and
V_r = radial velocity.

In the zone Z_2, there is an axial acceleration caused by the change of the rotational radius (see Figures 3&4). The axial velocity at I-I cross section (V_{z1}) is determined by the equation 9 and V_{z2} can be determined by the equation 12:

$$V_{z2} = \frac{8 * V_i}{\pi} \quad \text{(for } D_{II} = D_c/4 \text{ design)},$$

$$= \frac{2 * V_i}{\pi} \quad \text{(for } D_{II} = D_c/2 \text{ design)} \qquad (12)$$

The following equation can be used to determine the axial velocity as the Z cross section:

$$V_z = \frac{V_{z2} - V_{z1}}{Z_2} * Z + V_{z1} \qquad (13)$$

where:

V_z = the axial velocity at Z cross section,
V_{z1} = the axial velocity at I-I cross section,
V_{z2} = the axial velocity at II-II cross section,
Z_2 = the total height of the cone portion, and
Z = the high distance from I-I cross section to Z cross section.

The radial velocity V_r is determined by the V_z (see Figure 5)

$$\left| \vec{V}_r \right| = tg\theta * \left| \vec{V}_z \right| \qquad (14)$$

where:

V_r = the radial velocity at Z cross section,
V_z = the axial velocity at Z cross section, and
θ = cyclone cone angle.

$$tg\theta = \left(\frac{D_c - D_{II}}{2} \right) / Z_2$$

$$= \frac{3D_c}{8Z_2} \quad \text{(for } D_{II} = D_c/4 \text{ design)} \qquad (15)$$

The travel distance L_2 in the zone Z_2 can be calculated by combining equations (11) through (15).

$$L_2 = \frac{3 * \pi * Z_2}{22} \left[\frac{s}{a} - \frac{1}{2} \ln \left| \frac{a + s}{a - s} \right| . \right]_{z=0}^{z=z_2} \qquad (16)$$

where:

L_2 = travel distance in the zone Z_2,
a = mathematical calculation factor for integration,

$$a = \sqrt{\frac{V_t^2}{1 + tg^2\theta}} = \sqrt{\frac{V_i^2}{1 + tg^2\theta}}$$

s = integrating transformation,

$$s = \sqrt{a^2 + V_z^2} = V_i \sqrt{\frac{1}{1 + tg^2\theta} + \left(\frac{22 * Z + 2 * Z_2}{3 * \pi * Z_2} \right)^2}$$

The total travel distance L is as:

$$L = \frac{3}{2} * \pi * Z_1 * \sqrt{1 + \left(\frac{2}{3\pi} \right)^2} +$$

$$\frac{3 * \pi * Z_2}{22} \left[\frac{s}{a} - \frac{1}{2} \ln \left| \frac{a + s}{a - s} \right| . \right]_{z=0}^{z=z_2} \qquad (17)$$

The Pressure Loss Caused by the Change of the Flow Direction (ΔP_3)

When the air stream travels to the bottom of the cyclone, the inner vortex reverses the flow direction. The directional change is approximately 180°. The pressure loss caused by this change may be considered as two 90°-elbow losses. However, the air travels to the bottom of the cyclone as a spiral and then reverses the direction in the inner vortex. The directional change is not as sharp as the flow in the 90- degree elbow, therefore, the fitting loss factor should be smaller than that used to calculate the 90-degree elbow pipe.

$$\Delta P_3 = 2 * \Delta P_{90} = 2 * K_{90} * VP_{II} \qquad (18)$$

where:

ΔP_3 = pressure loss caused by directional change,
K_{90} = fitting loss factor, dimensionless, and
VP_{II} = axial velocity pressure at the bottom of the cyclone.

Entry Pressure Loss at the Inner Vortex Entrance (ΔP_4)

The assumption has been made that the rotation of the inner vortex forms a imaginary solid cylinder which starts at the bottom of the cyclone and ends at the bottom of the outlet tube. The pressure loss from the entrance of the imaginary cylinder through the outlet tube can be considered as entry loss (see Figure 6).

$$\Delta P_4 = C * VP_{II} \qquad (19)$$

where:

ΔP_4 = entry pressure loss at the entrance of the inner vortex,
C = dynamic loss constant, and
VP_{II} = axial velocity pressure at the bottom of the cyclone.

Sample Pressure Drop Calculation and Discussions

1D3D @ V_i = 3200 fpm:

Assume: standard air $\rho = 0.075$ lb/ft^3, $VP_i = (V_i/4005)^2 = 0.638$ in H_2O

(1) $\Delta P_1 = C^* VP_i = 1^* 0.638 = 0.638$ in H_2O

(2) ΔP_2 : For 1D3D: tg $\theta = 1/8$, a=0.99V_i , $S_{z=0} = V_i$, $S_{z=Z2} = 2.73V_i$

$L = L_1 + L_2 = 4.82D_c + 5.14\ D_c = 9.96D_c$

$D_s = D_c/4$

$V_{si} * (\pi * D_s^2/4) = V_i * (D_c^2/8)$

$V_{si} = (8/\pi) * V_i = 8153$ fpm

$VP_{si} = (8153/4005)^2 = 4.14$ in H_2O

$\Delta P_2 = f * (L/D_s) * VP_{si} = 3.3$ in H_2O

$\Delta P_1 + \Delta P_2 = 0.638 + 3.3 = 3.938$ inch H_2O

The previous research (Askew, 1993) suggested that 1D3D cyclone pressure drop at design velocity was approximately 4.5 inch H_2O. The above sample calculation indicates that cyclone entry pressure loss (ΔP_1) and frictional loss in the outer vortex (ΔP_2) are the major pressure losses for 1D3D cyclone.

The following observations are made:

- In the 1D3D barrel portion, the travel distance (L_1) is 4.82D_c. The number of turns in this portion can be approximated by the following equation:

$$N = \frac{L_1}{\pi * D_c} = \frac{4.82 D_c}{\pi * D_c} = 1.53 \qquad (20)$$

According to the previous research (Parnell, 1996), there are approximately six turns in the 1D3D. If there are 1.5 turns in the barrel portion, therefore there are approximately 4.5 turns in the cone portion.

- $$\frac{L}{D_s} = \frac{9.96 D_c}{\frac{D_c}{4}} = 39.84 \qquad (21)$$

Equations (6) and (21) demonstrate that the frictional pressure drop is independent of the cyclone diameter. The cyclone entry pressure drop is also independent of the cyclone diameter. Therefore, the total 1D3D cyclone pressure-drop should be constant regardless of the cyclone size.

2D2D @ V_i = 3000 fpm:

Assume: standard air $\rho = 0.075$ lb/ft^3, $VP_i = (V_i/4005)^2 = 0.561$ in H_2O

(3) $\Delta P_1 = C^* VP_i = 1^* 0.561 = 0.561$ in H_2O

(4) ΔP_2 : For 1D3D: tg $\theta = 3/16$, a=0.983V_i , $S_{z=0} = V_i$, $S_{z=Z2} = 2.73V_i$

$L = L_1 + L_2 = 9.63D_c + 3.45\ D_c = 13.08D_c$

$D_s = D_c/4$

$V_{si} * (\pi * D_s^2/4) = V_i * (D_c^2/8)$

$V_{si} = (8/\pi) * V_i = 7639$ fpm

$VP_{si} = (7639/4005)^2 = 3.64$ in H_2O

$\Delta P_2 = f * (L/D_s) * VP_{si} = 3.8$ in H_2O

$\Delta P_1 + \Delta P_2 = 0.561 + 3.8 = 4.371$ inch H_2O

The cyclone entry pressure loss (ΔP_1) and air flow frictional loss in the outer vortex (ΔP_2) are the major pressure losses for 2D2D cyclone.

Similar observations are made for the 2D2D cyclone.

- In the 2D2D barrel portion, the travel distance (L_1) is 9.63D_c. The number of turns in this portion is three. Six turns were observed in the 2D2D. Therefore, there are three turns in the cone portion of a 2D2D cyclone.
- For 2D2D design, $$\frac{L}{D_s} = \frac{13.08 D_c}{\frac{D_c}{4}} = 52.32 \qquad (22)$$

The frictional pressure drop is independent of the cyclone diameter. As was the case with the 1D3D cyclone, the entry pressure drop is also independent of the cyclone diameter. Again, the total 2D2D cyclone pressure-drop should be constant regardless of the cyclone size.

Problem

There is a problem in the process used to calculate the cyclone frictional pressure drop addressed in this paper. (L/D_s) is used to obtain the major pressure loss in a cyclone. Here, L is the flow travel distance in the outer vortex, and it is also the length of the imaginary spiral tube. D_s is the imaginary spiral tube diameter. It is treated as a constant. As a matter of fact, D_s is not constant. It varies with the rotational radius. The smaller the diameter, the higher the pressure drop. Thus, errors were introduced by using a constant stream flow diameter. For this reason the calculated pressure drop for the 1D2D design is larger than that for the 1D3D in the given example. To reduce this error, the stream diameter will varied in future research.

Summary

Cyclone frictional pressure loss is the major pressure loss in a cyclone. A new assumption has been made to calculate this pressure loss. Air flow in the outer vortex is considered as traveling in a downward spiral tube. The travel distance was calculated based on the three velocity components. The travel distance is the length of the imaginary spiral tube. The diameter of the imaginary spiral tube is a function of the cyclone diameter and the diameter of the cyclone outlet tube. The length of the stream tube divided by its diameter is a constant for a certain cyclone design. The cyclone pressure drop is independent of the cyclone size (diameter).

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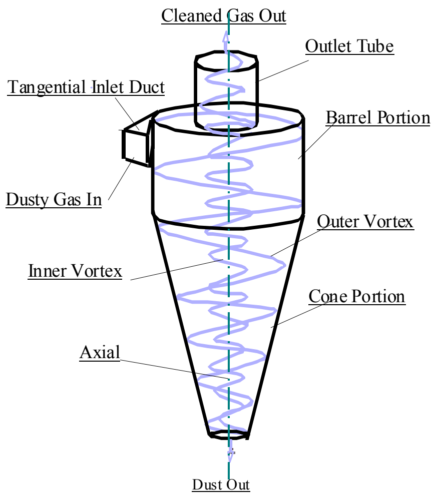

Figure 1. Schematic flow diagram of a cyclone

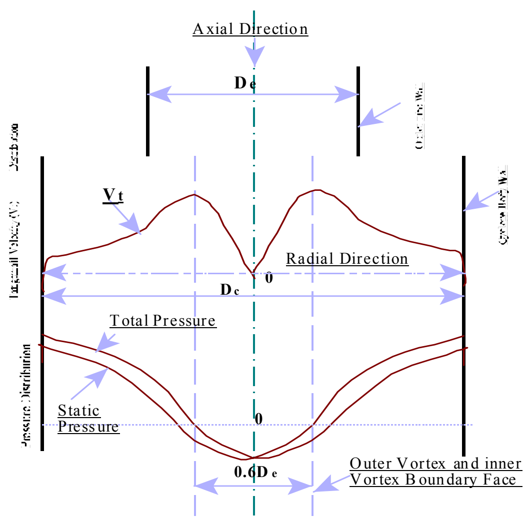

Figure 2. The tangential velocity and pressure distribution in a cyclone

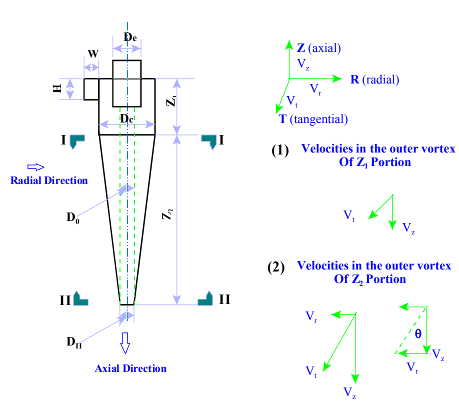

Figure 3. Cyclone dimensions and the velocity distributions

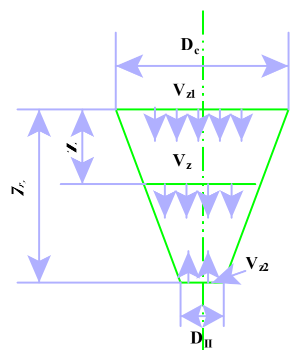

Figure 4. Axial velocity change zone

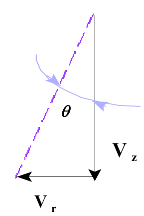

Figure 5. The radial velocity in the Z_2 zone

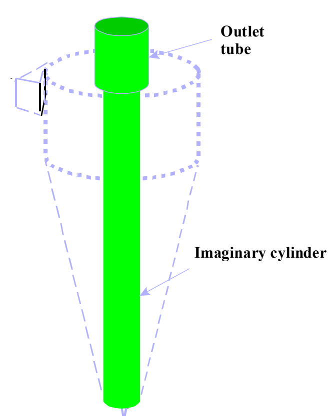

Figure 6. The imaginary inner vortex cylinder