CHAPTER 2

CYCLONES

Cyclone collectors use inertial force to separate particles from a rotating gas stream. There are two main types of cyclones: (1) large diameter cyclones and (2) small diameter multi-cyclones. Large diameter cyclones range in size from approximately 1 foot in diameter to more than 12 feet in diameter and are used for the collection of large diameter particulate matter that would otherwise settle out near the source and create a nuisance in the immediate area. Large diameter cyclones typically have operating pressure drops of 2 in. H_2O to 4 in. H_2O. Multi-cyclone collectors are groups of small diameter cyclones, typically 6 inches to 12 inches in diameter, which have better particulate removal capability than large diameter cyclones. The multi-cyclone units are used as stand-alone collectors on sources generating moderate-to-large particulate matter and are also used as pre-collectors to reduce the particle loading into fabric filters and electrostatic precipitators. Multi-cyclones typically have operating pressure drops greater than 4 in. H_2O.

Cyclone collectors are occasionally used as pre-collectors in air pollution control systems vulnerable to ember entrainment. While the embers do not damage cyclone components, the hoppers must be properly designed to prevent the accumulation of combustible material that could be ignited. Simmering fires in the hoppers could warp the tube sheet supporting the multi-cyclone tubes, crack welds and gaskets used to seal the tubes to the tube sheet, and damage the hopper casings.

Operating Principles

Cyclones use inertial force to separate particles from a gas stream. Because the inertial force is applied in a spinning gas stream, the inertial force is often termed centrifugal force. The first step in particle capture is the accumulation of particles along the inner wall of the cyclone due to centrifugal force.

For vertically oriented cyclones, settling the particles into a hopper is the second step in the overall process of particle capture. However, unlike electrostatic precipitators and fabric filters, there is little if any particle agglomeration to facilitate gravity settling, until the particles reach the cyclone tube discharge. The particles settle at a rate that is dependent partially on their terminal settling velocities. These settling rates are quite small for particles less than 10 micrometers in diameter. Fortunately, most particles in vertical cyclones also retain some momentum toward the hopper due to the motion of the gas stream passing through the cyclone. The combined effect of gravity settling and the momentum from the gas stream are sufficient to transport the particles from the cyclone wall to the cyclone tube discharge, and eventually to the hopper.

The third step in the overall particulate matter control process is the removal of accumulated solids from the hoppers. This is an especially important step because the cyclone outlets extend directly into the hoppers. The presence of high solids levels due to hopper discharge problems could block the outlets and make the cyclone entirely ineffective for particulate removal.

Several factors affect the performance of a cyclone collector. The more important ones are the size and mass of the particles, the gas velocity through the unit, the cyclone diameter, and the residence time of the gases in the cyclone. Since inertial forces are used to separate the particles from the gas stream, collection efficiency increases as the size and mass of the particle increases and as the gas velocity through the unit increases. Centrifugal force increases as the radius of turn decreases. As a result, smaller diameter cyclones are more efficient than larger diameter cyclones. Cyclones that have bodies and cones, that are long relative to their diameter have longer residence times and higher collection efficiencies. As a result of these factors and others, a range of performance can be achieved with cyclones, as shown in Figure 2-1.

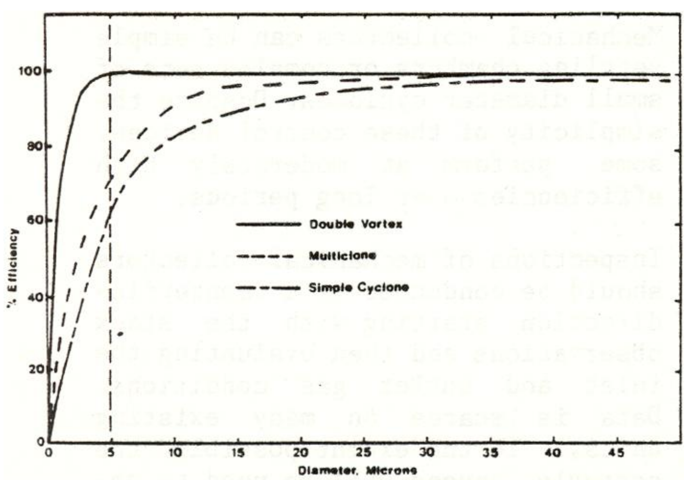

Figure 2-1. Cyclone fractional efficiency curves

In general, cyclones are not useful for the collection of sticky particulate matter. The main difficulties associated with these materials involve removal from the hoppers and build-up along the inner wall of the cyclone. Examples of hard-to-collect sticky material include partially polymerized oils, condensed high molecular weight organics, and ammonium sulfate and bisulfate particles. Sources emitting stringy material can cause build-up of material in the inlet vanes of multi-cyclone collectors. Partially blocked inlet spinner vanes do not generate the cyclonic flow patterns necessary for proper inertial separation.

Small diameter cyclones, including all multi-cyclone collectors, are vulnerable to severe erosion when treating gas streams having very large diameter particulate matter. Particles over twenty micrometers in diameter are very abrasive at the high tangential velocities achieved in the small diameter cyclones. The abrasiveness of particulate matter increases with the square of the particle diameter. Accordingly, cyclones handling particles in the twenty to more than one hundred micrometer size range can be vulnerable to high erosion rates.

Cyclone Systems

Large Diameter Cyclones

The inlet gas stream enters the large diameter cyclone through a tangentially mounted duct that imparts a spin to the gas stream. The inlet duct is usually at the top of the cyclone body, but large diameter cyclones may also have bottom inlets. Both arrangements are shown in Figure 2-2.

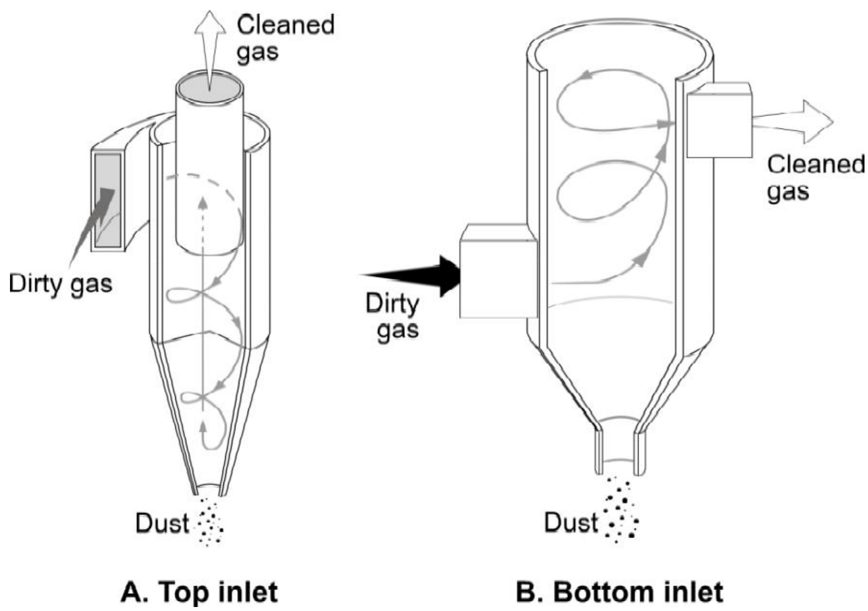

Figure 2-2. Large diameter cyclones

With the normal inlet gas stream velocity of 20 to 50 ft/sec, the gas stream spins approximately one-half to two complete rotations within the cyclone body of both types. An increase in the gas inlet velocity increases the spinning action of the gas stream, thereby improving inertial separation of the particles.

The gas flow pattern in a bottom inlet large diameter cyclone is relatively simple. The inlet gas stream begins to spin in the cyclone body because of the tangential inlet duct configuration. The gas stream forms an ascending vortex that rises up in the cyclone body to the outlet duct at the top of the unit. The particles that migrate across the gas streamlines settle by gravity when they approach the surface of the cyclone body where the gas velocity is low.

In the top inlet design, the gas stream spins in two separate vortices. The inlet stream creates an outer vortex due to the tangential location of the inlet duct and due to the presence of the outlet tube extension that prevents gas movement into the center of the cyclone body. As the gas stream passes down the cyclone body, it turns 180^o and forms an inner vortex that moves toward the gas outlet tube at the top of the cyclone. The outlet tube must extend sufficiently far into the cyclone to facilitate formation of the outer vortex and to prevent a short-circuit path for the gas stream.

The particles that have migrated toward the outer portion of the outer vortex break away from the gas stream when it turns 180^o to enter the inner vortex. Due to their inertia, the particles continue to move downward toward the cyclone hopper as the gas stream turns from the outer vortex to the inner vortex. The movement of the particles toward the hopper is controlled partially by inertial forces. The force of gravity also assists in particle movement toward the hopper.

Top-inlet, large-diameter cyclones can have a number of different inlet designs, as shown in Figure 2-3. The most common design is the simple tangential inlet (A). The deflector vane (B) reduces the gas stream turbulence at the inlet and can reduce the overall pressure drop. However, the deflector vanes can also impair vortex formation and thereby reduce particulate collection. Helical inlets (C) have been used in an attempt to reduce cyclone pressure drop and to improve performance. Involute entries (D) can also reduce turbulence-related pressure drop at the inlet. However, they usually provide improved efficiency due to the manner in which the outer vortex develops.

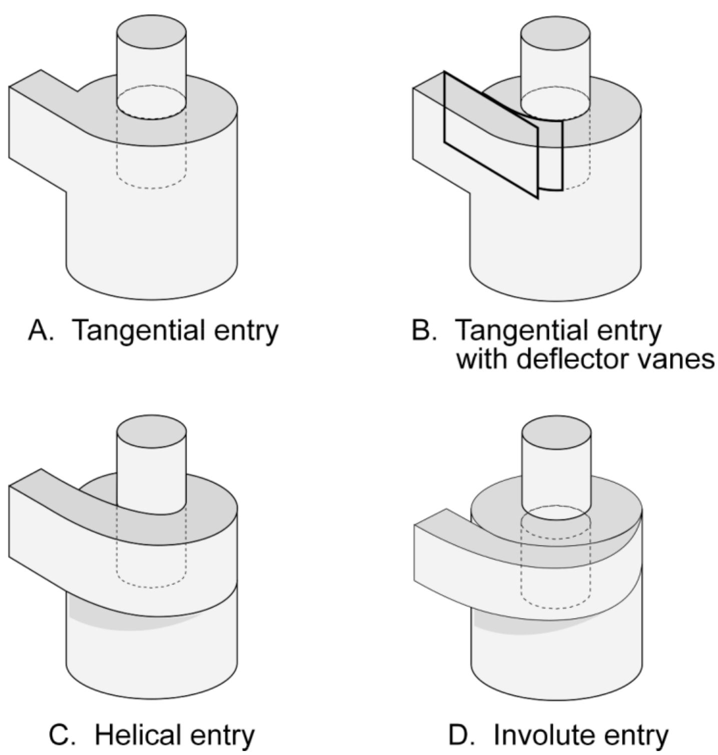

Figure 2-3. Types of cyclone inlets

The outlet gas tube is also an important consideration in the design of a large diameter cyclone. Some of the energy due to the radial motion of the ascending gases can be recovered by scroll devices (A) or outlet drums (B) placed on top of the outlet tube. These two cyclone enhancements, which are shown in Figure 2-4, are essentially flow straighteners that can effectively reduce the overall pressure drop across the unit without affecting the particulate matter removal efficiency.

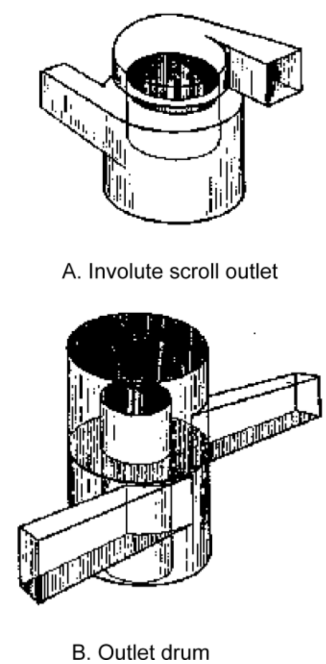

Figure 2-4. Special outlet configuration for large diameter cyclones

Large diameter cyclones can be used in series or parallel arrangements in order to increase particulate matter removal efficiency or to increase gas flow capability. A series arrangement (A) of two cyclones of equal size and a parallel arrangement (B) of four cyclones of equal size are shown in Figure 2-5.

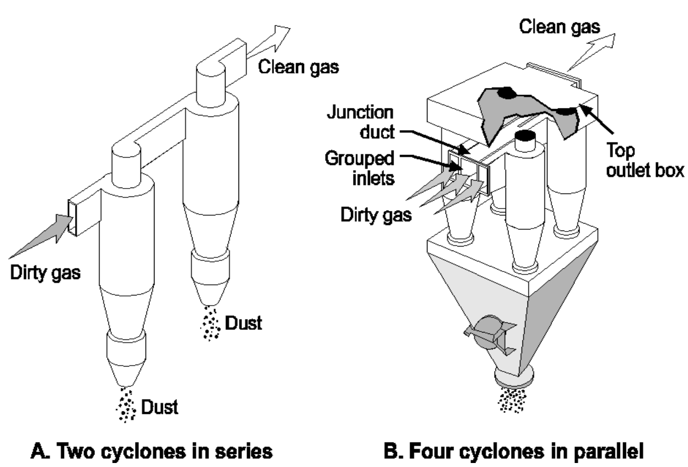

Figure 2-5. Series and parallel arrangement of cyclones

The dust discharge system for a large diameter cyclone is similar to that used in other dry particle collectors and consists of a hopper for receiving the collected solids and a solids discharge valve that allows solids to be removed from the hopper without letting air in or out of the system. Four common types of solids discharge valves are shown in Figure 2-6. The slide gate (A), the rotary discharge valve (B), and the double flapper valve (D) are all capable of providing an airtight seal. The screw conveyor arrangement (C) cannot provide an airtight seal unless a solids discharge valve is placed between the bottom of the cyclone and the screw conveyor.

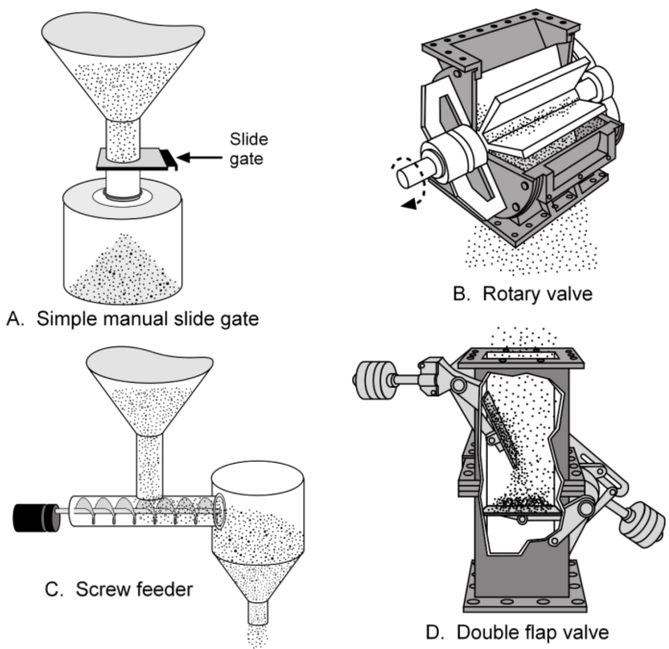

Figure 2-6. Types of solid discharge valves

Air infiltration into negative pressure cyclones, either through the solids discharge valve or through holes in the casing, can significantly reduce collection efficiency by disrupting the vortex and by entraining particles and carrying them toward the outlet flow. Also, collection of very large particles in high velocity vortexes can be difficult because of the tendency for the particles to bounce off the wall.

Small Diameter Multi-Cyclones

The particulate matter removal capability of a small diameter cyclone is greater than that of a large diameter cyclone because the gas stream is forced to spin in smaller vortices, imparting greater inertial force to the particles. However, it is not possible to handle a large gas volume in a single small diameter tube. In order to treat the entire gas stream, a large number of small diameter tubes can be used in a single collector in which the tubes are in a parallel arrangement. Multi-cyclone collectors have cyclone tubes that range in size from 6 to 12 in. in diameter. A small multi-cyclone collector, such as the one shown in Figure 2-7, can have as few as 16 tubes. Large units may have several hundred tubes.

These units are divided into three separate areas by two tube sheets. The *dirty gas tube sheet* is mounted horizontally, supporting the cyclone tubes and separating the inlet gas stream from the hopper area of the unit. The *clean gas tube sheet* stair-steps down from front to back at approximately a 45^{o} angle, dividing the inlet gas stream from the treated outlet gas stream. The outlet gas tubes from each of the cyclones pass through the clean gas tube sheet.

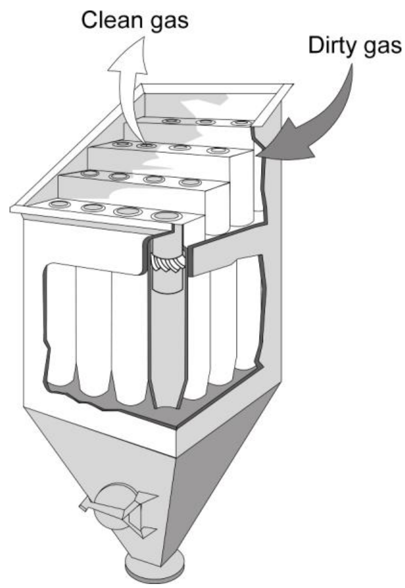

Figure 2-7. Multi-cyclone collector

Solids discharge valves are necessary under negative pressure multi-cyclone hoppers to prevent air infiltration upward through the hoppers and into each of the cyclone tubes. This air would impair cyclone particulate matter collection by disrupting the vortex of the inlet gas stream. Also, particles already in the hoppers could be entrained in the upward flowing air stream and driven out of the cyclone tube toward the outlet gas plenum. Air infiltration through broken welds, access hatches or corroded panel below the dirty gas tube sheet will have a similar effect on performance.

A small diameter cyclone tube used in multi-cyclone collectors is shown in Figure 2-8. The gas stream entering the cyclone is spun as it passes over the turning vanes mounted at the inlet. The gas stream turns one-half to three times depending on the gas flow rate and the length and diameter of the cyclone. As in the case with large diameter cyclones, particles move toward the wall of the cyclone and subsequently fall by gravity. The gas stream turns 180^{o} and passes out the center tube.

A variety of mechanical problems can reduce the performance of the small diameter cyclone tubes. The particulate-laden inlet gas stream can erode holes in the outlet tubes that pass through the inlet gas plenum. Once these holes develop, they can increase in size rapidly due to the static pressure drop across the unit. This will result in an increase in visible emissions and a decrease in static pressure drop, if the holes become large enough.

Increased visible emissions can also occur because of leaks in the gasketed or welded joints between the outlet tube and the clean gas tube sheet. Since the size of these leaking areas is typically small, there is usually no effect on static pressure drop.

Material that deposits on the turning vanes of the cyclone tubes can seriously disrupt the vortex. If the gas stream does not spin properly in the cyclone body, the collection efficiency will be significantly reduced, increasing visible emissions. These deposits also increase the static pressure drop through the collector by reducing the area available for flow through the turning vanes. Similarly, eroded turning vanes will disrupt the vortex in the cyclone tube and reduce collection efficiency. The static pressure drop will be reduced if the inlet turning vanes are significantly eroded.

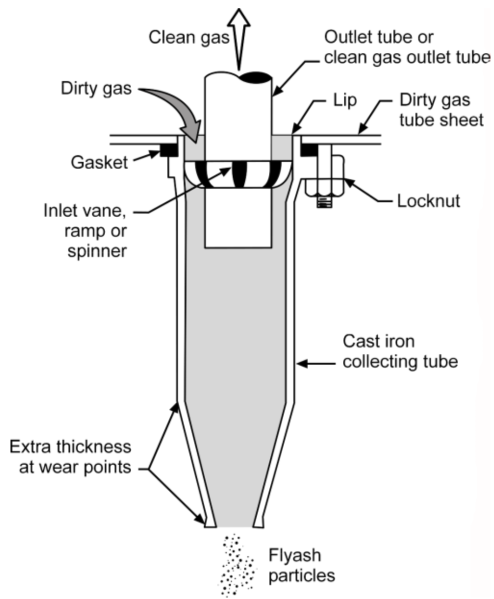

Figure 2-8. Cyclone tube used in multi-cyclone collector

Deposits that block the dust discharge into the hopper can completely impair the affected tubes. Collected particles that would normally exit the cyclone tube are reentrained in the spinning gas and discharged. These deposits usually occur when the hopper solids accumulate and block the cyclone dust outlets. However, after the solids are removed from the hopper, hardened deposits can remain at the tube outlet and continue to impair performance. There will generally be no effect on the static pressure drop.

Deposits that accumulate on the inner surfaces of the cyclone body can also reduce performance. These deposits increase wall roughness and increase turbulence near the wall. Particles attempting to move out of the gas vortex can bounce off these deposits and become reentrained in the gas stream. Significant deposits would result in an increase in static pressure drop; however, even modest deposits can reduce collector performance.

In large scale multi-cyclone collectors, the gas flow resistance of the outlet tubes can create an undesirable gas flow pattern called cross-hopper recirculation. As shown in Figure 2-9, the treated gas stream in the rows of cyclone tubes near the inlet can exit the bottom of the tube instead of the top, travel across the upper portions of the hopper, and pass upward through cyclone tubes near the back rows. This is possible due to the low gas flow resistance of the short outlet tubes for the cyclones on the back rows and the high gas flow resistance of the long outlet tubes for the inlet rows.

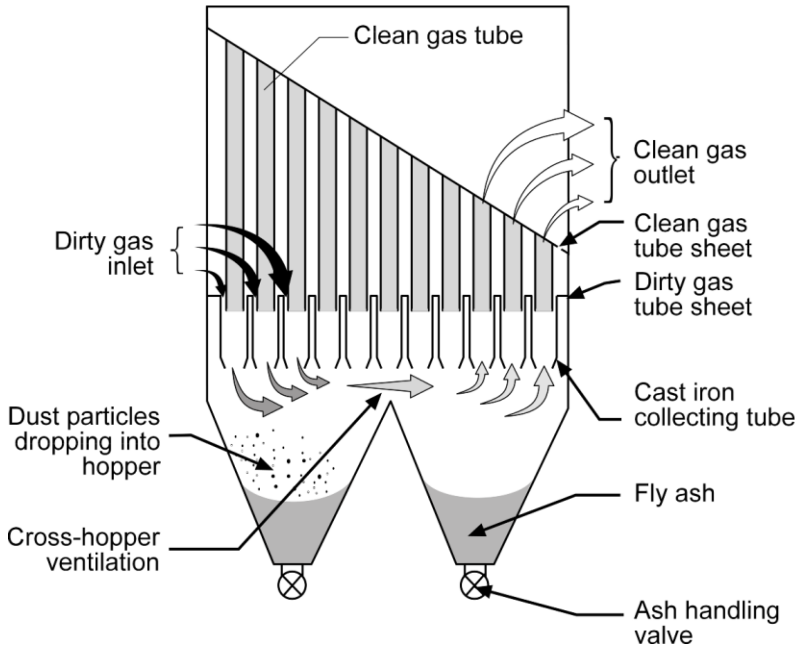

Figure 2-9. Cross hopper recirculation

Particulate matter emissions are increased substantially by cross-hopper recirculation because the gas stream passing through the hopper reentrains dust from the hopper and because this gas disrupts the vortex in the cyclone tube it reenters. Cross-hopper recirculation can be avoided by designing the outlet tubes to be of equal length throughout the collector or by placing baffles in the hopper to prevent gas flow from the front to the back of the unit.

Inspection

Cyclone collectors are simple units with limited instrumentation. Most of the data and information necessary to evaluate performance are obtained during the walkaround inspection. With the possible exception of static pressure drop data, the operating conditions are not usually monitored in the control room of the process served by the collector.

Unlike the more complicated control systems, the inspection procedures for cyclones are not divided into basic and follow-up lists.

- Visible emissions
- Fallout of large diameter particles (large diameter cyclones)
- Static pressure drop

- Gas inlet and outlet temperatures
- Gas inlet and outlet oxygen concentrations
- Air infiltration
- Dents or weld failures (large diameter cyclones)
- Solids discharge problems
- Internal inspection reports

Level 2: Visible Emissions

The stack visible emissions should be observed for at least 6 to 12 minutes using USEPA Reference Method 9 or an equivalent method. High opacities could indicate either multi-cyclone performance problems or a shift in the particle size distribution due to operational problems at the process source.

Large diameter cyclones are not designed to control particulate matter in the size range that exhibits significant opacity. Large particles have very little opacity, even at high mass loadings in the gas stream. The presence of a high opacity plume usually indicates that there is a high concentration of small particles and that the large diameter cyclone is an inappropriate control device for the process source.

Level 2: Fallout of Large Diameter Particles (Large Diameter Cyclones)

Large particles collected in large diameter cyclones have high terminal settling velocities. If these particles penetrate the cyclone, they usually deposit on adjacent surfaces or fall out in the immediate vicinity of the cyclone discharge. The presence of deposition patterns or piles of material near the discharge usually indicates that the cyclone is not working properly.

Level 2: Static Pressure Drop

As shown in Figure 2-10, the static pressure drop varies with the square of the gas flow rate and may be used to evaluate flow rate changes. However, the static pressure drop observed during the inspection must be corrected to the baseline flow rate condition, using the following equation, before it can be compared to the baseline value.

$$\Delta P_{expected} = \Delta P_{baseline} \left(\frac{Q_{inspection}}{Q_{baseline}} \right)^2 \tag{2-1}$$

The static pressure drop expected as a result of the flow rate change would be compared to the baseline value. If there is no difference, then the static pressure drop change is due solely to the flow rate change. If there is a difference, then there is something else affecting the static pressure drop in addition to the flow rate change. If flow rate information is not available to make the correction, a parameter that changes proportionally with flow rate can be used. For example, with a boiler it is reasonable to assume that the flow rate varies directly with the steam production rate.

Plugging of some of the inlet turning vanes in a multi-cyclone collector is probable if the static pressure drop is well above the baseline data. Deposits in this area prevent the formation of a proper vortex, and particulate matter emissions through the affected cyclone tubes are high. The static pressure drop increases because the area for gas flow is smaller because of these deposits.

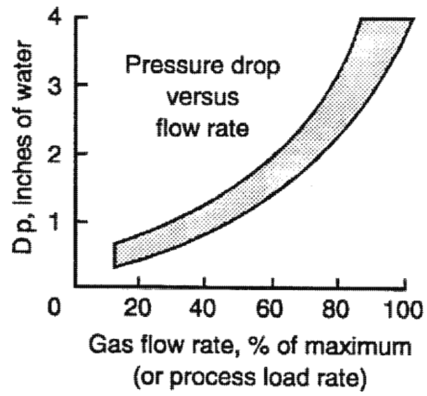

Figure 2-10. Static pressure drop of a cyclone collector

Erosion of the turning vanes will also prevent the formation of a proper vortex and cause increased emissions. In addition eroded turning vanes will cause reduced static pressure drop. Erosion of the outlet tubes is another possible problem if the static pressure drop has decreased. Gas short-circuiting through the unit will also cause increased visible emissions. The static pressure drop is low in this case because the gas does not pass through the turning vanes. Likewise, significant air infiltration into the hopper will cause reduced static pressure drop, since the quantity of gas going through the turning vanes is reduced.

Level 2: Gas Inlet and Outlet Temperatures

A significant increase in the difference between inlet and outlet gas temperatures, or a gas temperature difference greater than about 25°F, indicates air infiltration into the unit. Usually, temperature monitors are not placed immediately before and after the collector, so data must be obtained using available upstream and downstream gauges. For example, there are often temperature gauges at the economizer outlet of a boiler and at the induced draft fan inlet. The temperature drop between these two instruments should be compared with baseline data to determine if air infiltration has increased since the last inspection.

Changes in gas flow rate should be considered in evaluating temperature data. This is necessary because the gas temperature drop across the unit is a function of the gas flow rate. At high gas flow rates, the temperature drops are slightly lower than at low gas flow rates.

Level 2: Gas Inlet and Outlet Oxygen Concentrations

For combustion sources, air infiltration problems in cyclone collectors can be evaluated using oxygen concentration data. Many combustion sources have an oxygen monitor downstream of the economizer. If there is an additional oxygen monitor in the stack, the change in oxygen concentration between the two locations can be checked. If the oxygen level increases more than 0.5 percent (i.e. from 6 percent to >6.5 percent), air infiltration is probable.

Level 2: Air Infiltration

When the temperature drop across the unit is above the baseline range, air infiltration is highly probable somewhere between the two temperature gauges. Air infiltration may directly affect the efficiency of the cyclone by disrupting the vortex. However, it almost always reduces the air flow from the source, possibly resulting in fugitive emission losses. The most common sites of air infiltration include the following:

- Induced draft fan
- Solids discharge valves and hopper poke holes
- Hopper access hatches
- Side wall welds
- Ductwork expansion joints

Determining the specific location of these leaks is not the responsibility of the agency inspector. Cyclones are often mounted in areas that are difficult to reach or near hot surfaces. Furthermore, the walls of collectors serving some processes are hot. Checks for audible air infiltration are limited to units with safe and convenient access to the equipment.

Level 2: Dents or Weld Failures (Large Diameter Cyclones)

If it is safe to approach a large diameter cyclone, the body and conical sections should be checked for large dents or weld failures. These problems are often caused by operator inflicted hammer blows in order to dislodge solids building up inside the unit. The dents disrupt the vortex and provide a surface for particles to bounce back into the gas stream. Weld failures provide a location for air to infiltrate negative pressure units and impair the vortex or serve as a location for fugitive emissions from positive pressure units.

Level 2: Solids Discharge Problems

Solids bridging over the cyclone discharge can result in the reentrainment of particles attempting to settle into the hopper and is usually caused by overflow of the hopper or receiving enclosure that is used underneath the cyclone. In large diameter cyclones, moisture condensation on uninsulated metal walls of the body and conical section can also contribute to solids discharge problems.

Air infiltration through the solids discharge valve prevents solids discharge from the cyclone system, reentrains dust, and disrupts the cyclone vortex. In some cases, air can be heard rushing in through poorly sealed solids discharge valves.

Internal Inspection Reports

There are a variety of multi-cyclone problems that can not be easily detected as part of the Level 2 inspection:

- Deposits on the inside surfaces of the cyclone tubes
- Plugging of the bottom of the cyclone tubes
- Cross hopper recirculation

An internal inspection is needed to see these conditions or the symptoms of these conditions. Internal inspection reports prepared by plant maintenance personnel should be requested and reviewed if there have been chronic emission problems from the source. Agency personnel should not conduct internal inspections of air pollution control equipment.

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Review Problems

1. A Level 3 inspection is being conducted on a multi-cyclone collector serving a coal fired boiler. The Level 1 inspection indicated that the visible emissions have increased from the previous range of 12% to 15% to a range of 25% to 35% at the present time. There is no instrumentation on the collector. The following data were obtained by plant operators using portable instruments at the inlet and outlet ports of the collector.

	Inlet	Outlet
Static Pressure, in. H_2O	-5	-9
Gas Temperature, ^oF	412	403
Oxygen, %	7.5	8.0
Carbon Dioxide, %	11.0	10.9

During the previous inspection, the observed pressure drop was 3.8 in. H_2O, and the boiler steam rate was 100,000 pounds per hour. Now the steam rate of the boiler is 57,000 pounds per hour. What are possible causes of the increased opacity?

2. Level 2 inspection data for a multi-cyclone collector serving a bark boiler are summarized below. What are possible causes of the increased opacity?

	Inspection Data	Baseline Data
Visible Emissions, %	35	10
Static Pressure Drop, in. H_2O	2.5	3.5
Inlet Gas Temperature, ^oF	508	505
Outlet Gas Temperature, ^oF	501	500
Boiler Load, lb/hr	45,000	41,000
Boiler Draft, in. H_2O	-0.15	-0.10
Fuel Type	Bark	Bark

3. A large diameter cyclone is being used to collect wood chips and sawdust. Material is penetrating the cyclone and falling out near the discharge, despite the fact that it appears to be sufficiently large to be collected in the unit. The static pressure drop is presently 2.0 in. H_2O. This is close to the value of 2.2 in. H_2O observed during the last inspection. There are no obvious dents or side wall weld failures on the unit. What are possible explanations for the increased emissions?

4. The following Level 2 data were obtained during the inspection of a multi-cyclone collector serving a bark and oil fired power boiler at a pulp mill. What are possible causes of the increased opacity?

	Inspection Data	Baseline Data
Visible Emissions, %	50	10
Static Pressure Drop, in. H_2O	3.5	3.7
Inlet Gas Temperature, ^oF	510	500
Outlet Gas Temperature, ^oF	480	495
Boiler Load, lb/hr	44,000	40,000
Boiler Draft, in. H_2O	-0.05	-0.10
Fuel Type	Bark	Bark
Overfire Air Pressure, in. H_2O	25	28