CHAPTER 4

WET SCRUBBERS

Wet scrubbers are a diverse set of control devices that can be used to collect both particles and gases, but usually not simultaneously at high efficiency for both. This is because particulate scrubbers are designed to generate high inertial forces or electrostatic forces on particles to drive them into droplets or sheets of liquid. Gas absorbers are designed to have high liquid surface areas and relatively long residence times to maximize the absorption of contaminants into liquid droplets or sheets. Despite the fundamental operating differences, most particulate scrubbers have at least modest efficiencies for gaseous contaminant removal, and most gaseous absorbers have modest efficiencies for the removal of particulate larger than approximately 3 micrometers. In this chapter we will focus on wet scrubbers used for particle collection; however, the inspection procedures for the two categories of wet scrubbing systems are very similar.

Wet scrubbers use a three-step process for the treatment of particulate-laden gas streams:

- Particle capture in either droplets, liquid sheets, or liquid jets
- Capture of the liquid droplets entrained in the gas stream
- Treatment of the contaminated liquid prior to reuse or discharge

Particle capture is accomplished in a contacting vessel, such as a venturi scrubber, a tray tower scrubber, or a spray tower scrubber. Mist eliminators built into the scrubber vessel or provided as a separate vessel are used to collect the entrained water droplets after the scrubber. Clarifiers, vacuum filters, or settling ponds are used to treat the wastewater stream from the scrubber. Particle size is an important factor in all types of scrubbing systems. This is because they all use the same basic collection mechanisms—inertial impaction and Brownian motion, both of which are highly dependent on particle size.

Operating Principles

Inertial Impaction

Impaction occurs when a particle has too much inertia to avoid a target that it is approaching. It crashes into the target instead of flowing around it on the gas streamlines. If the particle is retained by the target (in this case, a droplet), a successful impaction has occurred. The efficiency of particle collection by impaction is proportional to the inertial impaction parameter shown in Equation 4-1.
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\[ \Psi_i = \frac{C_c d_p^2 \rho_p V_r}{18 \mu_g d_d} \]  

(4-1)

where:

- \( \Psi_i \) = inertial impaction parameter (dimensionless)
- \( C_c \) = Cunningham slip correction factor (dimensionless)
- \( d_p \) = physical particle diameter (cm)
- \( \rho_p \) = particle density (gm/cm\(^3\))
- \( V_r \) = relative velocity between particle and droplet (cm/sec)
- \( d_d \) = droplet diameter (cm)
- \( \mu_g \) = gas viscosity (gm/cm sec)

This equation indicates that impaction effectiveness is related to the square of the particle diameter. Impaction is much more efficient for large particles than for small particles, especially those particles less than 0.5 \( \mu \)m. Impaction rapidly becomes less efficient as the particle size decreases in the submicron range. To overcome this inherent limitation, the differences in droplet and particle velocities must be high when most of the particulate matter in the submicron range.

The impaction parameter indicates that impaction is directly proportional to the difference in the velocities of the particle and the droplet or liquid sheet target. There are substantial differences among the various types of scrubbers with respect to this relative velocity term. Furthermore, the difference in velocity does not remain constant throughout some types of scrubbers.

The effectiveness of impaction is inversely related to the diameter of the target. Small water droplets serve as better targets than large droplets. The formation of small droplets is favored by droplet atomization in high-velocity gas streams and droplet atomization in high-pressure nozzles. Low surface tension conditions in the liquid also favor small droplet size distributions.

**Brownian Motion**

Brownian motion, or diffusion, is the particle movement caused by the impact of gas molecules on the particle. Only very small particles are affected by the molecular collisions, since they possess little mass and, therefore, little inertial tendency. Brownian motion begins to be effective as a capture mechanism for particles less than approximately 0.3 \( \mu \)m, and it is significant for particles less than 0.1 \( \mu \)m. Most industrial sources of concern in the air pollution field do not generate large quantities of particulate matter in the less than 0.1 \( \mu \)m size range. Therefore, in most cases, Brownian motion is not a major factor influencing overall scrubber collection efficiencies.
**Liquid-to-Gas Ratio**

The rate of liquid flow to a scrubber is often expressed in terms of the liquid-to-gas ratio, with units of gallons of liquid per 1,000 actual cubic feet of gas flow. Most wet scrubber systems for particle collection operate with liquid-to-gas ratios between 4 and 20 gal/1,000 acf. Higher values do not usually improve performance, and they may have a slightly adverse impact due to changes in the droplet size distribution formed in the scrubber. Low values can have a highly adverse impact because there are simply too few impaction targets available. At low liquid-to-gas ratio conditions, a portion of the particle-containing gas stream may pass through the collection zone without encountering a liquid target.

**Mist Elimination**

Essentially all scrubber vessels generate relatively large water droplets that are entrained in the gas stream. Most of these droplets contain captured particles and must be removed from the gas stream prior to discharge to the atmosphere. A mist eliminator is used for this purpose. In addition to minimizing the carry-over of solids-containing droplets to the atmosphere, mist eliminators also protect downstream equipment, such as fans, from solids-containing droplets and minimize the amount of water lost from the system. Mist eliminators are usually equipped with one or more sets of spray nozzles to remove accumulated solids. Solids build-up is due to impaction of solids-containing water droplets and due to the chemical precipitation of dissolved solids from the scrubbing liquid. The three most common types of mist eliminators are chevrons, mesh or woven pads and cyclones.

**Chevrons**

Chevrons are simply zig-zag baffles that force the gas to turn sharply several times while passing through. As the gas stream turns to pass through the baffles, droplets impact on the baffles and run together to form large droplets that drain back into the scrubber. Chevrons are usually designed with one to four changes in gas stream direction, termed a *pass*. Separation efficiency increases with the number of passes. A three-pass chevron mist eliminator is shown in Figure 4-1.

Essentially all of the chevron mist eliminator designs are limited to gas velocities of less than approximately 20 ft/sec. At higher velocities, liquid on the blades can be driven toward the outlet side of the chevron where it can be reentrained into the gas stream. Higher velocities can occur in an operating system because of solids accumulation on the blades.

**Mesh and Woven Pads**

Mesh pads are composed of randomly interlaced metal fibers and can be up to 6 inches thick. As the gas stream turns to pass by the elements of the mesh, droplets impact on the baffles and run together to form large droplets that drain back into the scrubber. As in the case with the chevrons, there is a maximum gas velocity above which reentrainment is possible. That
maximum velocity is usually in the range of 12 ft/sec. A mesh pad mist eliminator pad is shown in Figure 4-2.

![Chevron mist eliminator](image)

**Figure 4-1.** Chevron mist eliminator

![Mesh pad mist eliminator](image)

**Figure 4-2.** Mesh pad mist eliminator

Woven pads have complex, interlaced synthetic fibers that serve as impaction targets. Mist eliminators composed of these materials are often layered. The inlet side layers are open weaves that are capable of removing large quantities of large-diameter material without overloading. The middle and outlet side layers have more compact weaves, which have high removal efficiencies for the small liquid droplets. These units have maximum velocities of 8 to 15 ft/sec, depending on the pad construction characteristics.

**Cyclones**

The smaller droplet size distributions created in venturi scrubbers are usually collected in a separate large diameter cyclone. The gas stream enters tangentially at the bottom of the vessel and, depending on the gas velocity, turns one-half to two revolutions prior to
discharge. They have reasonable efficiency when operated at close to the design inlet gas velocity. However, droplet removal decreases rapidly at gas flow rates less than 80% or more than 120% of the design value. As long as the drain is properly sized and remains open, the mist eliminator is not vulnerable to plugging caused by excessive carryover of solids-containing droplets from the scrubber vessel.

**Gas Cooling**

Process gases that are at elevated temperature are usually passed through an evaporative cooler before entering the scrubber. The primary purpose of the evaporative cooler is to reduce the gas temperature to protect temperature-sensitive components in the scrubber vessel, mist eliminators, and other components. For example, it is common to have corrosion-resistant liners on the scrubber vessels that can volatilize at temperatures exceeding 400°F to 1,000°F. Some scrubber vessels and many mist eliminators are fabricated with fiberglass reinforced plastics (FRP) that have temperature limitations of 180°F to 250°F. The evaporative cooler is provided to ensure that the gas temperatures in the scrubber vessel, mist eliminator, and other portions of the system do not exceed their design limitations even if the liquid recirculation system in the scrubber fails.

The evaporative cooler provides a secondary benefit in particulate matter control systems. By cooling the gas stream prior to particulate matter removal, the evaporation of droplets in the scrubber vessel is significantly reduced. The mass flux of water vapor away from evaporating droplets impedes particle capture by the droplets. Accordingly, the minimization of evaporation has a slight beneficial impact on the particulate matter collection efficiency.

**Liquid Recirculation**

The scrubbing liquid is recirculated to minimize the amount of liquid that must be treated and discharged. The scrubbing liquid is collected in the sump of the scrubber and mist eliminator. Most systems use a recirculation tank having a liquid residence time of several minutes. This provides sufficient time to introduce alkali additives to adjust the pH back to the proper range. The tank also supplies the recirculation pump used to recirculate the liquid back to the scrubber vessel.

**Alkali Addition**

An alkali addition system is used on wet scrubber systems that collect acidic particulate matter or treat gas streams that have acidic gases or vapors that could absorb in the liquid stream. The most common acid gases include sulfur dioxide, hydrogen chloride, and hydrogen fluoride. Carbon dioxide formed in most combustion processes is also mildly acidic.

The most common alkalis used for neutralization of acidic material in scrubbers include lime, soda ash, and sodium hydroxide. In some cases, limestone and nahcolite are used. With the exception of sodium hydroxide, all of these materials are typically stored and fed to the
recirculation tank in a powder form. Sodium hydroxide is usually fed in solution. The rate of addition of alkali is controlled by a pH meter that is usually mounted in the scrubber recirculation tank or the recirculation pipe leading to the scrubber vessel.

**Wastewater Treatment**

There is a wide variety of wastewater treatment systems for particulate matter wet scrubbers. Some small scrubbers at large industrial facilities discharge directly to the plant wastewater system, rather than using a dedicated system. Small scrubbers collecting nontoxic particulate matter, such as those at asphalt plants, sometimes use a small two-zone settling pond for wastewater treatment. In these cases, the effluent overflowing the second zone of the pond is returned to the scrubber system.

A small wastewater treatment system is usually installed for large wet scrubber systems. A clarifier is used for removal of the suspended solids that will settle by gravity. The overflow from the clarifier is returned to the scrubber recirculation tank. The clarifier underflow containing the concentrated solids is often sent to a rotary vacuum filter for removal of the suspended solids. The sludge from the rotary vacuum filter is sent to a landfill for disposal.

In some cases, a flocculent is added to the clarifier to optimize solids removal. However, addition of flocculates must not exceed the levels that cause an increase in the liquid surface tension. This can have an unintended detrimental effect on particulate removal efficiency of the scrubber by decreasing the effectiveness of particle impaction into the liquid droplets and by changing the droplet size distribution formed in the scrubber.

**Wet Scrubber Capabilities and Limitations**

Particulate matter wet scrubbers can provide high efficiency control in a wide variety of industrial applications. Certain types of scrubber systems can provide simultaneous control of both particulate matter and gaseous contaminants. Wet scrubbers are often the control device of choice if there is the potential for embers and/or explosive gases and vapors in the gas stream to be treated.

The main limitation that must be considered in a specific type of wet scrubber is the particle control capability in the submicrometer size range. Many types of wet scrubbers have very limited efficiencies when the inlet gas stream has particles that are mostly in the difficult-to-control size range of 0.1 to 1.0 μm. A typical fractional efficiency curve illustrating the range for performance for the various types of wet scrubbers is shown in Figure 4-3.

The extent of the efficiency decrease in this size range depends primarily on the intensity of the gas liquid contact in the scrubber vessel. Scrubber vessel types that use high energies to develop large differences in the particles and the liquid targets have excellent inertial impaction efficiencies in the difficult to control range. Those scrubbers designed primarily for gaseous contaminant control have low differences in particle-liquid velocities and little or no particle collection in the difficult-to-control size range.
Another limitation of wet scrubbers is the availability of water. Make-up water is needed to replace water evaporated with the effluent gas stream, water lost as part of the discharged wastewater, and water lost as part of sludge from rotary vacuum filters or similar processing units. In arid climates, there might be insufficient water to use a wet scrubber.

The ability to economically dispose of the wastewater stream in an environmentally sound manner is another limitation of wet scrubbers in some locations. The purge stream from the scrubber recirculation liquid stream might contain dissolved species that have poor leachability characteristics in disposal ponds.

Wet scrubbers usually generate very visible plumes composed of condensed water droplets. The highly visible water droplet plumes that can be quite persistent in cold weather and high humidity conditions can cause visibility problems for nearby roads and airports. Water droplet fallout from the plumes can, in unusual cases, cause freezing problems on walking surfaces and roadways near the facility.

**Scrubber Systems**

There are many equipment designs for contacting the liquid with the contaminated gas stream. The capability of a particular design can be approximated from the gas stream pressure drop across the scrubber. In general, higher pressure drops indicate more aggressive contact between the liquid and the gas stream, causing smaller particles to be collected with greater efficiency.
Scrubbers with pressure drops less than about 5 in. H₂O are capable of efficiently removing particles greater than about 5-10 µm in diameter. These are referred to as **low energy wet scrubbers**. **Medium energy wet scrubbers** have pressure drops from 5 to 25 in. H₂O. These collectors are capable of removing micrometer-sized particles, but are not very efficient on sub-micrometer particles. Removal of sub-micrometer particles requires significant energy input, ranging from 25 to over 100 in. H₂O, depending on the particle size. These collectors are referred to as **high energy wet scrubbers**.

The following sections discuss common designs that represent each of these categories. Not all scrubber designs will conform to these generalized categories. Collectors that may collect smaller particles than their pressure drop would indicate include electrostatically enhanced scrubbers and condensation growth scrubbers.

**Spray Tower Scrubbers**

The spray tower scrubber shown in Figure 4-4 is an example of a low energy wet scrubber. The scrubber consists of an open vessel with an array of spray nozzles mounted on multiple headers that are usually spaced about three feet apart. Full cone spray nozzles are used to generate droplets with a mean size of several hundred micrometers. As these droplets fall downward, they are contacted with the particle-laden gas stream passing upward. The particles are collected by impaction onto the droplets

![Figure 4-4. Spray tower scrubber](image)

Because of the large size of the droplets produced in the spray tower, mist eliminators may not be used. Instead, sufficient space is provided above the last spray header to allow any droplets carried upward by a turbulent eddy the time to drop downward. Also, because of the
relatively low volume occupied by the droplets, changes in the liquid flow rate do not significantly change the pressure drop.

**Packed Bed Scrubbers**

The packed bed scrubber is an example of a medium energy wet scrubber. In a typical packed bed scrubber, scrubbing liquid is introduced above the bed and trickles down over packing contained in one or more beds arranged in series. The beds can be in either a vertical tower or in a horizontal vessel. These packing materials are designed to provide the largest possible exposed liquid surface area per unit volume of bed, while maintaining a reasonable pressure drop. Some common types of packing materials are shown in Figure 4-5.

![Packing Materials](image)

**Figure 4-5. Common types of packing materials**

In the vertical packed bed scrubbers shown in Figure 4-6, the contaminated gas streams move upward through the irrigated packing. This arrangement provides the best collection of gases and vapors, but has the lowest collection efficiency for particles. Because of hydrostatic limitations, there is a limit on the upward velocity that can be used for a given quantity of liquid. This limit results in reduced impaction efficiency. Removal efficiencies for particulate matter less than approximately 3 μm are very low. In addition, a portion of the bed can become plugged if the particulate matter concentration is high. The scrubbing liquid flowing downward over the packing moves too slowly to purge out large quantities of particulate matter.

Somewhat better particle removal performance can be achieved in the crossflow packed bed scrubber shown in Figure 4-7. In the crossflow scrubber, the gas stream passes horizontally through the bed, while the scrubbing liquid is distributed on the top of the packing and passes downward. Since the hydrostatic limitations of the vertical arrangement are not present, larger quantities of liquid and higher gas velocities can be used. This provides a modest increase in collection efficiency and helps reduce plugging problems.
The most effective use of the scrubbing liquid is to have it spread out as a thin film on the surface of the packing. As long as this condition is maintained, increasing the liquid flow rate does not significantly affect pressure drop. However, if the liquid begins to accumulate in the spaces within the packing, the pressure drop will increase. This condition generally results in reduced collection efficiency.

Figure 4-6. Vertical packed bed scrubber

Figure 4-7. Horizontal packed bed scrubber
**Tray Scrubbers**

Another example of a medium energy scrubber is the tray scrubber. Tray scrubbers are vertical towers with multiple trays for contacting the gas and liquid streams. The liquid stream enters from the top, flows across the tray and then down to the next tray. The gas moves upward through holes in the tray, creating a bubbling action that provides for particle collection by impaction. Tray scrubbers are usually selected for applications involving particulate matter greater than approximately 1 μm. They have limited efficiency below 1 μm due to the limits to the gas stream velocities through the openings in the trays.

There are several tray designs to contact the gas with the liquid. A typical impingement tray scrubber is shown in Figure 4-8. The trays are metallic plates with numerous holes approximately 3/16 inches in diameter. Small baffle plates are mounted directly above each of the holes. Scrubbing liquid enters as a stream at the top of the unit. Overflow weirs set the height of the liquid on each tray to approximately 1 to 1.5 inches. After passing across the tray, the liquid passes down a vertical passage called the downcomer. A liquid seal at the bottom of each downcomer allows the liquid to flow freely to the next tray while preventing the gas stream from short-circuiting up the downcomer.

The gas stream is accelerated as it passes through the impingement tray holes. The gas jets atomize a portion of the liquid above the tray, creating droplets that serve as the impaction targets. The gas velocity through the holes must be high enough to provide for efficient atomization of the liquid and must have sufficient force to prevent liquid from dripping
through the holes. Excessive liquid dripping, termed *weepage*, reduces collection efficiency, particularly for gases and vapors.

Sieve tray scrubbers are conceptually similar to impingement tray scrubbers, but do not have baffle plates over the holes. These trays have larger holes and are, therefore, less vulnerable to pluggage. However, the gas velocities are slightly lower than impingement tray scrubbers, reducing the collection efficiency.

The performance of tray scrubbers is dependent on the physical condition of the tray and the holes in the tray. Bowed or sloped trays will imbalance the height of the scrubbing liquid. The gas stream will preferentially pass through the holes with the lowest liquid height, because this is the low resistance path. The portion of the gas stream that continues to pass through the holes with high liquid levels will be slow and have reduced collection efficiency.

Plugging the holes in the tray must be avoided. Tray scrubbers are vulnerable to plugging due to the small diameters of the holes. Suspended solids can accumulate in these holes and harden, making it necessary to drill or rod them out. Due to the vulnerability to solids accumulation, the liquor recirculation system and treatment system are especially important. The suspended solids must be restricted to low levels by use of clean scrubbing liquid, to the extent possible, and by effective treatment of the recirculated liquor.

Increasing the liquid flow rate into a tray scrubber will result in a modest increase in pressure drop. As the flow rate increases, flow over the weir causes the liquid level on each tray to rise slightly.

**Ionizing Wet Scrubbers**

The ionizing wet scrubber, shown in Figure 4-9, is the only type of scrubber that uses electrostatic attraction as the primary technique for particle capture. The inlet gas stream passes through a short ionizer section composed of a number of high voltage discharge electrodes separated by small, grounded collection plates. The ionizer section is conceptually similar to a conventional negative corona electrostatic precipitator field; however, it is designed to impart a high negative electrical charge to the particles and not to collect them. The ionizer section usually operates at secondary voltages of 20 to 30 kilovolts DC.

Following the ionizer section, the gas stream passes through a crossflow packed bed section. The particles are captured in the liquid layers surrounding the packing material due to the induced static charge in the liquid layers caused by the highly charged particles. These units are capable of the removing particles extending into the submicron range. However, they are not intended for sources generating high concentrations of submicron particulate matter.

**Venturi Scrubbers**

The venturi scrubber is an example of a high energy wet scrubber, although it can also be operated as a medium energy scrubber. The fixed throat venturi, shown in Figure 4-10, is
one of the most common designs. The gas stream entering the converging section of the venturi is accelerated to a velocity between 300 and 600 feet per second at the throat inlet. Liquid is injected into the throat and atomized into droplets with a mean size of 50 to 75 micrometers by the impact of the gas stream. These droplets are initially moving relatively slowly, and it takes time for them to accelerate to the same velocity as the rapidly moving particles entrained in the gas stream. Impaction occurs on the droplets due to the large difference in the gas stream velocity and the velocity of the accelerating droplets. The gas stream leaving the throat enters the diverging section. Here, the velocity of the gas stream is gradually reduced and the velocities of the particles and the droplets approach one another. Impaction does not occur efficiently in this section because the particles and droplets are moving at similar velocities and in the same direction.

Figure 4-9. Ionizing wet scrubber

The effectiveness of venturi scrubbers is related to the maximum difference in the droplet and gas stream velocities. Because the fixed throat has a constant open area, the actual gas velocity achieved in the throat section depends on the gas flow rate. Particle collection efficiency is, therefore, gas flow rate dependent. Fixed throat venturi scrubbers are used on sources where the gas flow rate is relatively constant or where the particle size distribution is sufficiently large that some variation in gas velocity is tolerable.

Proper liquid distribution is essential in obtaining optimum performance in a venturi scrubber. Because of the high gas velocities, the residence time of the gas stream in the venturi throat, where most collection occurs, is only 0.001 to 0.005 sec. Most of the particles that penetrate the throat will pass through the remainder of the scrubbing system uncollected. Obviously, portions of the venturi throat without any atomized scrubbing liquid will have no capability for collecting particulate matter.
The venturi scrubber system shown in Figure 4-10 includes a flooded section in the elbow directly below the venturi. This elbow leads from the diverging section to the mist eliminator. This 6 to 12 inch deep section is termed a *flooded elbow* and provides abrasion protection. Droplets that have accelerated to a high velocity in the venturi will erode the bottom of this duct if it is not protected.

One option for dealing with varying gas flow rate while maintaining good efficiency is the adjustable throat venturi shown in Figure 4-11. In this type of unit, moveable dampers are used to vary the throat area in order to control the gas velocity. The position of the dampers is usually set automatically to maintain a set pressure drop across the unit, although in some units they are positioned manually. These damper blades, and other types of flow restrictors, must be made of abrasion resistant materials because of the high velocities through the throat.

It should be recognized that, if the flow rate is varying, so is the liquid-to-gas ratio. If the variation in flow rate is large, the liquid-to-gas ratios at the extreme ranges of operation may result in reduced collection efficiency. Systems with large flow rate variation must also modulate the liquid flow in order to keep the liquid-to-gas ratio in an acceptable range for optimum performance.

The venturi shown in Figure 4-11 uses spray headers to distribute the liquid onto the side walls of the converging section. This technique is called *wetted approach* and serves to protect the section from abrasion by the entering particles. The liquid is sheared off the side walls and entrained in the gas stream as it enters the throat. Alternatively, the liquid can be introduced from a series of tangentially oriented pipes and swirled down the converging section of the venturi until the liquid is entrained. In addition, a centrally mounted nozzle is used to distribute liquid to the center of the throat. Because of the very high gas velocities in
the throat, it is difficult for the liquid droplets entrained from the wall to penetrate to the center.

![Adjustable throat venturi scrubber](image.png)

Figure 4-11. Adjustable throat venturi scrubber

The typical static pressure drop across a venturi scrubber varies from a low of 5 in. H₂O to values exceeding 100 in. H₂O. High static pressure drops are used only in situations demanding high efficiency removal of very small particulate matter. The static pressure drop is related to the gas velocities in the throat and the quantity of scrubbing liquid used. Because the energy for atomization comes from the gas stream, changes in the liquid flow rate will cause significant changes in the pressure drop.

**Inspection**

High efficiency particulate scrubber systems are relatively complex. There are a number of inspection points included in the Basic Level 2 inspection partly because of the complexity of the systems and partly because of monitoring requirements included in NSPS regulations.

**Basic Level 2**

- Visible emissions
- Droplet reentrainment
- Scrubber static pressure drop
- Liquid flow rate
- Inlet and outlet gas temperature
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Follow-up Level 2

- Mist eliminator static pressure drop
- Spray nozzle supply header pressure
- Recirculation pump discharge pressure
- Gas cooler outlet temperature
- Evaporative cooler spray liquid quality
- Liquid pH
- T-R set electrical data (ionizing wet scrubbers)
- Corrosion and erosion
- Component failure records
- Internal inspection reports

This list of inspection points does not include opacity monitoring systems. These are not used on particulate scrubber systems or absorber systems since the condensed water droplets (that are often present in the gas stream) scatter light. It is not possible to differentiate between light scattering caused by particulate matter and by water droplets. Accordingly, opacity data are limited to visible observations.

**Basic Level 2: Visible Emissions**

The condensed water droplets in the gas stream that preclude the use of an opacity monitor also complicate visible emission observations of the plume. It is necessary to observe the plume at a point immediately downwind of the point where the condensed water droplets evaporate. The point of droplet evaporation is clear in Figure 4-12.

![Figure 4-12. Visible emission of a scrubber plume](image)
The point at which the water droplet plume (often termed a steam plume) dissipates is often characterized by a change in the color and texture of the plume. A residual plume caused by particulate matter or nucleated acids is often bluish-white, brownish-white, or gray. The portion of the plume dominated by water droplets is often a bright white. When the relative humidity is high, the water droplet plume does not dissipate until the plume has traveled a long distance. In this case, the observed opacity can be substantially below the true value that would be visible at the stack discharge if the water droplets were not present. Visible emission observations of the residual plume are not always possible. In Figure 4-12, plumes from several sources have merged into a single plume. Therefore, the observed opacity is higher than the true opacity from any one of the sources.

**Basic Level 2: Droplet Reentrainment**

The symptoms of droplet reentrainment include the following:

- Fallout of droplets within 50 yards downwind of the stack
- Discoloration of adjacent surfaces
- Mud lip around the stack
- Heavy drainage from open ports on the stack

During cold weather, droplet reentrainment could also be indicated by the build-up of ice on structural steel and adjacent surfaces near the scrubber stack. It is important to note that many particulate scrubbers and gaseous absorbers serve batch processes, and the reentrainment emissions can be very intermittent. Therefore, the long-term symptoms such as deposition patterns and drainage patterns are especially useful. A stack with droplet reentrainment problems is shown in Figure 4-13.

![Figure 4-13. Drainage pattern on wet scrubber stack](image)

When droplet reentrainment is noticed, it is usually helpful to conduct a follow-up check for mist eliminator cleaning frequency. Solids build-up on the mist eliminator can increase the
localized gas velocities and cause droplet reentrainment off the trailing edges of the mist eliminator.

**Basic Level 2: Scrubber Static Pressure Drop**

The static pressure drop is a useful indirect indicator of scrubber performance. High values of static pressure drop are associated with the high gas velocities that favor high efficiency particle impaction.

The relationship between particulate emissions and static pressure drop is indicated by the test data shown in Figure 4-14. These data are from two high efficiency venturi scrubber systems serving two identical Q-BOPF furnaces in a single plant and were taken during the oxygen blowing cycle when the emission quantities peaked.

![Graph showing the relationship between particulate emissions and static pressure drop](image)

**Figure 4-14. Efficiency of two venturi scrubbers serving BOPF operations**

Static pressure drop-removal efficiency graphs like this one can only be prepared when the source has been tested on numerous occasions. If only a few tests on a specific site have been conducted, the statistical confidence interval is too large, and conclusions can not be based on the correlation. Also, data from units at different plants cannot be combined into a single correlation because there are site specific differences in particle size distributions, gas-liquid distributions, and liquid surface tension. All four factors can have a large impact on the particulate emissions without necessarily influencing the observed static pressure drop. Accordingly, the static pressure drop data can only be evaluated for a specific site.

Static pressure drop data are a useful qualitative indicator of scrubber performance as long as the process operating conditions are similar to baseline conditions. A decrease of more than several inches of water in the static pressure drop during peak gas flow periods could be associated with decreased collection efficiency. An increase in the residual opacity of the stack further supports this conclusion. Changes in static pressure drop can occur because of a variety of problems:
Erosion of adjustable throat mechanisms
- Intentional changes in the position of adjustable throat mechanisms
- Decrease in gas flow rates
- Severe decrease in the liquid flow rate
- Malfunctioning static pressure drop gauge

Evaluation of changes in the gas flow rate and liquid flow rate will be discussed in later sections of the Basic Level 2 inspection. This information will be helpful in evaluating changes in the static pressure drop.

The adequacy of the gauge should be evaluated to confirm that there has, in fact, been a significant change in scrubber performance. The monitoring conditions inside particulate scrubbers are relatively hostile, and a variety of instrument problems are possible:

- Plugging of the upstream or downstream ports
- Water condensation within the gauge
- Freezing of condensed water within the gauge
- Heat-related damage to a gauge mounted too close to a hot surface
- Evaporation of water from the manometer

The adequacy of the gauge can be checked by comparing the static pressure gauges and static pressure drop data throughout the entire system. For example, the sum of all of the static pressure drops across cyclones, scrubbers, absorbers, evaporative coolers, and other vessels should be slightly less than the fan inlet static pressure. The difference between the two values is the frictional loss encountered by the gas stream passing through the ductwork and the loss associated with accelerating the pollutant-laden gas stream into the hood. Obviously, the accuracy of this mathematical check is limited because all the gauges are subject to some error.

Changes in the static pressure drop are typically due to changes in the gas flow rate or to significant physical problems with the components. These changes usually impair the gas-liquid contact and thereby reduce the collection efficiency of the system. For example, high static pressure drop in packed bed scrubbers is often due to partial plugging of the bed. This causes poor gas-liquid distribution. Low static pressure drop across the bed can be due to the corrosion and collapse of the retention screens supporting the bed. In the case of tray scrubbers, low static pressure can be due to bowing, warping, or sloping of the trays or corrosion of the tray overflow weirs that maintain adequate liquid levels on the trays. Erosion of adjustable throat mechanisms in venturi scrubbers can cause reduced static pressure drop. All of these potential problems should be checked by plant personnel during each major scrubber outage.

**Basic Level 2: Liquid Flow Rate**

Monitoring the liquid flow rate is required by New Source Performance Standards (NSPS) and is also included in many operating permits for existing sources. The rationale for these
requirements is that scrubber performance is impaired when the liquid recirculation rate is low.

The liquid flow rate is monitored in terms of gallons per minute and is evaluated in terms of the gallons per minute per 1,000 actual cubic feet per minute of gas flow. High efficiency particulate scrubbers usually operate with liquid-to-gas ratios of 5 to 20 gallons per 1,000 acf. Particulate removal efficiency decreases significantly at liquid-to-gas ratios less than 4 gallons per 1,000 acf. The liquid-to-gas ratio for gaseous absorbers ranges from 5 gallons per 1,000 acf to more than 100 gallons per 1,000 acf.

On moderate-to-large particulate scrubbers and gaseous absorbers, the liquid flow rate is monitored continuously. The types of flowmeters include the following:

- Magnetic flowmeters
- Ultrasonic flowmeters
- Swinging vane flowmeters
- Rotameters
- Orifice meters

Liquid flow rate data are usually included on process log sheets. On large systems, it may also be recorded continuously. The available data should be reviewed for the time period since the last inspection to confirm that the scrubber has been operated properly. Also, calibration data for the flowmeter should be evaluated whenever it is available.

The liquid flow rate during the inspection should be compared with baseline values. If the flow rate has decreased, the present liquid-to-gas ratio should be calculated using estimated gas flow rate data in the agency files. If the value is significantly below the baseline level, the following additional inspection data should be evaluated:

- Liquid supply header pressures at the scrubber inlet
- Recirculation pump discharge pressures
- Symptoms of pipe freezing or blockage
- Symptoms of centrifugal pump cavitation

The liquid pH levels during the previous several weeks should also be checked. Liquid pH levels above 9 can lead to the precipitation of calcium and magnesium solids. Solids build-up in piping, nozzle supply headers, and nozzles can restrict liquid flow.

Malfunctions of the liquid flow rate meter can lead to low indicated flow rates. For example, solids build-up problems in the piping can blind the sensors of magnetic flow meters and can cause low readings. If the recirculation flow rates are low, there should be other symptoms of problems. These symptoms could include increased plume residual opacity, increased scrubber outlet gas temperature, decreased pump discharge pressure, and decreased supply header pressures.
Basic Level 2: Inlet and Outlet Gas Temperature

The inlet gas temperature should be compatible with the scrubber materials of construction. It should also be below the vaporization temperature of the liquid, if a cooling section has not been provided inside the scrubber. Inlet gas temperature is additionally important for absorbers, since the solubility of gaseous contaminants is inversely related to the gas temperature. Increases of 10°F to 30°F over the baseline temperature can reduce the collection efficiency of the absorber.

Temperature information is also a useful indicator of gas-liquid distribution problems. If the liquid distribution is not adequate, collection efficiency will be reduced. When the gas-liquid distribution is good, the outlet gas stream temperature will be at the adiabatic saturation temperature. This simply means that the gas stream will be saturated with water vapor. The adiabatic saturation temperature can be easily determined with a psychometric chart, if the inlet gas stream dry bulb temperature and absolute humidity are known. Unfortunately, the absolute humidity of the entering gas stream is rarely available. While it could be estimated, errors can significantly affect the value of the saturation temperature determined from the psychometric chart, possibly leading to erroneous conclusions.

A more direct way to evaluate liquid distribution problems is to look at the difference between the inlet and outlet gas temperatures. If that temperature difference has decreased, liquid distribution problems are likely. Other symptoms that are useful for identifying possible distribution problems include:

- Higher-than-normal supply header pressures
- Apparent pipe or header freezing
- Malfunctioning adjustable throat linkages or actuators

During outages, plant maintenance personnel can conduct internal inspections to search for symptoms of maldistribution. In some cases, erosion patterns on the inlet ductwork provide a clear indication of maldistribution. Other symptoms of maldistribution include severely eroded or corroded adjustable throat mechanisms and solids deposits.

Follow-up Level 2: Mist Eliminator Static Pressure Drop

The static pressure drop across the mist eliminator is used as an indicator of the physical condition of the mist eliminator. The static pressure drop is strictly a function of the geometry of the mist eliminator, the gas flow rate through the mist eliminator, and the gas density.

Deviations from the baseline static pressure drop levels indicate either changes in the gas flow rates or buildup of solids on the mist eliminator. Usually, the pressure drops across mist eliminators vary from 0.5 in. H₂O to 2 in. H₂O. Some commercial designs have pressure drops as high as 4 in. H₂O. Increases in the static pressure drop of more than 1 in. H₂O could
indicate the potential for reentrainment. Increases of more than this value could indicate that excessive forces are being placed on the mist eliminator elements and supports. Because of the large area of the mist eliminator, a large pressure differential across the unit can cause damage.

Mist eliminator static pressure drop records should be evaluated for a number of operating days since the last inspection to confirm that the static pressure drop levels have increased from baseline levels. If high pressure drop is occurring, it might be necessary to activate the cleaning system more frequently or for a longer operating time. Usually, mist eliminator washing lasts from several minutes to more than 15 minutes. When there is a chronic problem with high static pressure drop, it might be advisable for plant maintenance personnel to inspect the spray nozzles used to clean the mist eliminator elements. The solids deposition pattern remaining on the mist eliminator provides a clear indication of inadequate coverage. In addition, problems with the nozzles or supply headers can be identified during these internal inspections.

Values well below the baseline range suggest that part of the mist eliminator has fallen apart or otherwise been damaged. Structural failure of the mist eliminator is possible because of the forces that can be imposed on the surface when it is significantly blinded. For example, a 6-foot diameter mist eliminator immediately upstream of a fan with an inlet static pressure of -10 in. H₂O can be subject to a force of more than 1,400 pounds if it is totally plugged. Corrosion related weakening of the supporting frame on the mist eliminator can cause the entire mist eliminator to break into parts and be pulled toward the fan. Also, some mist eliminators constructed of FRP and other synthetic materials can suffer adhesive failure if there is a gas temperature spike. This can cause part of the mist eliminator to break away. The gaps left in the mist eliminator have a very low static pressure drop, and most of the gas stream channels through this area. Accordingly, the effectiveness of the mist eliminator is compromised.

**Follow-up Level 2: Spray Nozzle Supply Header Pressure**

The supply headers are the pipes that deliver recirculation liquid to the groups of nozzles surrounding the inlet of the scrubber or absorber. The supply header pressures are used primarily as indicators of the physical condition of the spray nozzles and piping. Assuming that the recirculation liquid flow rate is relatively constant at the baseline levels, an increase in the supply header pressure suggests solids build-up. If the supply header pressure is lower than baseline values, the nozzle orifices could have eroded.

Nozzle spray angles are distorted when solids begin to build-up in the nozzle. If the problem continues, it is possible for the solids to completely block the nozzle or a portion of the header supplying some of the nozzles. The latter condition is common when the suspended solids levels in the liquid are high and there is a dead end in the header where solids can accumulate and pack tightly. Build-up of solids within the nozzle and the blockage of flow to a group of nozzles can adversely affect gas-liquid distribution in the scrubber or absorber.
Erosion of the nozzle orifices can be caused by the erosive action of the suspended solids in the liquid stream or by corrosive action at low liquid pH levels. Erosion and corrosion of the nozzle orifices also disturbs gas-liquid distribution.

Pressure gauge malfunctions can cause apparent changes from baseline pressure levels. The accumulation of either solids or ice in the inlet line to the pressure gauge can cause false readings.

Changes in the liquid flow rate and pressure obviously affect the pressures in the supply headers. Changes in the recirculation liquor flow rate can be identified based on the discharge pressures of the recirculation pumps and based on the recirculation liquid flow rate meter.

**Follow-up Level 2: Recirculation Pump Discharge Pressure**

Most centrifugal pumps have a discharge pressure gauge to provide a general indication of pump operations. Problems that reduce the pumping rate usually decrease this pressure:

- Pump cavitation
- Air infiltration into the pump
- Pump impeller erosion and corrosion
- Pump inlet strainer blockage

Pump cavitation is the vaporization of liquid as it passes over the pump impeller. Vaporization is caused by the reduced pressure that occurs as the liquid enters the pump. Cavitation is possible whenever the liquid temperature is relatively high or when there is insufficient Net Positive Suction Head (NPSH). The latter is simply a measure of the pressure existing in the inlet piping to the centrifugal pump. This pressure must be sufficiently high so that the suction effect at the pump inlet is not large enough to reduce the pressure to a level where vaporization can occur. The vapor bubbles created during passage across the pump impeller can cause severe metal erosion. The presence of cavitation is indicated by a distressed pump sound and by reduced liquid flow rates and discharge pressures.

Pump impeller erosion and corrosion are caused primarily by the abrasive action of suspended solids in the recirculation liquid or by corrosive fluorides, chlorides, or other materials present in the liquid. The rate of corrosion is relatively fast at low pH levels.

Pockets of air trapped in the inlet piping to scrubbers can impede recirculation liquid flow. The entrainment of air in the liquid stream can be caused by poor pump intake piping from the recirculation tanks or by air infiltration into the piping. The pump inlet piping is usually sloped at least one degree to ensure that air does not build up in pockets within the pipe and suddenly move into the pump.
Strainers are used on piping to protect the pump impellers from abrasive particles of metal that become entrained in the recirculation liquid stream. Bypass lines around the strainers are sometimes used to allow for cleaning. Strainers are not appropriate for all scrubber applications.

**Follow-up Level 2: Gas Cooler Outlet Gas Temperature**

The outlet temperature of the cooling system must be below the temperature limits for the materials of construction used in the scrubber or absorber system. In some cases, corrosion and erosion resistant linings are used on metal components. These can be damaged at high temperatures. High temperatures also cause water evaporation from the atomized droplets in the scrubber, impeding particle impaction. For both of these reasons, the outlet gas temperature of the cooling system must be below the limits for the specific system being inspected.

Cooling system outlet gas temperatures should be evaluated using the temperature monitoring data recorded in the control room for the process being inspected. Peak gas temperatures are most important for those processes with cyclic operations such as charging and tapping.

**Follow-up Level 2: Evaporative Cooler Spray Liquid Quality**

Suspended or dissolved solids contained in water sprayed into evaporative coolers can be released as difficult-to-control submicron particles as the droplets evaporate to dryness. The spray water used in evaporative coolers should be as clean as possible. A sample of the water should have little, if any, turbidity.

This particle formation mechanism can have a significant impact on the overall scrubber performance if recirculation liquid from the scrubber is used for evaporative cooling. The typical solids levels in the recirculation liquid are relatively high. Accordingly, the type of liquid being used in the evaporative cooler should be determined.

**Follow-up Level 2: Liquid pH**

The liquid pH should usually be in the range of 5 to 9, with higher values at the inlet to the scrubber and lower values at the outlet. If the pH is too high, calcium and magnesium compounds precipitate to form scale deposits in piping, headers, nozzles, and tanks. If the pH is too low, the reactions in absorbers of acid compounds such as sulfur dioxide and hydrogen chloride can stop, and some of the dissolved acid gases can volatilize back into the gas stream. Also, the rate of corrosion increases as the pH decreases below 5.

Some variations in the liquid pH are common due to variations in the rate of acid gas generation in the process and variations in the rate of alkali feed to the scrubber. Short term excursions below 5 or above 9 will not cause significant damage. However, long term operation outside of the normal pH range can lead to a variety of scrubber performance
problems. The operating records should be evaluated for the time period since the last inspection to determine if pH fluctuations are chronic or severe.

Instruments for measuring pH are prone to mechanical damage, scale-related blinding, and drift. The instruments must be checked frequently to ensure that the data are accurate and representative of the liquid at the monitoring location.

**Follow-up Level 2: T-R Set Electrical Data (Ionizing Wet Scrubbers)**

The secondary voltage, secondary current, and spark rate of ionizing wet scrubbers should be checked if high opacity is observed. The packed bed scrubber section of this unit has a limited ability to collect small particles unless the particles are highly charged.

The secondary voltage should be compared with the baseline value and with industrial averages for this type of collector. Secondary voltages lower than 18 kilovolts are often associated with increased particulate emissions.

The secondary current should also be compared with baseline data. Low values are usually caused by solids build-up on the small plates or on the small diameter discharge wires. The plates are cleaned approximately once every four hours. The discharge wires are cleaned approximately once every eight hours, unless solids loadings in the inlet gas stream are high. During cleaning of the discharge wires, the T-R set is deenergized for a period of approximately 5 minutes.

High sparking rates are due primarily to misalignment problems in the ionizer section. Unlike conventional precipitators, the solids build-up on the surfaces should be small, and dust layer resistivity related sparking is not an issue.

**Follow-up Level 2: Corrosion and Erosion**

Corrosion or erosion damage to the scrubber or absorber shell can occur due to high gas velocities and the potentially corrosive chemicals in the system. A visual inspection should be conducted to visually identify any areas with apparent damage.

In addition to the obvious financial implications for the operators, the corrosion and erosion damage can contribute to particulate emissions. Air infiltration through the gaps and openings can reduce the total quantity of gas being pulled from the process hoods. Air infiltration can be especially severe in the case of high efficiency venturi scrubbers because the outlet static pressures are often -40 in. H2O to -80 in. H2O. It is often possible to hear the air infiltration leaks caused by these high differences between the ambient pressure and the system pressure.
Follow-up Level 2: Component Failure Records

When frequent scrubber or absorber malfunction or upset reports have been submitted, it might be helpful to evaluate the component failure records. The purpose of this review is to confirm that plant personnel have identified the fundamental problems and that there is reason to believe that the frequency of these excess emission incidents will decrease.

For example, records should be maintained indicating the locations of all spray nozzles that plug or erode. All the nozzles removed should be inspected to evaluate possible causal factors. If deposits are present, it might be helpful to chemically identify the materials responsible. The nozzle failure spatial distribution data and other analyses will be helpful for determining means to correct the problem by redesigning the supply header, by switching to a different type of nozzle, or by improving the recirculation liquid quality.

The rate of component failure should be carefully tracked by plant personnel. An increase from the normal or baseline rate should initiate a detailed evaluation of the scrubber system. For example, scale build-up in piping or around pH sensors could create erroneous instrument pH readings. Unexpectedly high levels could be causing solids build-up in nozzles, headers, and scrubber internals. Unexpectedly low pH levels or high chloride levels could cause rapid corrosion related damage. In either case, it is advantageous for plant personnel to identify and correct the problem before significant equipment damage and excessive emissions occur.

Follow-up Level 2: Internal Inspection Reports

These should be reviewed by agency personnel when chronic emission problems have been occurring. The scope of these internal inspections often includes the following:

- Physical condition of liquid distributors in packed bed scrubbers
- Physical condition of spray nozzles
- Solids accumulation in mist eliminators or packed beds
- Bows, warps, and slopes in impingement trays
- Corrosion of packed bed retention screens
- Obvious gas maldistribution patterns

The reports prepared by plant maintenance personnel are useful in reviewing the plant’s proposed correction actions. Agency personnel should not, under any circumstances, accompany plant personnel during the internal inspections. Therefore, these reports are the only source of information concerning physical problems that are not directly indicated by the operating data for the absorber system.
Review Problems

1. An impingement tray scrubber has the following operating conditions. Is there any reason to conduct a follow-up inspection of this unit?

<table>
<thead>
<tr>
<th>Inspection Data</th>
<th>Baseline Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible emissions, %</td>
<td>5</td>
</tr>
<tr>
<td>Mist eliminator pressure drop, in. H₂O</td>
<td>0.6</td>
</tr>
<tr>
<td>Outlet gas temperature, °F</td>
<td>91</td>
</tr>
<tr>
<td>Inlet gas temperature, °F</td>
<td>86</td>
</tr>
<tr>
<td>Tray pressure drops, in. H₂O</td>
<td></td>
</tr>
<tr>
<td>Tray 1</td>
<td>0.6</td>
</tr>
<tr>
<td>Tray 2</td>
<td>1.4</td>
</tr>
<tr>
<td>Tray 3</td>
<td>0.8</td>
</tr>
<tr>
<td>Recirculation liquid pH</td>
<td>7.0</td>
</tr>
<tr>
<td>Recirculation liquid flow, gpm</td>
<td>30</td>
</tr>
</tbody>
</table>

2. An adjustable throat venturi scrubber serving a hot mix asphaltic concrete plant dryer has the following operating conditions. What are possible causes of the increased opacity?

<table>
<thead>
<tr>
<th>Inspection Data</th>
<th>Baseline Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible Emissions, %</td>
<td>15</td>
</tr>
<tr>
<td>Static Pressure Drop, in. H₂O</td>
<td>23</td>
</tr>
<tr>
<td>Inlet Gas Temperature, °F</td>
<td>290</td>
</tr>
<tr>
<td>Outlet Gas Temperature, °F</td>
<td>142</td>
</tr>
<tr>
<td>Mist Elim. Pressure Drop, in. H₂O</td>
<td>1.0</td>
</tr>
<tr>
<td>Recirculation Liquid Flow, gpm</td>
<td>100</td>
</tr>
<tr>
<td>Recirculation Liquid pH</td>
<td>6.0</td>
</tr>
<tr>
<td>Dryer Aggregate Outlet Temp., °F</td>
<td>295</td>
</tr>
<tr>
<td>Asphalt Binder</td>
<td>AC 40</td>
</tr>
<tr>
<td>Production Rate, ton/day</td>
<td>100</td>
</tr>
</tbody>
</table>

3. The pressure gauge on the liquor line leading to the nozzles of a spray tower scrubber increased from a baseline value of 60 psig to a present value of 88 psig. What is one possible explanation for this condition?

   a. Plugging of some of the nozzles
   b. Erosion of the pump impeller
   c. Erosion of the nozzles
4. Why are the inlet and outlet gas temperatures used in the evaluation of wet scrubbers?

   a. To evaluate gas-liquid distribution in the scrubber
   b. To evaluate mass transfer driving forces in the scrubber
   c. To evaluate the solubility of dissolved solids in the recirculated liquor
   d. None of the above

5. What is the normal liquid-to-gas ratio for high static pressure drop venturi scrubbers used for particulate matter control?

   a. 1 to 2 gallons per 1,000 acf
   b. 2 to 5 gallons per 1,000 acf
   c. 5 to 20 gallons per 1,000 acf
   d. 20 to 50 gallons per 1,000 acf
   e. 50 to 75 gallons per 1,000 acf
   f. 75 to 150 gallons per 1,000 acf

6. What is the pressure drop across the scrubber shown below if the static pressure at Point 1 is -16 in. H₂O and the static pressure at Point 4 is -0.5 in. H₂O?

7. A static pressure measurement at Point 1 indicates a value of +4 in. H₂O. Can this be dismissed as being obviously in error?
8. The differential pressure indicator (DPI) on the system below is reporting 18 in. H₂O. Using portable instruments, the measured static pressure at AT#1 is -12 in H₂O and at AT#3 is -20 in. H₂O. Is there reason to suspect the accuracy of the permanently mounted gauge?
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