Handbook of
Air Pollution
Control Systems and Devices

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Chapter- 1

Electrostatic Precipitator

An **electrostatic precipitator** (ESP), or **electrostatic air cleaner** is a particulate collection device that removes particles from a flowing gas (such as air) using the force of an induced electrostatic charge. Electrostatic precipitators are highly efficient filtration devices that minimally impede the flow of gases through the device, and can easily remove fine particulate matter such as dust and smoke from the air stream. In contrast to wet scrubbers which apply energy directly to the flowing fluid medium, an ESP applies energy only to the particulate matter being collected and therefore is very efficient in its consumption of energy (in the form of electricity).

Invention of the electrostatic precipitator

The first use of corona to remove particles from an aerosol was by Hohlfeld in 1824. However, it was not commercialized until almost a century later. In 1907 Dr. Frederick G. Cottrell applied for a patent on a device for charging particles and then collecting them through electrostatic attraction — the first electrostatic precipitator. He was then a professor of chemistry at the University of California, Berkeley. Cottrell first applied the device to the collection of sulfuric acid mist and lead oxide fume emitted from various acid-making and smelting activities. Vineyards in northern California were being adversely affected by the lead emissions.

At the time of Cottrell's invention, the theoretical basis for operation was not understood. The operational theory was developed later in the 1920s, in Germany.

Prof. Cottrell used proceeds from his invention to fund scientific research through the creation of a foundation called Research Corporation in 1912 to which he assigned the patents. The intent of the organization was to bring inventions made by educators (such as Cottrell) into the commercial world for the benefit of society at large. The operation of Research Corporation is perpetuated by royalties paid by commercial firms after commercialization occurs. Research Corporation has provided vital funding to many scientific projects: Goddard's rocketry experiments, Lawrence's cyclotron, production methods for vitamins A and B_1, among many others. By a decision of the U.S. Supreme Court the Corporation had to be split into two entities, the Research Corporation and two

commercial firms making the hardware: Research-Cottrell Inc. (operating east of the Mississippi River) and Western Precipitation operating in the Western states. The Research Corporation continues to be active to this day and the two companies formed to commercialize the invention for industrial and utility applications are still in business as well.

Electrophoresis is the term used for migration of gas-suspended charged particles in a direct-current electrostatic field. If your television set accumulates dust on the face it is because of this phenomenon (a CRT is a direct-current machine operating at about 35kV).

The plate precipitator

The most basic precipitator contains a row of thin vertical wires, and followed by a stack of large flat metal plates oriented vertically, with the plates typically spaced about 1 cm to 18 cm apart, depending on the application. The air or gas stream flows horizontally through the spaces between the wires, and then passes through the stack of plates.

A negative voltage of several thousand volts is applied between wire and plate. If the applied voltage is high enough an electric (corona) discharge ionizes the gas around the electrodes. Negative ions flow to the plates and charge the gas-flow particles.

The ionized particles, following the negative electric field created by the power supply, move to the grounded plates.

Particles build up on the collection plates and form a layer. The layer does not collapse, thanks to electrostatic pressure (given from layer resistivity, electric field, and current flowing in the collected layer).

Collection efficiency (R)

Precipitator performance is very sensitive due to two particulate properties: 1) Resistivity; and 2) Particle size distribution. These properties can be determined economically and accurately in the laboratory. A widely taught concept to calculate the collection efficiency is the Deutsch model, which assumes infinite remixing of the particles perpendicular to the gas stream.

Resistivity can be determined as a function of temperature in accordance with IEEE Standard 548. This test is conducted in an air environment containing a specified moisture concentration. The test is run as a function of ascending or descending temperature or both. Data are acquired using an average ash layer electric field of 4 kV/cm. Since relatively low applied voltage is used and no sulfuric acid vapor is present in the environment, the values obtained indicate the maximum ash resistivity.

Usually the descending temperature test is suggested when no unusual circumstances are involved. Before the test, the ash is thermally equilibrated in dry air at 454 °C (850°F) for

about 14 hours. It is believed that this procedure anneals the ash and restores the surface to pre-collection condition.

If there is a concern about the effect of combustibles, the residual effect of a conditioning agent other than sulfuric acid vapor, or the effect of some other agent that inhibits the reaction of the ash with water vapor, the combination of the ascending and descending test mode is recommended. The thermal treatment that occurs between the two test modes is capable of eliminating the foregoing effects. This results in ascending and descending temperature resistivity curves that show a hysteresis related to the presence and removal of some effect such as a significant level of combustibles.

With particles of high resistivity (cement dust for example) Sulfur trioxide is sometimes injected into a flue gas stream to lower the resistivity of the particles in order to improve the collection efficiency of the electrostatic precipitator.

Modern industrial electrostatic precipitators

ESPs continue to be excellent devices for control of many industrial particulate emissions, including smoke from electricity-generating utilities (coal and oil fired), salt cake collection from black liquor boilers in pulp mills, and catalyst collection from fluidized bed catalytic cracker units in oil refineries to name a few. These devices treat gas volumes from several hundred thousand ACFM to 2.5 million ACFM (1,180 m³/s) in the largest coal-fired boiler applications. For a coal-fired boiler the collection is usually performed downstream of the air preheater at about 160 °C (320 deg.F) which provides optimal resistivity of the coal-ash particles. For some difficult applications with low-sulfur fuel hot-end units have been built operating above 371 °C (700 deg.F).

The original parallel plate–weighted wire design (described above) has evolved as more efficient (and robust) discharge electrode designs were developed, today focusing on rigid (pipe-frame) discharge electrodes to which many sharpened spikes are attached (barbed wire), maximizing corona production. Transformer-rectifier systems apply voltages of 50 – 100 kV at relatively high current densities. Modern controls, such as an automatic voltage control, minimize sparking and prevent arcing (sparks are quenched within 1/2 cycle of the TR set), avoiding damage to the components. Automatic plate-rapping systems and hopper-evacuation systems remove the collected particulate matter while on line, theoretically allowing ESPs to stay in operation for years at a time.

Wet electrostatic precipitator

A wet electrostatic precipitator (WESP or wet ESP) operates with saturated air streams (100% relative humidity). WESPs are commonly used to remove liquid droplets such as sulfuric acid mist from industrial process gas streams. The WESP is also commonly used where the gases are high in moisture content, contain combustible particulate, have particles that are sticky in nature.

The preferred and most modern type of WESP is a downflow tubular design. This design allows the collected moisture and particulate to form a slurry that helps to keep the collection surfaces clean.

Plate style and upflow design WESPs are very unreliable and should not be used in applications where particulate is sticky in nature.

Consumer-oriented electrostatic air cleaners

Plate precipitators are commonly marketed to the public as air purifier devices or as a permanent replacement for furnace filters, but all have the undesirable attribute of being somewhat messy to clean. A negative side-effect of electrostatic precipitation devices is the production of toxic ozone and NO_x. However, electrostatic precipitators offer benefits over other air purifications technologies, such as HEPA filtration, which require expensive filters and can become "production sinks" for many harmful forms of bacteria.

The two-stage design (charging section ahead of collecting section) has the benefit of minimizing ozone production which would adversely affect health of personnel working in enclosed spaces. For shipboard engine rooms where gearboxes generate an oil fog, two-stage ESP's are used to clean the air improving the operating environment and preventing buildup of flammable oil fog accumulations. Collected oil is returned to the gear lubricating system.

With electrostatic precipitators, if the collection plates are allowed to accumulate large amounts of particulate matter, the particles can sometimes bond so tightly to the metal plates that vigorous washing and scrubbing may be required to completely clean the collection plates. The close spacing of the plates can make thorough cleaning difficult, and the stack of plates often cannot be easily disassembled for cleaning. One solution, suggested by several manufacturers, is to wash the collector plates in a dishwasher.

Some consumer precipitation filters are sold with special soak-off cleaners, where the entire plate array is removed from the precipitator and soaked in a large container overnight, to help loosen the tightly bonded particulates.

A study by the Canada Mortgage and Housing Corporation testing a variety of forced-air furnace filters found that ESP filters provided the best, and most cost-effective means of cleaning air using a forced-air system.

Chapter- 2

Dust Collector

Dust collector in Pristina, Kosovo

Designed to handle heavy dust loads, a **dust collector** system consists of a blower, dust filter, a filter-cleaning system, and a dust receptacle or dust removal system. It is distinguished from air cleaners which use disposable filters to remove dust.

Types of dust collectors

Five principal types of industrial dust collectors are:

- Inertial separators
- Fabric filters
- Wet scrubbers
- Electrostatic precipitators
- Unit collectors

Inertial separators

Inertial separators separate dust from gas streams using a combination of forces, such as centrifugal, gravitational, and inertial. These forces move the dust to an area where the forces exerted by the gas stream are minimal. The separated dust is moved by gravity into a hopper, where it is temporarily stored.

The three primary types of inertial separators are:

- Settling chambers
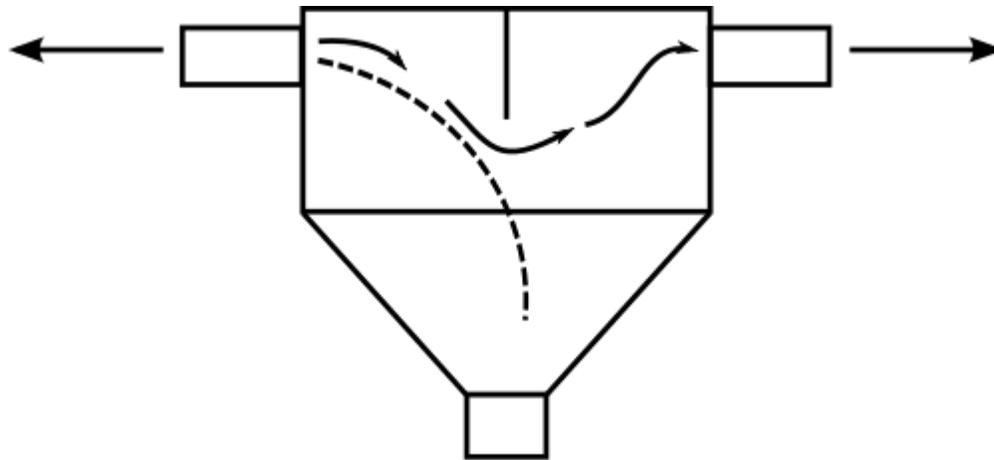- Baffle chambers
- Centrifugal collectors

Neither settling chambers nor baffle chambers are commonly used in the minerals processing industry. However, their principles of operation are often incorporated into the design of more efficient dust collectors.
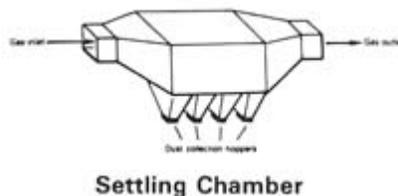
Settling Chamber

Settling chamber

A settling chamber consists of a large box installed in the ductwork. The sudden expansion of size at the chamber reduces the speed of the dust-filled airstream and heavier particles settle out.

Settling chambers are simple in design and can be manufactured from almost any material. However, they are seldom used as primary dust collectors because of their large space requirements and low efficiency. A practical use is as precleaners for more efficient collectors.
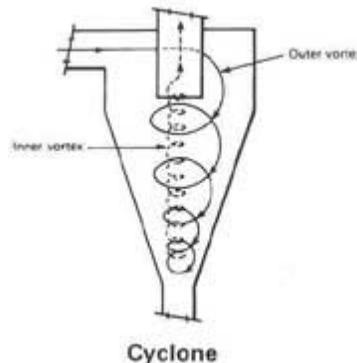
Baffle Chamber

Baffle chamber diagram.

Baffle chamber

Baffle chambers use a fixed baffle plate that causes the conveying gas stream to make a sudden change of direction. Large-diameter particles do not follow the gas stream but continue into a dead air space and settle. Baffle chambers are used as precleaners

Cyclone

Centrifugal collectors

Centrifugal collectors use cyclonic action to separate dust particles from the gas stream. In a typical cyclone, the dust gas stream enters at an angle and is spun rapidly. The centrifugal force created by the circular flow throws the dust particles toward the wall of the cyclone. After striking the wall, these particles fall into a hopper located underneath.

The most common types of centrifugal, or inertial, collectors in use today are:

Single-cyclone separators

They create a dual vortex to separate coarse from fine dust. The main vortex spirals downward and carries most of the coarser dust particles. The inner vortex, created near the bottom of the cyclone, spirals upward and carries finer dust particles.
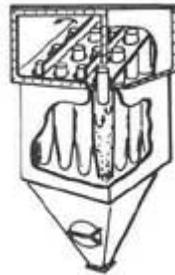
Multiclone

Multiple-cyclone separators

Also known as multiclones®, consist of a number of small-diameter cyclones, operating in parallel and having a common gas inlet and outlet, as shown in the figure. Multiclones® operate on the same principle as cyclones—creating a main downward vortex and an ascending inner vortex.

Multiclones® are more efficient than single cyclones because they are longer and smaller in diameter. The longer length provides longer residence time while the smaller diameter creates greater centrifugal force. These two factors result in better separation of dust particulates. The pressure drop of multiclone® collectors is higher than that of single-cyclone separators.

Babcock & Wilcox is the original manufacturer and trademark holder of Multiclone® dust collectors and replacement parts formerly offered by Western Precipitation. Multiclone® dust collectors are found in all types of power and industrial applications, including pulp and paper plants, cement plants, steel mills, petroleum coke plants, metallurgical plants, saw mills and other kinds of facilities that process dust.

Secondary Air Flow Separators

This type of cyclone uses a secondary air flow, injected into the cyclone to accomplish several things. The secondary air flow increases the speed of the cyclonic action making the separator more efficient; it intercepts the particulate before it reaches the interior walls of the unit; and it forces the separated particulate toward the collection area. The secondary air flow protects the separator from particulate abrasion and allows the separator to be installed horizontally because gravity is not depended upon to move the separated particulate downward.

Fabric filters
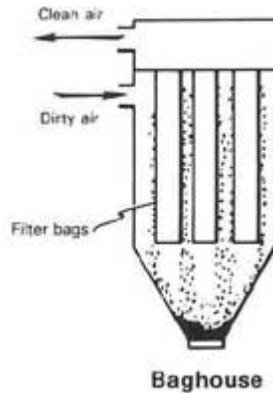
Baghouse

Commonly known as baghouses, fabric collectors use filtration to separate dust particulates from dusty gases. They are one of the most efficient and cost effective types of dust collectors available and can achieve a collection efficiency of more than 99% for very fine particulates.

Dust-laden gases enter the baghouse and pass through fabric bags that act as filters. The bags can be of woven or felted cotton, synthetic, or glass-fiber material in either a tube or envelope shape.

The high efficiency of these collectors is due to the dust cake formed on the surfaces of the bags. The fabric primarily provides a surface on which dust particulates collect through the following four mechanisms:

- Inertial collection - Dust particles strike the fibers placed perpendicular to the gas-flow direction instead of changing direction with the gas stream.
- Interception - Particles that do not cross the fluid streamlines come in contact with fibers because of the fiber size.
- Brownian movement - Submicrometre particles are diffused, increasing the probability of contact between the particles and collecting surfaces.
- Electrostatic forces - The presence of an electrostatic charge on the particles and the filter can increase dust capture.

A combination of these mechanisms results in formation of the dust cake on the filter, which eventually increases the resistance to gas flow. The filter must be cleaned periodically.

Types of baghouses

As classified by cleaning method, three common types of baghouses are:

Mechanical-Shaker Baghouse
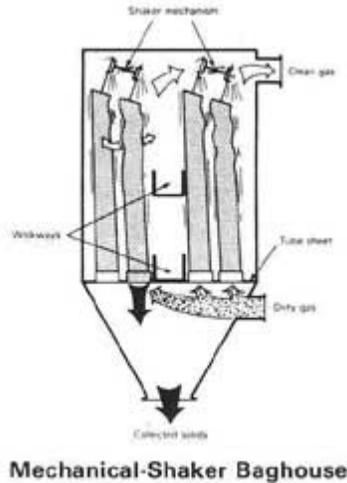
Mechanical shaker

In mechanical-shaker baghouses, tubular filter bags are fastened onto a cell plate at the bottom of the baghouse and suspended from horizontal beams at the top. Dirty gas enters the bottom of the baghouse and passes through the filter, and the dust collects on the inside surface of the bags.

Cleaning a mechanical-shaker baghouse is accomplished by shaking the top horizontal bar from which the bags are suspended. Vibration produced by a motor-driven shaft and cam creates waves in the bags to shake off the dust cake.

Shaker baghouses range in size from small, handshaker devices to large, compartmentalized units. They can operate intermittently or continuously. Intermittent units can be used when processes operate on a batch basis-when a batch is completed, the baghouse can be cleaned. Continuous processes use compartmentalized baghouses; when one compartment is being cleaned, the airflow can be diverted to other compartments.

In shaker baghouses, there must be no positive pressure inside the bags during the shake cycle. Pressures as low as 0.02 in. wg can interfere with cleaning.

The air to cloth ratio for shaker baghouses is relatively low, hence the space requirements are quite high. However, because of the simplicity of design, they are popular in the minerals processing industry.

Reverse air
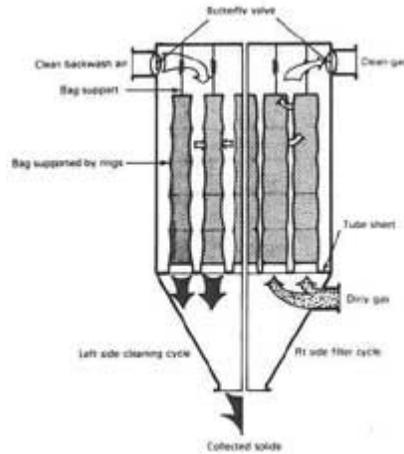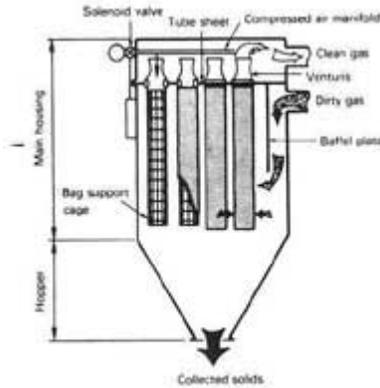
Reverse-Air Baghouse

In reverse-air baghouses, the bags are fastened onto a cell plate at the bottom of the baghouse and suspended from an adjustable hanger frame at the top. Dirty gas flow normally enters the baghouse and passes through the bag from the inside, and the dust collects on the inside of the bags.

Reverse-air baghouses are compartmentalized to allow continuous operation. Before a cleaning cycle begins, filtration is stopped in the compartment to be cleaned. Bags are cleaned by injecting clean air into the dust collector in a reverse direction, which pressurizes the compartment. The pressure makes the bags collapse partially, causing the dust cake to crack and fall into the hopper below. At the end of the cleaning cycle, reverse airflow is discontinued, and the compartment is returned to the main stream.

The flow of the dirty gas helps maintain the shape of the bag. However, to prevent total collapse and fabric chafing during the cleaning cycle, rigid rings are sewn into the bags at intervals.

Space requirements for a reverse-air baghouse are comparable to those of a shaker baghouse; however, maintenance needs are somewhat greater.

Reverse jet

Reverse-Jet Baghouse

In reverse-pulse-jet baghouses, individual bags are supported by a metal cage, which is fastened onto a cell plate at the top of the baghouse. Dirty gas enters from the bottom of the baghouse and flows from outside to inside the bags. The metal cage prevents collapse of the bag.

Bags are cleaned by a short burst of compressed air injected through a common manifold over a row of bags. The compressed air is accelerated by a venturi nozzle mounted at the reverse-jet baghouse top of the bag. Since the duration of the compressed-air burst is short (0.1s), it acts as a rapidly moving air bubble, traveling through the entire length of the bag and causing the bag surfaces to flex. This flexing of the bags breaks the dust cake, and the dislodged dust falls into a storage hopper below.

Reverse-pulse-jet dust collectors can be operated continuously and cleaned without interruption of flow because the burst of compressed air is very small compared with the total volume of dusty air through the collector. Because of this continuous-cleaning feature, reverse-jet dust collectors are usually not compartmentalized.

The short cleaning cycle of reverse-jet collectors reduces recirculation and redeposit of dust. These collectors provide more complete cleaning and reconditioning of bags than shaker or reverse-air cleaning methods. Also, the continuous-cleaning feature allows them to operate at higher air-to-cloth ratios, so the space requirements are lower.

This cleaning system works with the help of digital sequential timer attached to the fabric filter. this timer indicates the solenoid valve to inject the air to the blow pipe.

Fabric filters generally have the following parts:

1. Clean plenum
2. Dusty pleanum
3. Bag, cage, ventury assembly
4. Tubeplate
5. RAV/SCREW
6. Compressed air header

7. Blow pipe
8. Housing and hopper

Cartridge collectors

Cartridge collectors are another commonly used type of dust collector. Unlike baghouse collectors, in which the filtering media is woven or felt bags, this type of collector employs perforated metal cartridges that contain a pleated, nonwoven filtering media. Due to its pleated design, the total filtering surface area is greater than in a conventional bag of the same diameter, resulting in reduced air to media ratio, pressure drop, and overall collector size.

Cartridge collectors are available in single use or continuous duty designs. In single-use collectors, the dirty cartridges are changed while the collector is off. In the continuous duty design, the cartridges are cleaned by the conventional pulse-jet cleaning system.

Almost always includes a steel enclosure containing porous filter media that separate fine dust particles from a flowing stream of dirty air. The most common filter media used in collectors are filter bags and cartridges. Dust particles build up on the outside of the media and form a coating called "dust cake." It is this layer that does the actual job of filtering fine particles. As the cake builds up, the pressure drop across the filter bag rises.

Wet scrubbers
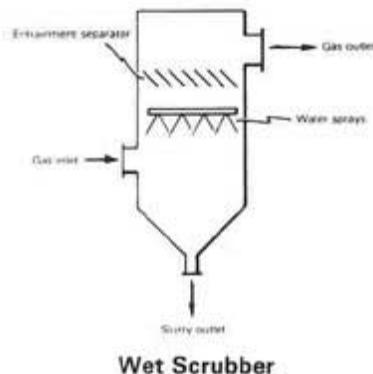
Wet Scrubber

Dust collectors that use liquid are commonly known as wet scrubbers. In these systems, the scrubbing liquid (usually water) comes into contact with a gas stream containing dust particles. The greater the contact of the gas and liquid streams, the higher the dust removal efficiency.

There are a large variety of wet scrubbers; however, all have one of three basic operations:

- Gas-humidification - The gas-humidification process conditions fine particles to increase their size so they can be collected more easily.

- Gas-liquid contact - This is one of the most important factors affecting collection efficiency. The particle and droplet come into contact by four primary mechanisms:
  - Inertial impaction - When water droplets placed in the path of a dust-laden gas stream, the stream separates and flows around them. Due to inertia, the larger dust particles will continue on in a straight path, hit the droplets, and become encapsulated.
  - Interception - Finer particles moving within a gas stream do not hit droplets directly but brush against them and adhere to them.
  - Diffusion - When liquid droplets are scattered among dust particles, the particles are deposited on the droplet surfaces by Brownian movement, or diffusion. This is the principal mechanism in the collection of submicrometre dust particles.
  - Condensation nucleation - If a gas passing through a scrubber is cooled below the dewpoint, condensation of moisture occurs on the dust particles. This increase in particle size makes collection easier.
- Gas-liquid separation - Regardless of the contact mechanism used, as much liquid and dust as possible must be removed. Once contact is made, dust particulates and water droplets combine to form agglomerates. As the agglomerates grow larger, they settle into a collector.

The "cleaned" gases are normally passed through a mist eliminator (demister pads) to remove water droplets from the gas stream. The dirty water from the scrubber system is either cleaned and discharged or recycled to the scrubber. Dust is removed from the scrubber in a clarification unit or a drag chain tank. In both systems solid material settles on the bottom of the tank. A drag chain system removes the sludge and deposits in into a dumpster or stockpile.

Types of scrubbers

Spray-tower scrubber wet scrubbers may be categorized by pressure drop as follows:

- Low-energy scrubbers (0.5 to 2.5 inches water gauge - 124.4 to 621.9 Pa)
- Low- to medium-energy scrubbers (2.5 to 6 inches water gauge - 0.622 to 1.493 kPa)
- Medium- to high-energy scrubbers (6 to 15 inches water gauge - 1.493 to 3.731 kPa)
- High-energy scrubbers (greater than 15 inches water gauge - greater than 3.731 kPa)

Due to the large number of commercial scrubbers available, it is not possible to describe each individual type here. However, the following sections provide examples of typical scrubbers in each category.

Low-energy scrubbers

In the simple, gravity-spray-tower scrubber, liquid droplets formed by liquid atomized in spray nozzles fall through rising exhaust gases. Dirty water is drained at the bottom.

These scrubbers operated at pressure drops of 1 to 2 in. water gauge (¼ to ½ kPa) and are approximately 70% efficient on 10 μm particles. Their efficiency is poor below 10 μm. However, they are capable of treating relatively high dust concentrations without becoming plugged.

Low- to medium-energy scrubbers

Wet cyclones use centrifugal force to spin the dust particles (similar to a cyclone), and throw the particulates upon the collector's wetted walls. Water introduced from the top to wet the cyclone walls carries these particles away. The wetted walls also prevent dust reentrainment.

Pressure drops for these collectors range from 2 to 8 in. water (½ to 2 kPa), and the collection efficiency is good for 5 μm particles and above.

Medium- to high-energy scrubbers co-current-flow scrubber

Packed-bed scrubbers consist of beds of packing elements, such as coke, broken rock, rings, saddles, or other manufactured elements. The packing breaks down the liquid flow into a high-surface-area film so that the dusty gas streams passing through the bed achieve maximum contact with the liquid film and become deposited on the surfaces of the packing elements. These scrubbers have a good collection efficiency for respirable dust.

Three types of packed-bed scrubbers are-

- Cross-flow scrubbers
- Co-current flow scrubbers
- Counter-current flow scrubbers

Efficiency can be greatly increased by minimizing target size, i.e., using 0.003 in. (7.62 mm) diameter stainless steel wire and increasing gas velocity to more than 1,800 ft/min (9.14 m/s).

High-energy scrubbers

Venturi scrubbers consist of a venturi-shaped inlet and separator. The dust-laden gases venturi scrubber enter through the venturi and are accelerated to speeds between 12,000 and 36,000 ft/min (60.97-182.83 m/s). These high-gas velocities immediately atomize the coarse water spray, which is injected radially into the venturi throat, into fine droplets. High energy and extreme turbulence promote collision between water droplets and dust particulates in the throat. The agglomeration process between particle and droplet

continues in the diverging section of the venturi. The large agglomerates formed in the venturi are then removed by an inertial separator.

Venturi scrubbers achieve very high collection efficiencies for respirable dust. Since efficiency of a venturi scrubber depends on pressure drop, some manufacturers supply a variable-throat venturi to maintain pressure drop with varying gas flows.

Electrostatic precipitators (ESP)

Electrostatic precipitators use electrostatic forces to separate dust particles from exhaust gases. A number of high-voltage, direct-current discharge electrodes are placed between grounded collecting electrodes. The contaminated gases flow through the passage formed by the discharge and collecting electrodes. Electrostatic precipitators operate on the same principle as home "Ionic" air purifiers.

The airborne particles receive a negative charge as they pass through the ionized field between the electrodes. These charged particles are then attracted to a grounded or positively charged electrode and adhere to it.

The collected material on the electrodes is removed by rapping or vibrating the collecting electrodes either continuously or at a predetermined interval. Cleaning a precipitator can usually be done without interrupting the airflow.

The four main components of all electrostatic precipitators are-

- Power supply unit, to provide high-voltage DC power
- Ionizing section, to impart a charge to particulates in the gas stream
- A means of removing the collected particulates
- A housing to enclose the precipitator zone

The following factors affect the efficiency of electrostatic precipitators:

- Larger collection-surface areas and lower gas-flow rates increase efficiency because of the increased time available for electrical activity to treat the dust particles.
- An increase in the dust-particle migration velocity to the collecting electrodes increases efficiency. The migration velocity can be increased by-
  - Decreasing the gas viscosity
  - Increasing the gas temperature
  - Increasing the voltage field

Types of precipitators

There are two main types of precipitators:

- High-voltage, single-stage - Single-stage precipitators combine an ionization and a collection step. They are commonly referred to as Cottrell precipitators.
- Low-voltage, two-stage - Two-stage precipitators use a similar principle; however, the ionizing section is followed by collection plates.

Described below is the high-voltage, single-stage precipitator, which is widely used in minerals processing operations. The low-voltage, two-stage precipitator is generally used for filtration in air-conditioning systems.

Plate precipitators

The majority of electrostatic precipitators installed are the plate type. Particles are collected on flat, parallel surfaces that are 8 to 12 in. (20 to 30 cm) apart, with a series of discharge electrodes spaced along the centerline of two adjacent plates. The contaminated gases pass through the passage between the plates, and the particles become charged and adhere to the collection plates. Collected particles are usually removed by rapping the plates and deposited in bins or hoppers at the base of the precipitator.

Tubular precipitators

Tubular precipitators consist of cylindrical collection electrodes with discharge electrodes located on the axis of the cylinder. The contaminated gases flow around the discharge electrode and up through the inside of the cylinders. The charged particles are collected on the grounded walls of the cylinder. The collected dust is removed from the bottom of the cylinder.

Tubular precipitators are often used for mist or fog collection or for adhesive, sticky, radioactive, or extremely toxic materials.

Unit collectors

Unlike central collectors, unit collectors control contamination at its source. They are small and self-contained, consisting of a fan and some form of dust collector. They are suitable for isolated, portable, or frequently moved dust-producing operations, such as bins and silos or remote belt-conveyor transfer points. Advantages of unit collectors include small space requirements, the return of collected dust to main material flow, and low initial cost. However, their dust-holding and storage capacities, servicing facilities, and maintenance periods have been sacrificed.

A number of designs are available, with capacities ranging from 200 to 2,000 ft³/min (90 to 900 L/s). There are two main types of unit collectors:

- Fabric collectors, with manual shaking or pulse-jet cleaning - normally used for fine dust
- Cyclone collectors - normally used for coarse dust

Fabric collectors are frequently used in minerals processing operations because they provide high collection efficiency and uninterrupted exhaust airflow between cleaning cycles. Cyclone collectors are used when coarser dust is generated, as in woodworking, metal grinding, or machining.

The following points should be considered when selecting a unit collector:

- Cleaning efficiency must comply with all applicable regulations.
- The unit should maintain its rated capacity while accumulating large amounts of dust between cleanings.
- The cleaning operations should be simple and should not increase the surrounding dust concentration.
- The unit should be capable of operating unattended for extended periods of time (for example, 8 hours).
- The unit should have an automatic discharge or sufficient dust storage space to hold at least one week's accumulation.
- If renewable filters are used, they should not have to be replaced more than once a month.
- The unit should be durable.
- The unit should be quiet.

Use of unit collectors may not be appropriate if the dust-producing operations are located in an area where central exhaust systems would be practical. Dust removal and servicing requirements are expensive for many unit collectors and are more likely to be neglected than those for a single, large collector.

Selecting a dust collector

Dust collectors vary widely in design, operation, effectiveness, space requirements, construction, and capital, operating, and maintenance costs. Each type has advantages and disadvantages. However, the selection of a dust collector should be based on the following general factors:

- Dust concentration and particle size - For minerals processing operations, the dust concentration can range from 0.1 to 5.0 grains (0.32 g) of dust per cubic feet of air (0.23 to 11.44 grams per standard cubic meter), and the particle size can vary from 0.5 to 100 μm.
- Degree of dust collection required - The degree of dust collection required depends on its potential as a health hazard or public nuisance, the plant location, the allowable emission rate, the nature of the dust, its salvage value, and so forth. The selection of a collector should be based on the efficiency required and should consider the need for high-efficiency, high-cost equipment, such as electrostatic precipitators; high-efficiency, moderate-cost equipment, such as baghouses or wet scrubbers; or lower cost, primary units, such as dry centrifugal collectors.
- Characteristics of airstream - The characteristics of the airstream can have a significant impact on collector selection. For example, cotton fabric filters cannot

be used where air temperatures exceed 180°F (82°C). Also, condensation of steam or water vapor can blind bags. Various chemicals can attach fabric or metal and cause corrosion in wet scrubbers.

- Characteristics of dust - Moderate to heavy concentrations of many dusts (such as dust from silica sand or metal ores) can be abrasive to dry centrifugal collectors. Hygroscopic material can blind bag collectors. Sticky material can adhere to collector elements and plug passages. Some particle sizes and shapes may rule out certain types of fabric collectors. The combustible nature of many fine materials rules out the use of electrostatic precipitators.

- Methods of disposal - Methods of dust removal and disposal vary with the material, plant process, volume, and type of collector used. Collectors can unload continuously or in batches. Dry materials can create secondary dust problems during unloading and disposal that do not occur with wet collectors. Disposal of wet slurry or sludge can be an additional material-handling problem; sewer or water pollution problems can result if wastewater is not treated properly.

Fan and motor

The fan and motor system supplies mechanical energy to move contaminated air from the dust-producing source to a dust collector.

Types of fans

There are two main kinds of industrial fans:

- Centrifugal fans
- Axial-flow fans

Centrifugal fans

Centrifugal fans consist of a wheel or a rotor mounted on a shaft that rotates in a scroll-shaped housing. Air enters at the eye of the rotor, makes a right-angle turn, and is forced through the blades of the rotor by centrifugal force into the scroll-shaped housing. The centrifugal force imparts static pressure to the air. The diverging shape of the scroll also converts a portion of the velocity pressure into static pressure.

There are three main types of centrifugal fans:

- Radial-blade fans - Radial-blade fans are used for heavy dust loads. Their straight, radial blades do not get clogged with material, and they withstand considerable abrasion. These fans have medium tip speeds and medium noise factors.

- Backward-blade fans - Backward-blade fans operate at higher tip speeds and thus are more efficient. Since material may build up on the blades, these fans should be used after a dust collector. Although they are noisier than radial-blade fans,

backward-blade fans are commonly used for large-volume dust collection systems because of their higher efficiency.

- Forward-curved-blade fans - These fans have curved blades that are tipped in the direction of rotation. They have low space requirements, low tip speeds, and a low noise factor. They are usually used against low to moderate static pressures.

Axial-flow fans

Axial-flow fans are used in systems that have low resistance levels. These fans move the air parallel to the fan's axis of rotation. The screw-like action of the propellers moves the air in a straight-through parallel path, causing a helical flow pattern.

The three main kinds of axial fans are-

- Propeller fans - These fans are used to move large quantities of air against very low static pressures. They are usually used for general ventilation or dilution ventilation and are good in developing up to 0.5 in. wg (124.4 Pa).

- Tube-axial fans - Tube-axial fans are similar to propeller fans except they are mounted in a tube or cylinder. Therefore, they are more efficient than propeller fans and can develop up to 3 to 4 in. wg (743.3 to 995 Pa). They are best suited for moving air containing substances such as condensible fumes or pigments.

- Vane-axial fans - Vane-axial fans are similar to tube-axial fans except air-straightening vanes are installed on the suction or discharge side of the rotor. They are easily adapted to multistaging and can develop static pressures as high as 14 to 16 in. wg (3.483 to 3.98 kPa). They are normally used for clean air only.

Fan selection

When selecting a fan, the following points should be considered:

- Volume required
- Fan static pressure
- Type of material to be handled through the fan (For example, a radial-blade fan should be used with fibrous material or heavy dust loads, and nonsparking construction must be used with explosive or inflammable materials.)
- Type of drive arrangement, such as direct drive or belt drive
- Space requirements
- Noise levels
- Operating temperature (For example, sleeve bearings are suitable to 250°F/121.1°C; ball bearings to 550°F/287.8°C)
- Sufficient size to handle the required volume and pressure with minimum horsepower

- Need for special coatings or construction when operating in corrosive atmospheres
- Ability of fan to accommodate small changes in total pressure while maintaining the necessary air volume
- Need for an outlet damper to control airflow during cold starts (If necessary, the damper may be interlocked with the fan for a gradual start until steady-state conditions are reached.)

Fan Rating Tables

After the above information is collected, the actual selection of fan size and speed is usually made from a rating table published by the fan manufacturer. This table is known as a multirating table, and it shows the complete range of capacities for a particular size of fan.

Points to note:

- The multirating table shows the range of pressures and speeds possible within the limits of the fan's construction.
- A particular fan may be available in different construction classes (identified as class I through IV) relating to its capabilities and limits.
- For a given pressure, the highest mechanical efficiency is usually found in the middle third of the volume column.
- A fan operating at a given speed can have an infinite number of ratings (pressure and volume) along the length of its characteristic curve. However, when the fan is installed in a dust collection system, the point of rating can only be at the point at which the system resistance curve intersects the fan characteristic curve.
- In a given system, a fan at a fixed speed or at a fixed blade setting can have a single rating only. This rating can be changed only be changing the fan speed, blade setting, or the system resistance.
- For a given system, an increase in exhaust volume will result in increases in static and total pressures. For example, for a 20% increase in exhaust volume in a system with 5 in. pressure loss, the new pressure loss will be $5 \times (1.20)^2 = 7.2$ in.
- • For rapid estimates of probable exhaust volumes available for a given motor size, the equation for brake horsepower, as illustrated, can be useful.

Fan installation Typical fan discharge conditions Fan ratings for volume and static pressure, as described in the multirating tables, are based on the tests conducted under ideal conditions. Often, field installation creates airflow problems that reduce the fan's air delivery. The following points should be considered when installing the fan:

- Avoid installation of elbows or bends at the fan discharge, which will lower fan performance by increasing the system's resistance.
- Avoid installing fittings that may cause non-uniform flow, such as an elbow, mitred elbow, or square duct.

- Check that the fan impeller is rotating in the proper direction-clockwise or counterclockwise.
- For belt-driven fans-

    -
        o Check that the motor sheave and fan sheave are aligned properly.

    -
        o Check for proper belt tension.

- Check the passages between inlets, impeller blades, and inside of housing for buildup of dirt, obstructions, or trapped foreign matter.

Electric motors

Electric motors are used to supply the necessary energy to drive the fan.

Integral-horsepower electric motors are normally three-phase, alternating-current motors. Fractional-horsepower electric motors are normally single-phase, alternating-current motors and are used when less than 1 hp (0.75 kW) is required. Since most dust collection systems require motors with more than 1 hp (0.75 kW), only integral-horsepower motors are discussed here.

The two most common types of integral-horsepower motors used in dust collection systems are-

- Squirrel-cage motors - These motors have a constant speed and are of a nonsynchronous, induction type.
- Wound-rotor motors - These motors are also known as slip-ring motors. They are general-purpose or continuous-rated motors and are chiefly used when an adjustable-speed motor is desired.

Squirrel-cage and wound-rotor motors are further classified according to the type of enclosure they use to protect their interior windings. These enclosures fall into two broad categories:

- Open
- Totally enclosed

Drip-proof and splash-proof motors are open motors. They provide varying degrees of protection; however, they should not be used where the air contains substances that might be harmful to the interior of the motor.

Totally enclosed motors are weather-protected with the windings enclosed. These enclosures prevent free exchange of air between the inside and the outside, but they are not airtight.

Totally enclosed, fan-cooled (TEFC) motors are another kind of totally enclosed motor. These motors are the most commonly used motors in dust collection systems. They have an integral-cooling fan outside the enclosure, but within the protective shield, that directs air over the enclosure.

Both open and totally-enclosed motors are available in explosion-proof and dust-ignition-proof models to protect against explosion and fire in hazardous environments.

Motors are selected to provide sufficient power to operate fans over the full range of process conditions (temperature and flow rate).
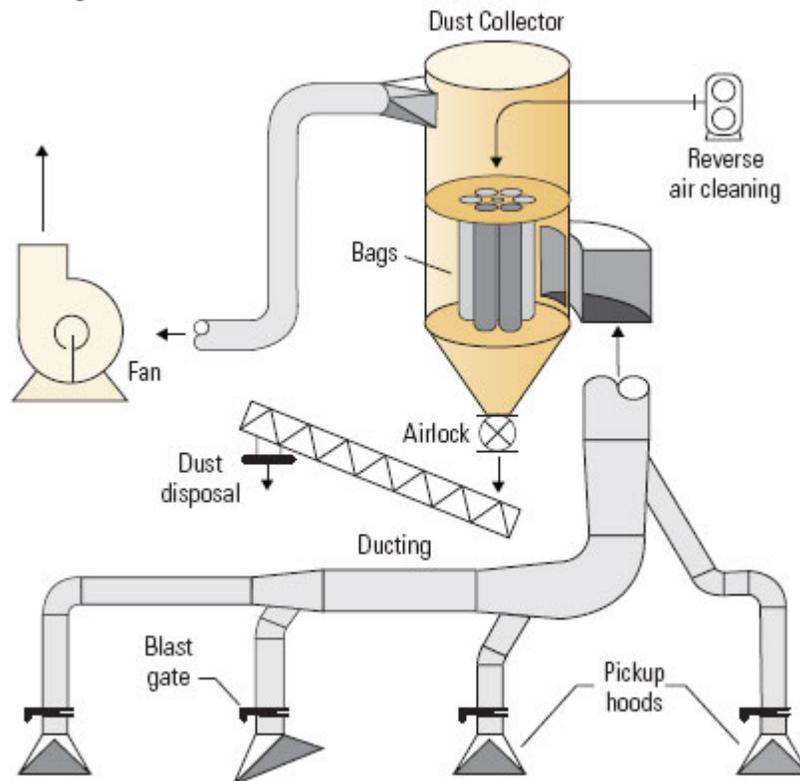

Figure 1. Dust Collection System Example

Uses

Dust collectors are used in many processes to either recover valuable granular solid or powder from process streams, or to remove granular solid pollutants from exhaust gases prior to venting to the atmosphere. Dust collection is an online process for collecting any process-generated dust from the source point on a continuous basis. Dust collectors may be of single unit construction, or a collection of devices used to separate particulate matter from the process air. They are often used as an air pollution control device to maintain or improve air quality.

Mist collectors remove particulate matter in the form of fine liquid droplets from the air. They are often used for the collection of metal working fluids, and coolant or oil mists. Mist collectors are often used to improve or maintain the quality of air in the workplace environment.

Fume and smoke collectors are used to remove sub micrometre size particulate from the air. They effectively reduce or eliminate particulate matter and gas streams from many industrial processes such as welding, rubber and plastic processing, high speed machining with coolants, tempering, and quenching.

Configurations

Dust collectors can be configured into one of five common types.

1. Ambient units - Ambient units are free-hanging systems for use when applications limit the use of source-capture arms or ductwork.
2. Collection booths - Collector booths require no ductwork, and allow the worker greater freedom of movement. They are often portable.
3. Downdraft tables - A downdraft table is a self-contained portable filtration system that removes harmful particulates and returns filtered air back into the facility with no external ventilation required.
4. Source collector or Portable units - Portable units are for collecting dust, mist, fumes, or smoke at the source.
5. Stationary units - An example of a stationary collector is a baghouse.

Parameters involved in specifying dust collectors

Important parameters in specifying dust collectors include airflow the velocity of the air stream created by the vacuum producer; system power, the power of the system motor, usually specified in horsepower; storage capacity for dust and particles, and minimum particle size filtered by the unit. Other considerations when choosing a dust collection system include the temperature, moisture content, and the possibility of combustion of the dust being collected.

Systems for fine removal may only contain a single filtration system (such as a filter bag or cartridge). However, most units utilize a primary and secondary separation/filtration system. In many cases the heat or moisture content of dust can negatively affect the filter media of a baghouse or cartridge dust collector. A cyclone separator or dryer may be placed before these units to reduce heat or moisture content before reaching the filters. Furthermore, some units may have third and fourth stage filtration. All separation and filtration systems used within the unit should be specified.
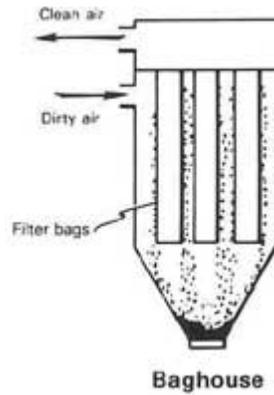
Baghouse

A baghouse is an air pollution abatement device used to trap particulate by filtering gas streams through large fabric bags. They are typically made of glass fibers or fabric.
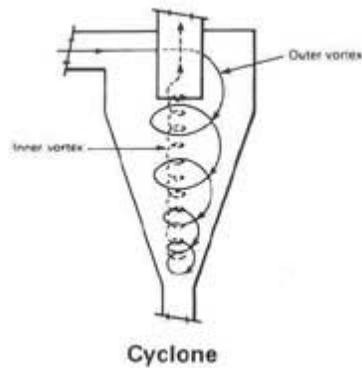
Cyclone

A cyclone separator is an apparatus for the separation, by centrifugal means, of fine particles suspended in air or gas.

Electrostatic Precipitator
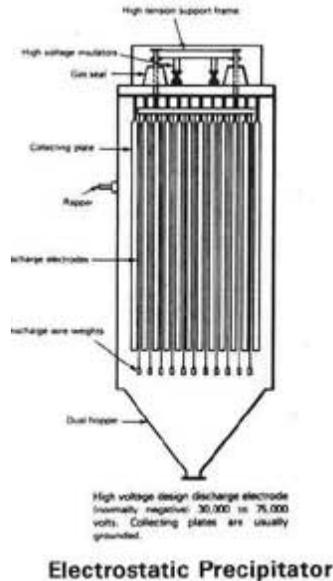
Electrostatic precipitators are a type of air cleaner, which charges particles of dust by passing dust-laden air through a strong (50-100 kV) electrostatic field. This causes the particles to be attracted to oppositely charged plates so that they can be removed from the air stream.

An impinger system is a device in which particles are removed by impacting the aerosol particles into a liquid. Modular media type units combine a variety of specific filter modules in one unit. These systems can provide solutions to many air contaminant problems. A typical system incorporates a series of disposable or cleanable pre-filters, a disposable vee-bag or cartridge filter. HEPA or carbon final filter modules can also be added. Various models are available, including free-hanging or ducted installations, vertical or horizontal mounting, and fixed or portable configurations. Filter cartridges are made out of a variety of synthetic fibers and are capable of collecting sub-micrometre particles without creating an excessive pressure drop in the system. Filter cartridges require periodic cleaning.

A wet scrubber, or venturi scrubber, is similar to a cyclone but it has an orifice unit that sprays water into the vortex in the cyclone section, collecting all of the dust in a slurry system. The water media can be recirculated and reused to continue to filter the air. Eventually the solids must be removed from the water stream and disposed of.

Filter cleaning methods

Online cleaning – automatically timed filter cleaning which allows for continuous, uninterrupted dust collector operation for heavy dust operations.

Offline cleaning – filter cleaning accomplished during dust collector shut down. Practical whenever the dust loading in each dust collector cycle does not exceed the filter capacity. Allows for maximum effectiveness in dislodging and disposing of dust.

On-demand cleaning – filter cleaning initiated automatically when the filter is fully loaded, as determined by a specified drop in pressure across the media surface.

Reverse-pulse/Reverse-jet cleaning – Filter cleaning method which delivers blasts of compressed air from the clean side of the filter to dislodge the accumulated dust cake.

Impact/Rapper cleaning – Filter cleaning method in which high-velocity compressed air forced through a flexible tube results in a random rapping of the filter to dislodge the dust cake. Especially effective when the dust is extremely fine or sticky.

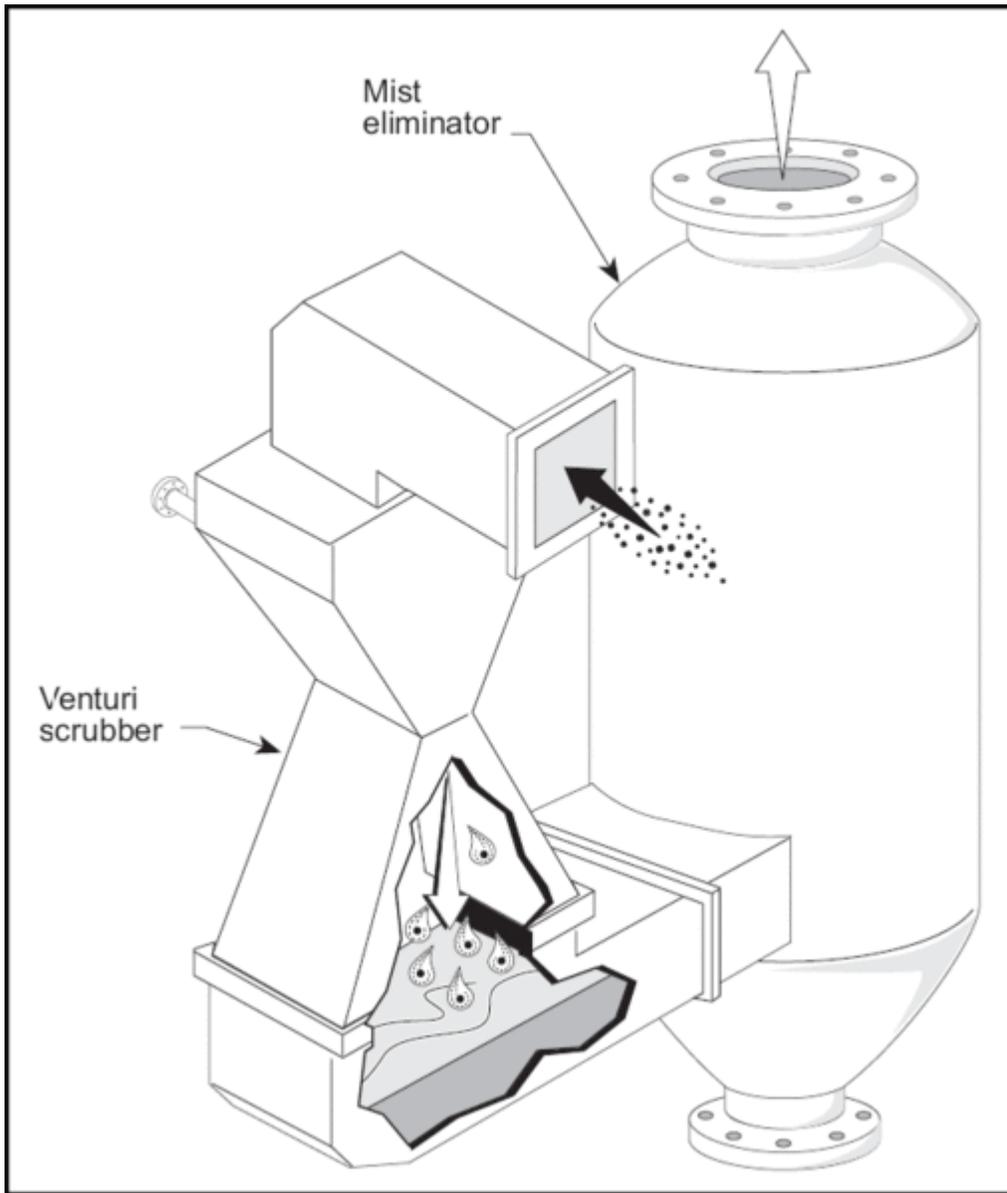# Chapter- 3

Wet Scrubber

Figure 1

The term **wet scrubber** describes a variety of devices that remove pollutants from a furnace flue gas or from other gas streams. In a wet scrubber, the polluted gas stream is brought into contact with the scrubbing liquid, by spraying it with the liquid, by forcing it through a pool of liquid, or by some other contact method, so as to remove the pollutants.

The design of wet scrubbers or any air pollution control device depends on the industrial process conditions and the nature of the air pollutants involved.

Inlet gas characteristics and dust properties (if particles are present) are of primary importance. Scrubbers can be designed to collect particulate matter and/or gaseous pollutants. Wet scrubbers remove dust particles by *capturing* them in liquid droplets. Wet scrubbers remove pollutant gases by *dissolving* or *absorbing* them into the liquid.

Any droplets that are in the scrubber inlet gas must be separated from the outlet gas stream by means of another device referred to as a mist eliminator or entrainment separator (these terms are interchangeable). Also, the resultant scrubbing liquid must be treated prior to any ultimate discharge or being reused in the plant.

There are numerous configurations of scrubbers and scrubbing systems, all designed to provide good contact between the liquid and polluted gas stream.

Figures 1 and 2 show two examples of wet scrubber designs, including their mist eliminators. **Figure 1** is a venturi scrubber design. The mist eliminator for a venturi scrubber is often a separate device called a cyclonic separator.
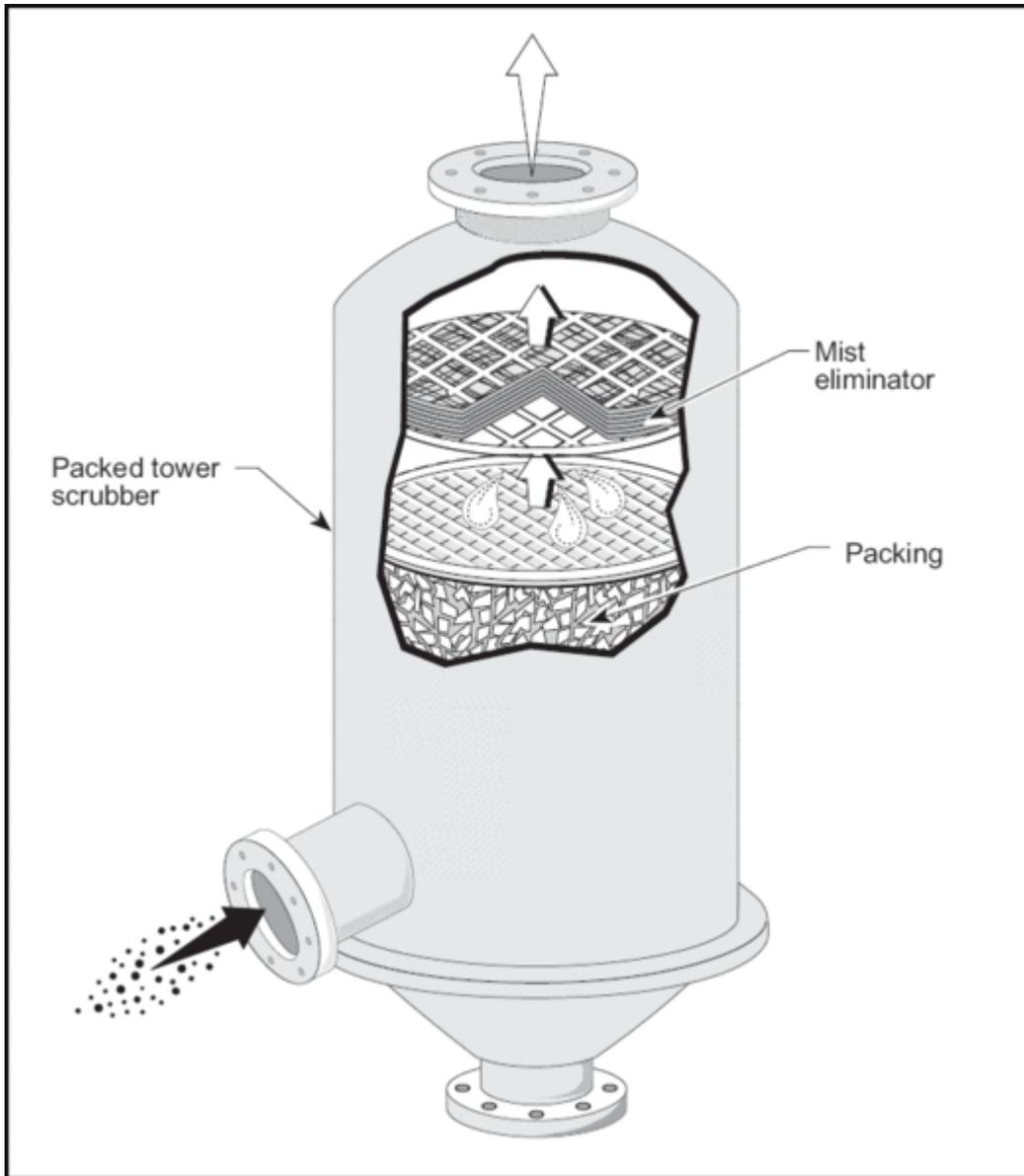
Figure 2 - Packed bed tower

Figure 2 has a tower design where the mist eliminator is built into the top of the structure. Various tower designs exist.

A wet scrubber's ability to collect small particles is often directly proportional to the power input into the scrubber. Low energy devices such as spray towers are used to collect particles larger than 5 micrometers. To obtain high efficiency removal of 1 micrometer (or less) particles generally requires high energy devices such as venturi scrubbers or augmented devices such as condensation scrubbers. Additionally, a properly designed and operated entrainment separator or mist eliminator is important to achieve high removal efficiencies. The greater the number of liquid droplets that are not captured by the mist eliminator the higher the potential emission levels.

Wet scrubbers that remove gaseous pollutants are referred to as *absorbers*. Good gas-to-liquid contact is essential to obtain high removal efficiencies in absorbers. A number of wet scrubber designs are used to remove gaseous pollutants, with the packed tower and the plate tower being the most common.

If the gas stream contains both particle matter and gases, wet scrubbers are generally the only single air pollution control device that can remove both pollutants. Wet scrubbers can achieve high removal efficiencies for either particles or gases and, in some instances, can achieve a high removal efficiency for both pollutants in the same system. However, in many cases, the best operating conditions for particles collection are the poorest for gas removal.

In general, obtaining high simultaneous gas and particulate removal efficiencies requires that one of them be easily collected (i.e., that the gases are very soluble in the liquid or that the particles are large and readily captured) or by the use of a scrubbing reagent such as lime or sodium hydroxide.

Advantages and disadvantages

For particulate control, wet scrubbers (also referred to as wet collectors) are evaluated against fabric filters and electrostatic precipitators (ESPs). Some *advantages* of wet scrubbers over these devices are as follows:

- Wet scrubbers have the ability to handle high temperatures and moisture.
- In wet scrubbers, flue gases are cooled, resulting in smaller overall size of equipment.
- Wet scrubbers can remove both gases and particulate matter.
- Wet scrubbers can neutralize corrosive gases.

Some *disadvantages* of wet scrubbers include corrosion, the need for entrainment separation or mist removal to obtain high efficiencies and the need for treatment or reuse of spent liquid.

Table 1 summarizes these advantages and disadvantages. Wet scrubbers have been used in a variety of industries such as acid plants, fertilizer plants, steel mills, asphalt plants, and large power plants.

Table 1. Relative advantages and disadvantages of wet scrubbers compared to other control devices

Advantages	Disadvantages

Small space requirements

Scrubbers reduce the temperature and volume of the unsaturated exhaust stream. Therefore, vessel sizes, including fans and ducts downstream, are smaller than those of other control devices. Smaller sizes result in lower capital costs and more flexibility in site location of the scrubber.

No secondary dust sources

Once particulate matter is collected, it cannot escape from hoppers or during transport.

Handles high-temperature, high-humidity gas streams

No temperature limits or condensation problems can occur as in baghouses or ESPs.

Minimal fire and explosion hazards

Various dry dusts are flammable. Using water eliminates the possibility of explosions.

Ability to collect both gases and particulate matter

Corrosion problems

Water and dissolved pollutants can form highly corrosive acid solutions. Proper construction materials are very important. Also, wet-dry interface areas can result in corrosion.

High power requirements

High collection efficiencies for particulate matter are attainable only at high pressure drops, resulting in high operating costs.

Water-disposal problems

Settling ponds or sludge clarifiers may be needed to meet waste-water regulations.

Difficult product recovery

Dewatering and drying of scrubber sludge make recovery of any dust for reuse very expensive and difficult.

Wet scrubber systems

Wet scrubber systems generally consist of the following components:

- Ductwork and fan system
- A saturation chamber (optional)
- Scrubbing vessel
- Entrainment separator or mist eliminator
- Pumping (and possible recycle system)
- Spent scrubbing liquid treatment and/or reuse system
- An exhaust stack

A typical wet scrubbing process can be described as follows:

- Hot flue gas from a furnace enters a saturator (if present) where gases are cooled and humidified prior to entering the scrubbing area. The saturator removes a small percentage of the particulate matter present in the flue gas.
- Next, the gas enters a venturi scrubber where approximately half of the gases are removed. Venturi scrubbers have a minimum particle removal efficiency of 95%.

- The gas flows through a second scrubber, a packed bed absorber, where the rest of the gases (and particulate matter) are collected.
- An entrainment separator or mist eliminator removes any liquid droplets that may have become entrained in the flue gas.
- A recirculation pump moves some of the spent scrubbing liquid back to the venturi scrubber where it is recycled and the remainder is sent to a treatment system.
- Treated scrubbing liquid is recycled back to the saturator and the packed bed absorber.
- Fans and ductwork move the flue gas stream through the system and eventually out the stack.

Categorization of wet scrubbers

Since wet scrubbers vary greatly in complexity and method of operation, devising categories into which all of them neatly fit is extremely difficult. Scrubbers for particle collection are usually categorized by the gas-side pressure drop of the system. Gas-side pressure drop refers to the pressure difference, or pressure drop, that occurs as the exhaust gas is pushed or pulled through the scrubber, disregarding the pressure that would be used for pumping or spraying the liquid into the scrubber.

Scrubbers may be classified *by pressure drop* as follows:

- **Low-energy scrubbers** have pressure drops of less than 12.7 cm (5 in) of water.
- **Medium-energy scrubbers** have pressure drops between 12.7 and 38.1 cm (5 and 15 in) of water.
- **High-energy scrubbers** have pressure drops greater than 38.1 cm (15 in) of water.

However, most scrubbers operate over a wide range of pressure drops, depending on their specific application, thereby making this type of categorization difficult.

Another way to classify wet scrubbers is by their *use* - to primarily collect either particulates or gaseous pollutants. Again, this distinction is not always clear since scrubbers can often be used to remove both types of pollutants.

Wet scrubbers can also be categorized by the manner in which the gas and liquid phases are brought into contact. Scrubbers are designed to use power, or energy, from the gas stream or the liquid stream, or some other method to bring the pollutant gas stream into contact with the liquid. These categories are given in **Table 2**.

Table 2. Categories of wet collectors by energy source used for contact

Wet collector	Energy source used for gas-liquid contact

Gas-phase contacting	Gas stream
Liquid-phase contacting	Liquid stream
Wet film	Liquid and gas streams
Combination	Energy source:

- Liquid phase and gas phase
- Mechanically aided

- Liquid and gas streams
- Mechanically driven rotor

Material of construction and design

Corrosion can be a prime problem associated with chemical industry scrubbing systems. Fibre-reinforced plastic and dual laminates are often used as most dependable materials of construction.

Chapter- 4

Scrubber

Scrubber systems are a diverse group of air pollution control devices that can be used to remove some particulates and/or gases from industrial exhaust streams. Traditionally, the term "scrubber" has referred to pollution control devices that use liquid to wash unwanted pollutants from a gas stream. Recently, the term is also used to describe systems that inject a dry reagent or slurry into a dirty exhaust stream to "wash out" acid gases. Scrubbers are one of the primary devices that control gaseous emissions, especially acid gases. Scrubbers can also be used for heat recovery from hot gases by flue gas condensation.

Removal and neutralization

The exhaust gases of combustion may contain substances considered harmful to the environment, and the scrubber may remove or neutralize those substances.

Wet scrubbing

A wet scrubber is used to clean air, flue gas or other gases of various pollutants and dust particles. Wet scrubbing works via the contact of target compounds or particulate matter with the scrubbing solution. Solutions may simply be water (for dust) or solutions of reagents that specifically target certain compounds.

Removal efficiency of pollutants is improved by increasing residence time in the scrubber or by the increase of surface area of the scrubber solution by the use of a spray nozzle, packed towers or an aspirator. Wet scrubbers may increase the proportion of water in the gas, resulting in a visible stack plume, if the gas is sent to a stack.

Dry scrubbing

A dry or semi-dry scrubbing system, unlike the wet scrubber, does not saturate the flue gas stream that is being treated with moisture. In some cases no moisture is added; while in other only the amount of moisture that can be evaporated in the flue gas without condensing is added. Therefore, dry scrubbers do generally not have a stack steam plume

or wastewater handling/disposal requirements. Dry scrubbing systems are used to remove acid gases (such as SO_2 and HCl) primarily from combustion sources.

There are a number of dry type scrubbing system designs. However, all consist of two main sections or devices: a device to introduce the acid gas sorbent material into the gas stream and a particulate matter control device to remove reaction products, excess sorbent material as well as any particulate matter already in the flue gas.

Dry scrubbing systems can be categorized as dry sorbent injectors (DSIs) or as spray dryer absorbers (SDAs). Spray dryer absorbers are also called semi-dry scrubbers or spray dryers.

Dry scrubbing systems are often used for the removal of odorous and corrosive gases from wastewater treatment plant operations. The media used is typically an activated alumina compound impregnated with materials to handle specific gases such as hydrogen sulfide. Media used can be mixed together to offer a wide range of removal for other odorous compounds such as methyl mercaptans, aldehydes, volatile organic compounds, dimethyl sulfide, and dimethyl disulfide.

Dry sorbent injection involves the addition of an alkaline material (usually hydrated lime or soda ash) into the gas stream to react with the acid gases. The sorbent can be injected directly into several different locations: the combustion process, the flue gas duct (ahead of the particulate control device), or an open reaction chamber (if one exists). The acid gases react with the alkaline sorbets to form solid salts which are removed in the particulate control device. These simple systems can achieve only limited acid gas (SO_2 and HCl) removal efficiencies. Higher collection efficiencies can be achieved by increasing the flue gas humidity (i.e., cooling using water spray). These devices have been used on medical waste incinerators and a few municipal waste combustors.

In **spray dryer absorbers**, the flue gases are introduced into an absorbing tower (dryer) where the gases are contacted with a finely atomized alkaline slurry. Acid gases are absorbed by the slurry mixture and react to form solid salts which are removed by the particulate control device. The heat of the flue gas is used to evaporate all the water droplets, leaving a non-saturated flue gas to exit the absorber tower. Spray dryers are capable of achieving high (80+%) acid gas removal efficiencies. These devices have been used on industrial and utility boilers and municipal waste incinerators.

Mercury removal

Mercury is a highly toxic compound commonly found in coal and municipal waste. Wet scrubbers are only effective for mercury removal under certain conditions. Mercury vapor in its elemental form, Hg^0, is insoluble in the scrubber slurry and not removed. Oxidized mercury, Hg^{2+}, compounds are more soluble in the scrubber slurry and can be captured. The type of coal burned as well as the presence of a selective catalytic reduction unit both affect the ratio of elemental to oxidized mercury in the flue gas and thus the degree to which the mercury is removed.

Heat recovery

Wet scrubbers can be used for heat recovery from hot gases by flue gas condensation. In this mode, termed a condensing scrubber, water from the scrubber drain is circulated through a cooler to the nozzles at the top of the scrubber. The hot gas enters the scrubber at the bottom. If the gas temperature is above the water dew point, it is initially cooled by evaporation of water drops. Further cooling cause water vapors to condense, adding to the amount of circulating water.

The condensation of water release significant amounts of low temperature heat (more than 2 gigajoules (560 kW·h) per ton of water), that can be recovered by the cooler for e.g. district heating purposes.

Excess condensed water must continuosly be removed from the circulating water.

The gas leaves the scrubber at its dew point, so even though significant amounts of water may have been removed from the cooled gas, it is likely to leave a visible stack plume of water vapor.

Scrubber waste products

One side effect of scrubbing is that the process only moves the unwanted substance from the exhaust gases into a liquid solution, solid paste or powder form. This must be disposed of safely, if it can not be reused.

For example, mercury removal results in a waste product that either needs further processing to extract the raw mercury, or must be buried in a special hazardous wastes landfill that prevents the mercury from seeping out into the environment.

As an example of reuse, limestone-based scrubbers in coal fired power plants can produce a synthetic gypsum of sufficient quality that can be used to manufacture drywall and other industrial products.

Bacteria spread

Poorly maintained scrubbers have the potential to spread disease-causing bacteria. The problem is a result of inadequate cleaning. For example, the cause of a 2005 outbreak of Legionnaires' disease in Norway was just a few infected scrubbers. The outbreak caused 10 deaths and more than 50 cases of infection.

Types of Scrubbers
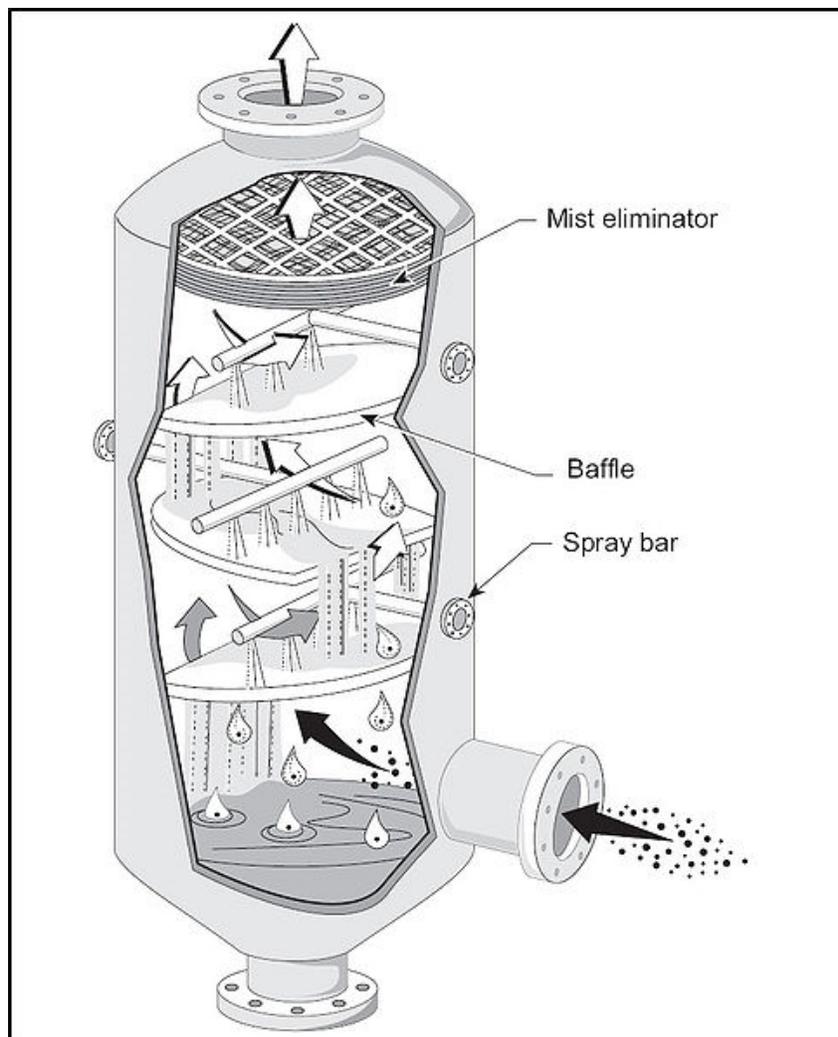
Baffle spray scrubber

Figure 1 - Baffle spray scrubber

Baffle spray scrubbers are a technology for air pollution control. They are very similar to spray towers in design and operation. However, in addition to using the energy provided by the spray nozzles, baffles are added to allow the gas stream to atomize some liquid as it passes over them.

A simple baffle scrubber system is shown in **Figure 1**. Liquid sprays capture pollutants and also remove collected particles from the baffles. Adding baffles slightly increases the pressure drop of the system.

This type of technology is a part of the group of air pollution controls collectively referred to as wet scrubbers.

A number of wet-scrubber designs use energy from both the gas stream and liquid stream to collect pollutants. Many of these combination devices are available commercially.

A seemingly unending number of scrubber designs have been developed by changing system geometry and incorporating vanes, nozzles, and baffles.

Particle collection

These devices are used much the same as spray towers - to preclean or remove particles larger than 10 μm in diameter. However, they will tend to plug or corrode if particle concentration of the exhaust gas stream is high.

Gas collection

Even though these devices are not specifically used for gas collection, they are capable of a small amount of gas absorption because of their large wetted surface.

Summary

These devices are most commonly used as precleaners to remove large particles (>10 μm in diameter). The pressure drops across baffle scrubbers are usually low, but so are the collection efficiencies. Maintenance problems are minimal. The main problem is the buildup of solids on the baffles.
Table 1 summarizes the operating characteristics of baffle spray scrubbers.

Table 1. Operating characteristics of baffle spray scrubbers

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p_L)	Removal efficiency	Applications
Gases	2.5-7.5 cm of water	0.13 l/m^3 (1 gal/1,000 ft^3)	< 100 kPa (< 15 psig)	very low	Mining operations

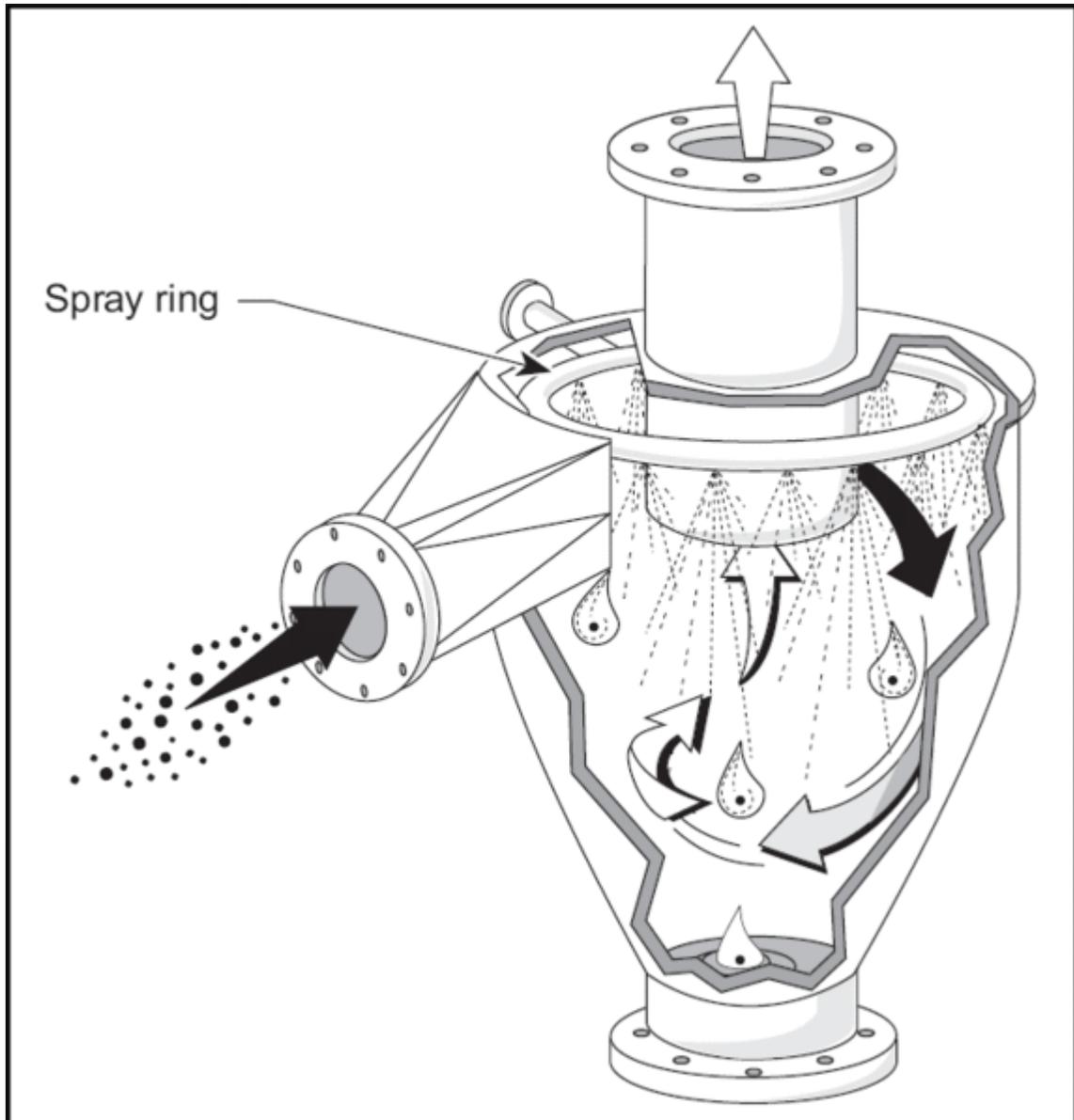| Particles	1-3 in of water		10 μm diameter	Incineration Chemical process industry

Cyclonic spray scrubber

Spray ring

Figure 1 - Irrigated cyclone scrubber

Cyclonic spray scrubbers are an air pollution control technology. They use the features of both the dry cyclone and the spray chamber to remove pollutants from gas streams.

Generally, the inlet gas enters the chamber tangentially, swirls through the chamber in a corkscrew motion, and exits. At the same time, liquid is sprayed inside the chamber. As the gas swirls around the chamber, pollutants are removed when they impact on liquid droplets, are thrown to the walls, and washed back down and out.

Cyclonic scrubbers are generally low- to medium-energy devices, with pressure drops of 4 to 25 cm (1.5 to 10 in) of water. Commercially available designs include the **irrigated cyclone scrubber** and the **cyclonic spray scrubber**.

In the *irrigated cyclone* (**Figure 1**), the inlet gas enters near the top of the scrubber into the water sprays. The gas is forced to swirl downward, then change directions, and return upward in a tighter spiral. The liquid droplets produced capture the pollutants, are eventually thrown to the side walls, and carried out of the collector. The "cleaned" gas leaves through the top of the chamber.

The *cyclonic spray* scrubber (**Figure 2**) forces the inlet gas up through the chamber from a bottom tangential entry. Liquid sprayed from nozzles on a center post (manifold) is directed toward the chamber walls and through the swirling gas. As in the *irrigated cyclone*, liquid captures the pollutant, is forced to the walls, and washes out. The "cleaned" gas continues upward, exiting through the straightening vanes at the top of the chamber.

This type of technology is a part of the group of air pollution controls collectively referred to as wet scrubbers.
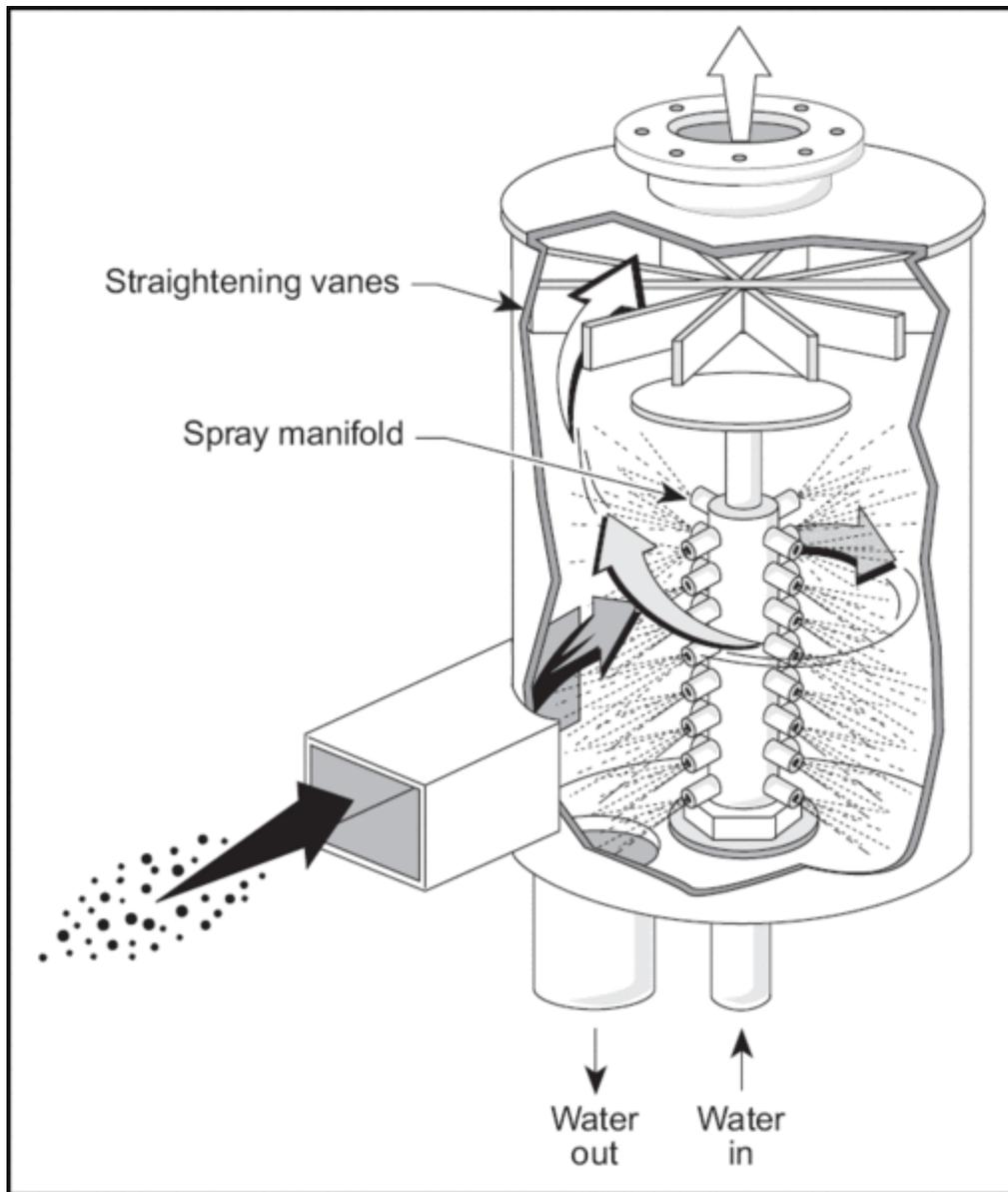
Particulate collection

Figure 2 - Cyclonic spray scrubber

Cyclonic spray scrubbers are more efficient than spray towers, but not as efficient as venturi scrubbers, in removing particulate from the inlet gas stream. Particulates larger than 5 μm are generally collected by impaction with 90% efficiency. In a simple spray tower, the velocity of the particulates in the gas stream is low: 0.6 to 1.5 m/s (2 to 5 ft/s).

By introducing the inlet gas tangentially into the spray chamber, the cyclonic scrubber increases gas velocities (thus, particulate velocities) to approximately 60 to 180 m/s (200 to 600 ft/s). The velocity of the liquid spray is approximately the same in both devices. This higher particulate-to-liquid relative velocity increases particulate collection efficiency for this device over that of the spray chamber. Gas velocities of 60 to 180 m/s are equivalent to those encountered in a venturi scrubber.

However, cyclonic spray scrubbers are not as efficient as venturi scrubbers because they are not capable of producing the same degree of useful turbulence.

Gas collection

High gas velocities through these devices reduce the gas-liquid contact time, thus reducing absorption efficiency. Cyclonic spray scrubbers are capable of effectively removing some gases; however, they are rarely chosen when gaseous pollutant removal is the only concern.

Maintenance problems

The main maintenance problems with cyclonic scrubbers are nozzle plugging and corrosion or erosion of the side walls of the cyclone body. Nozzles have a tendency to plug from particulates that are in the recycled liquid and/or particulates that are in the gas stream. The best solution is to install the nozzles so that they are easily accessible for cleaning or removal.

Due to high gas velocities, erosion of the side walls of the cyclone can also be a problem. Abrasion-resistant materials may be used to protect the cyclone body, especially at the inlet.

Summary

The pressure drops across cyclonic scrubbers are usually 4 to 25 cm (1.5 to 10 in) of water; therefore, they are low- to medium-energy devices and are most often used to control large-sized particulates. Relatively simple devices, they resist plugging because of their open construction. They also have the additional advantage of acting as entrainment separators because of their shape. The liquid droplets are forced to the sides of the cyclone and removed prior to exiting the vessel. Their biggest disadvantages are that they are not capable of removing submicrometer partculates and they do not efficiently absorb most pollutant gases.
Table 1 lists typical operating characteristics of cyclonic scrubbers.

Table 1. Operating characteristics of spray towers

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p_L)	Removal efficiency	Applications
Gases	4-25 cm of water (1.5-10 in of water)	0.3-1.3 l/m^3 (2-10 gal/1,000 ft^3)	280-2,800 kPa (40-400 psig)	Only effective for very soluble gases	Mining operations Drying operations Food
Particulates				2-3 μm	

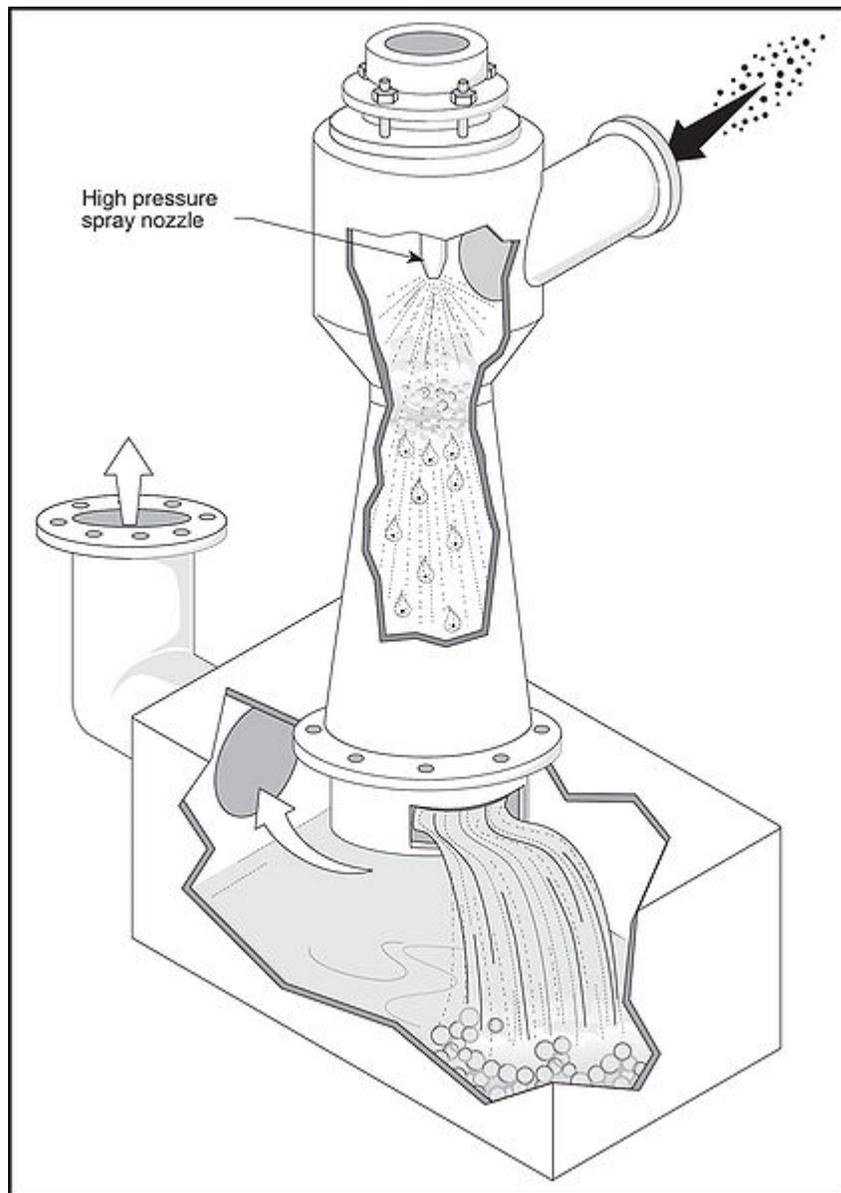# Ejector venturi scrubber

Figure 1 - Ejector venturi scrubber

This type of technology is a part of the group of air pollution controls collectively referred to as wet scrubbers.

An **ejector** or **venturi scrubber** is an industrial pollution control device, usually installed on the exhaust flue gas stacks of large furnaces, but may also be used on any number of other air exhaust systems. To this end, an ejector venturi scrubber (as well as the spray tower) uses a preformed spray, the difference is that only a single nozzle is used instead of many nozzles. This nozzle operates at higher pressures and higher injection rates than those in most spray chambers. The high-pressure spray nozzle (up to 689 kPa or 100 psig) is aimed at the throat section of a venturi constriction.

The ejector venturi is unique among available scrubbing systems since it can move the process gas without the aid of a blower or fan. The liquid spray coming from the nozzle creates a partial vacuum in the side duct of the scrubber. This has the same effect as the water aspirator used in high school chemistry labs to pull a small vacuum for filtering precipitated materials (due to the Bernoulli effect). This partial vacuum can be used to move the process gas through the venturi as well as through the facility's process system. In the case of explosive or extremely corrosive atmospheres, the elimination of a fan in the system can avoid many potential problems.

The energy for the formation of scrubbing droplets comes from the injected liquid. The high pressure sprays passing through the venturi throat form numerous fine liquid droplets that provide turbulent mixing between the gas and liquid phases. Very high liquid-injection rates are used to provide the gas-moving capability and higher collection efficiencies. As with other types of venturis, a means of separating entrained liquid from the gas stream must be installed. Entrainment separators are commonly used to remove remaining small droplets.

Particle collection

Ejector venturis are effective in removing particles larger than 1.0 μm in diameter. These scrubbers are not used on submicrometer-sized particles unless the particles are condensable [Gilbert, 1977]. Particle collection occurs primarily by impaction as the exhaust gas (from the process) passes through the spray.

The turbulence that occurs in the throat area also causes the particles to contact the wet droplets and be collected. Particle collection efficiency increases with an increase in nozzle pressure and/or an increase in the liquid-to-gas ratio. Increases in either of these two operating parameters will also result in an increase in pressure drop for a given system. Therefore, an increase in pressure drop also increases particle collection efficiency. Ejector venturis operate at higher L/G ratios than most other particulate scrubbers (i.e., 7 to 13 l/m³ compared to 0.4-2.7 l/m³ for most other designs).

Gas collection

Ejector venturis have a short gas-liquid contact time because the exhaust gas velocities through the vessel are very high. This short contact time limits the absorption efficiency of the system. Although ejector venturis are not used primarily for gas removal, they can be effective if the gas is very soluble or if a very reactive scrubbing reagent is used. In these instances, removal efficiencies of as high as 95% can be achieved [Gilbert, 1977].

Maintenance problems

Ejector venturis are subject to abrasion problems in the high-velocity areas - nozzle and throat. Both must be constructed of wear-resistant materials because of the high liquid injection rates and nozzle pressures. Maintaining the pump that recirculates liquid is also very important. In addition, the high gas velocities necessitate the use of entrainment separators to prevent excessive liquid carryover. The separators should be easily accessible or removable so that they can be cleaned if plugging occurs.

Summary

Because of their open design and the fact that they do not require a fan, ejector venturis are capable of handling a wide range of corrosive and/or sticky particles. However, they are not very effective in removing submicrometer particles. They have an advantage in being able to handle small, medium and large exhaust flows. They can be used singly or in multiple stages of two or more in series, depending on the specific application. Multiple-stage systems have been used where extremely high collection efficiency of particles or gaseous pollutants was necessary. Multiple-stage systems provide increased gas-liquid contact time, thus increasing absorption efficiency.
Table 1 lists the operating parameters for ejector venturis.

Table 1. Operating characteristics of ejector venturis

| Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p_L)	Removal efficiency	Applications
Gases	1.3–13 cm of water	7-13 l/m^3	100-830 kPa	95% for very soluble gases	Pulp and paper industry Chemical process industry
Particles	0.5-5 in of water	50-100 gal/1,000 ft^3	15-120 psig	1 μm diameter	Food industry Metals processing industry

Mechanically aided scrubber
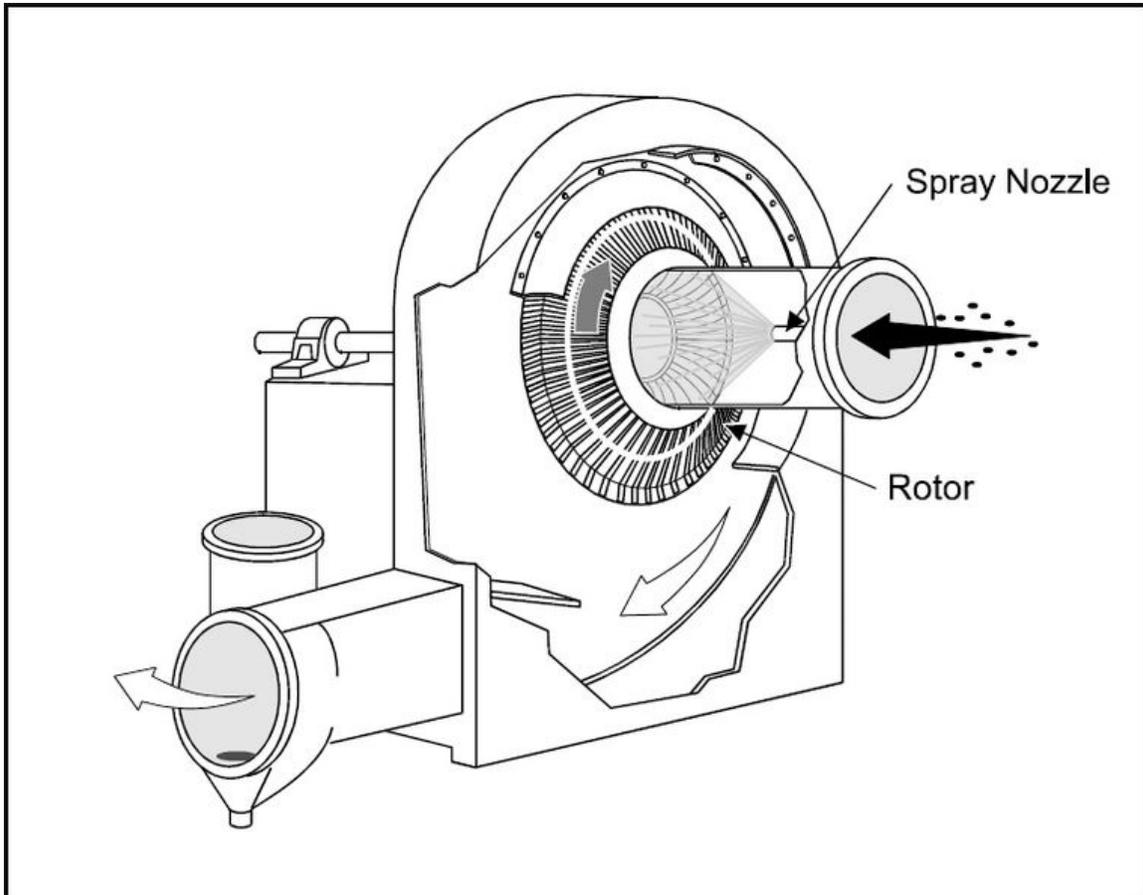
Figure 1 -Centrifugal fan scrubber

Mechanically aided scrubbers are a form of pollution control technology. This type of technology is a part of the group of air pollution controls collectively referred to as wet scrubbers.

In addition to using liquid sprays or the exhaust stream, scrubbing systems can use motors to supply energy. The motor drives a rotor or paddles which, in turn, generate water droplets for gas and particle collection.

Systems designed in this manner have the advantage of requiring less space than other scrubbers, but their overall power requirements tend to be higher than other scrubbers of equivalent efficiency. Significant power losses occur in driving the rotor. Therefore, not all the power used is expended for gas-liquid contact.
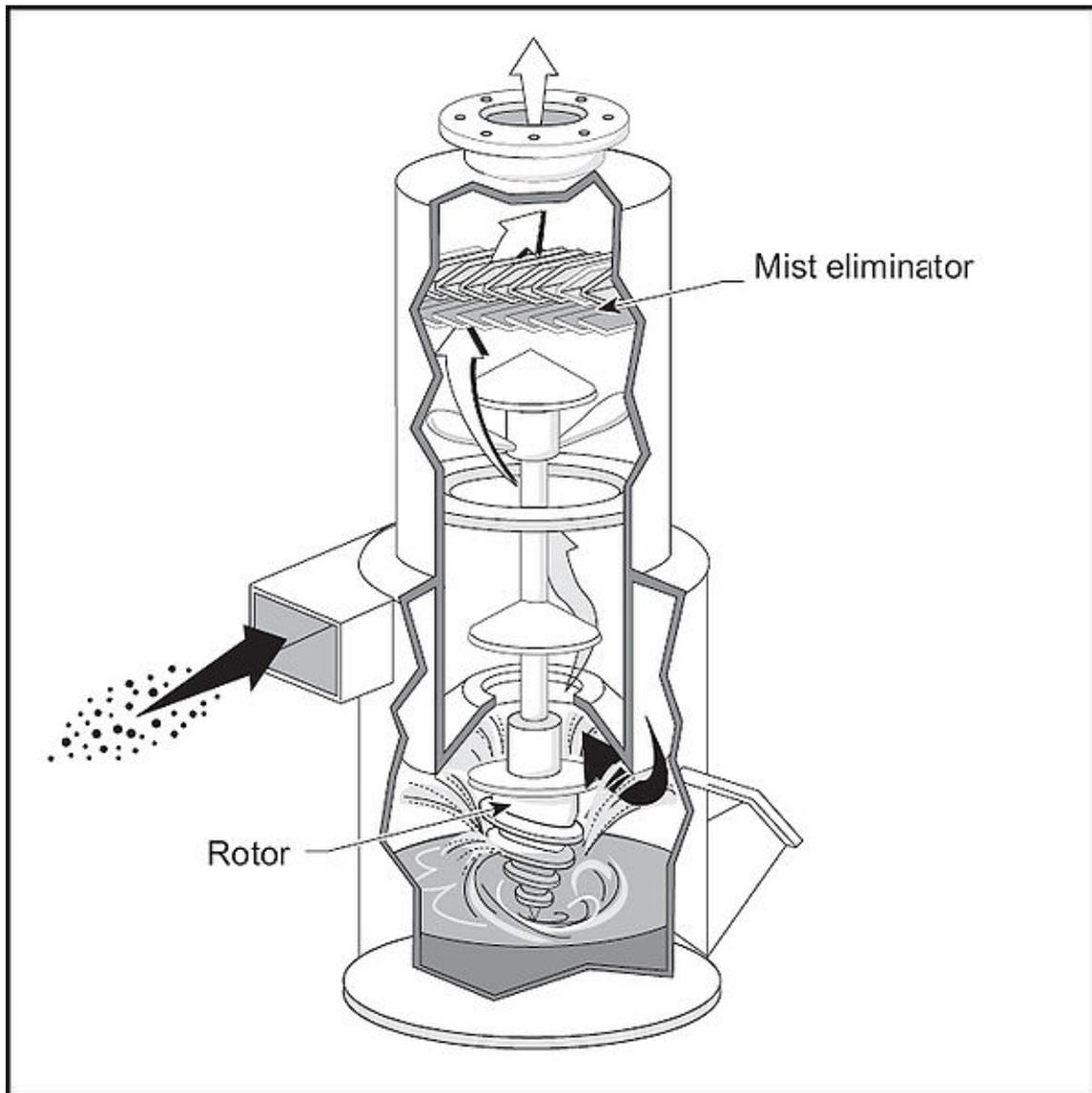
Types

Figure 2 - Induced spray scrubber

There are fewer mechanically aided scrubber designs available than liquid- and gas-phase contacting collector designs. Two are more common: *centrifugal fan scrubbers* and *mechanically induced spray scrubbers*.

A *centrifugal-fan scrubber* can serve as both an air mover and a collection device. **Figure 1** shows such a system, where water is sprayed onto the fan blades cocurrently with the moving exhaust gas. Some gaseous pollutants and particles are initially removed as they pass over the liquid sprays.
The liquid droplets then impact on the blades to create smaller droplets for additional collection targets. Collection can also take place on the liquid film that forms on the fan

blades. The rotating blades force the liquid and collected particles off the blades. The liquid droplets separate from the gas stream because of their centrifugal motion.

Centrifugal-fan collectors are the most compact of the wet scrubbers since the fan and collector comprise a combined unit. No internal pressure loss occurs across the scrubber, but a power loss equivalent to a pressure drop of 10.2 to 15.2 cm (4 to 6 in) of water occurs because the blower efficiency is low.

Another mechanically aided scrubber, the *induced-spray*, consists of a whirling rotor submerged in a pool of liquid. The whirling rotor produces a fine droplet spray. By moving the process gas through the spray, particles and gaseous pollutants can subsequently be collected.

Figure 2 shows an induced-spray scrubber that uses a vertical-spray rotor.

Particle collection

Mechanically aided scrubbers are capable of high collection efficiencies for particles with diameters of 1 μm or greater. However, achieving these high efficiencies usually requires a greater energy input than those of other scrubbers operating at similar efficiencies. In mechanically aided scrubbers, the majority of particle collection occurs in the liquid droplets formed by the rotating blades or rotor.

Gas collection

Mechanically aided scrubbers are generally not used for gas absorption. The contact time between the gas and liquid phases is very short, limiting absorption. For gas removal, several other scrubbing systems provide much better removal per unit of energy consumed.

Maintenance problems

As with almost any device, the addition of moving parts leads to an increase in potential maintenance problems. Mechanically aided scrubbers have higher maintenance costs than other wet collector systems. The moving parts are particularly susceptible to corrosion and fouling. In addition, rotating parts are subject to vibration-induced fatigue or wear, causing them to become unbalanced. Corrosion-resistant materials for these scrubbers are very expensive; therefore, these devices are not used in applications where corrosion or sticky materials could cause problems.

Summary

Mechanically aided scrubbers have been used to control exhaust streams containing particulate matter. They have the advantage of being smaller than most other scrubbing

systems, since the fan is incorporated into the scrubber. In addition, they operate with low liquid-to-gas ratios. Their disadvantages include their generally high maintenance requirements, low absorption efficiency, and high operating costs.

The performance characteristics of mechanically aided scrubbers are given in **Table 1**.

Table 1. Operating characteristics of mechanically aided scrubbers

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p_L)	Particle diameter	Applications
Particles	10-20 cm of water (4.0-8.0 in of water)	0.07-0.2 l/m^3 (centrifugal) 0.5-1.5 gal/1,000 ft^3 (centrifugal) 0.5-0.7 l/m^3 (spray rotor) 4-5 gal/1,000 ft^3 (spray rotor)	20-60 psig (centrifugal)	1 μm	Mining operations Food product industries Chemical industry Foundries and steel mills

Note: These devices are used mainly for particle collection; however, they can also remove gaseous pollutants that are present in the exhaust stream.
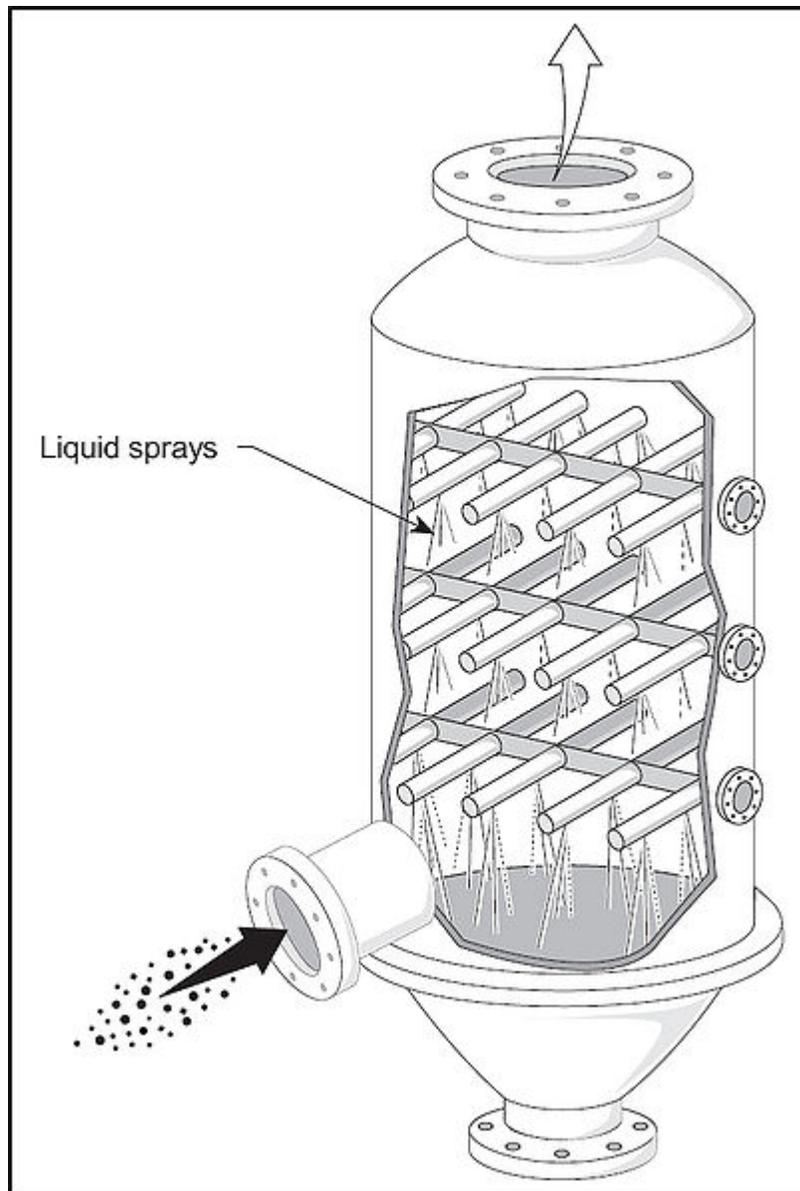
Spray tower

Figure 1 - Countercurrent-flow spray tower

Spray towers or **spray chambers** are a form of pollution control technology. They consist of empty cylindrical vessels made of steel or plastic and nozzles that spray liquid into the vessels. The inlet gas stream usually enters the bottom of the tower and moves upward, while liquid is sprayed downward from one or more levels. This flow of inlet gas and liquid in the opposite direction is called countercurrent flow. **Figure 1** shows a typical countercurrent-flow spray tower. This type of technology is a part of the group of air pollution controls collectively referred to as wet scrubbers.

Countercurrent flow exposes the outlet gas with the lowest pollutant concentration to the freshest scrubbing liquid. Many nozzles are placed across the tower at different heights to spray all of the gas as it moves up through the tower. The reasons for using many nozzles

is to maximize the number of fine droplets impacting the pollutant particles and to provide a large surface area for absorbing gas.

Theoretically, the smaller the droplets formed, the higher the collection efficiency achieved for both gaseous and particulate pollutants. However, the liquid droplets must be large enough to not be carried out of the scrubber by the scrubbed outlet gas stream. Therefore, spray towers use nozzles to produce droplets that are usually 500 to 1,000 μm in diameter. Although small in size, these droplets are large compared to those created in the venturi scrubbers that are 10 to 50 μm in size. The gas velocity is kept low, from 0.3 to 1.2 m/s (1 to 4 ft/s) to prevent excess droplets from being carried out of the tower.

In order to maintain low gas velocities, spray towers must be larger than other scrubbers that handle similar gas stream flow rates. Another problem occurring in spray towers is that after the droplets fall short distances, they tend to agglomerate or hit the walls of the tower. Consequently, the total liquid surface area for contact is reduced, reducing the collection efficiency of the scrubber.
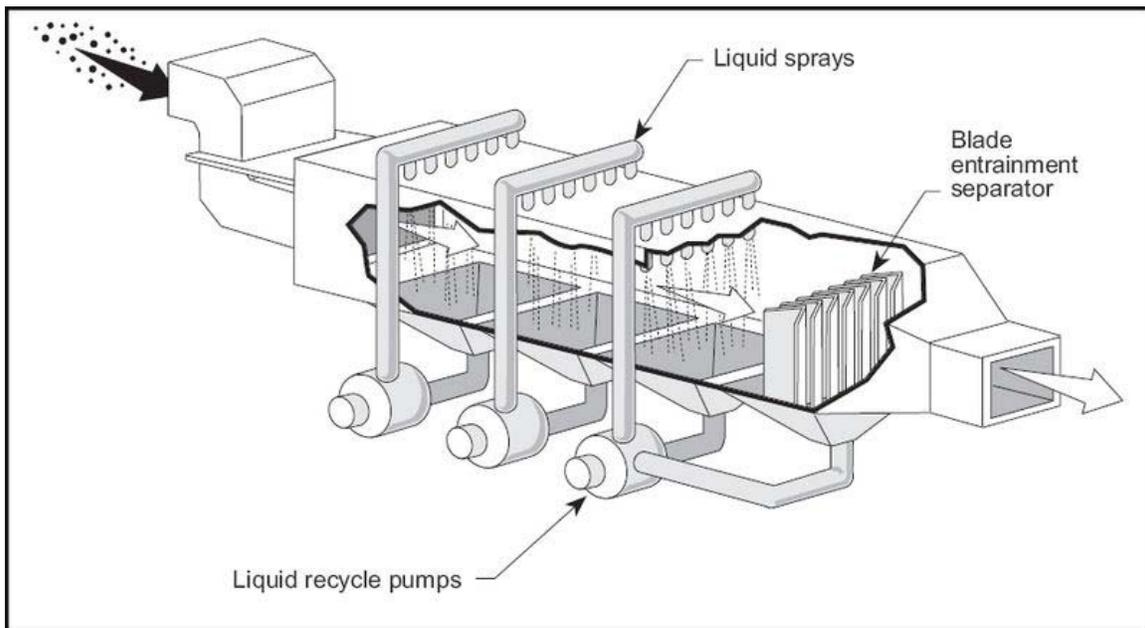
Figure 2 - Crosscurrent-flow spray tower

In addition to a countercurrent-flow configuration, the flow in spray towers can be either a cocurrent or crosscurrent in configuration.

In cocurrent-flow spray towers, the inlet gas and liquid flow in the same direction. Because the gas stream does not "push" against the liquid sprays, the gas velocities through the vessels are higher than in countercurrentflow spray towers. Consequently, cocurrent-flow spray towers are smaller than countercurrent-flow spray towers treating the same amount of exhaust flow. In crosscurrent-flow spray towers, also called

horizontal-spray scrubbers, the gas and liquid flow in directions perpendicular to each other (**Figure 2**).

In this vessel, the gas flows horizontally through a number of spray sections. The amount and quality of liquid sprayed in each section can be varied, usually with the cleanest liquid (if recycled liquid is used) sprayed in the last set of sprays.

Particle collection

Spray towers are low energy scrubbers. Contacting power is much lower than in venturi scrubbers, and the pressure drops across such systems are generally less than 2.5 cm (1 in) of water. The collection efficiency for small particles is correspondingly lower than in more energy-intensive devices. They are adequate for the collection of coarse particles larger than 10 to 25 μm in diameter, although with increased liquid inlet nozzle pressures, particles with diameters of 2.0 μm can be collected.

Smaller droplets can be formed by higher liquid pressures at the nozzle. The highest collection efficiencies are achieved when small droplets are produced and the difference between the velocity of the droplet and the velocity of the upward-moving particles is high. Small droplets, however, have small settling velocities, so there is an optimum range of droplet sizes for scrubbers that work by this mechanism.

This range of droplet sizes is between 500 to 1,000 μm for gravity-spray (counter current) towers. The injection of water at very high pressures – 2,070 to 3,100 kPa (300 to 450 psi) - creates a fog of very fine droplets. Higher particle-collection efficiencies can be achieved in such cases since collection mechanisms other than inertial impaction occur. However, these spray nozzles may use more power to form droplets than would a venturi operating at the same collection efficiency.

Gas collection

Spray towers can be used for gas absorption, but they are not as effective as packed or plate towers. Spray towers can be very effective in removing pollutants if the pollutants are highly soluble or if a chemical reagent is added to the liquid.

For example, spray towers are used to remove HCl gas from the tail-gas exhaust in manufacturing hydrochloric acid. In the production of superphosphate used in manufacturing fertilizer, SiF_4 and HF gases are vented from various points in the processes. Spray towers have been used to remove these highly soluble compounds. Spray towers are also used for odor removal in bone meal and tallow manufacturing industries by scrubbing the exhaust gases with a solution of $KMnO_4$.

Because of their ability to handle large gas volumes in corrosive atmospheres, spray towers are also used in a number of flue gas desulfurization systems as the first or second stage in the pollutant removal process.

In a spray tower, absorption can be increased by decreasing the size of the liquid droplets and/or increasing the liquid-to-gas ratio (L/G). However, to accomplish either of these, an increase in both power consumed and operating cost is required. In addition, the physical size of the spray tower will limit the amount of liquid and the size of droplets that can be used.

Maintenance problems

The main advantage of spray towers over other scrubbers is their completely open design; they have no internal parts except for the spray nozzles. This feature eliminates many of the scale buildup and plugging problems associated with other scrubbers.
The primary maintenance problems are spray-nozzle plugging or eroding, especially when using recycled scrubber liquid. To reduce these problems, a settling or filtration system is used to remove abrasive particles from the recycled scrubbing liquid before pumping it back into the nozzles.

Summary

Spray towers are inexpensive control devices primarily used for gas conditioning (cooling or humidifying) or for first-stage particle or gas removal. They are also being used in many flue gas desulfurization systems to reduce plugging and scale buildup by pollutants.

Many scrubbing systems use sprays either prior to or in the bottom of the primary scrubber to remove large particles that could plug it.

Spray towers have been used effectively to remove large particles and highly soluble gases. The pressure drops across the towers are very low - usually less than 2.5 cm (1.0 in) of water; thus, the scrubber operating costs are relatively low. However, the liquid pumping costs can be very high.

Spray towers are constructed in various sizes - small ones to handle small gas flows of 0.05 m³/s (106 ft³/min) or less, and large ones to handle large exhaust flows of 50 m³/s (106,000 m³/min) or greater. Because of the low gas velocity required, units handling large gas flow rates tend to be large in size. Operating characteristics of spray towers are presented in **Table 1**.

Table 1. Operating characteristics of spray towers

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p_L)	Removal efficiency	Applications

Gases	1.3-7.6 cm of water	0.07-2.70 l/m³ (0.5-20 gal/1,000 ft³	70-2,800 kPa	50-90$^+$% (high efficiency only when the gas is very soluble)	Mining industries Chemical process industry
Particles	0.5-3.0 in of water	5 gal/1,000 ft³ is normal; >10 when using pressure sprays	10-400 psig	2-8 μm diameter	Boilers and incinerators Iron and steel industry

Chapter- 6

Catalytic Converter

Catalytic converter on a 1996 Dodge Ram Van (2004)

A **catalytic converter** (colloquially, "cat" or "catcon") is a device used to reduce the toxicity of emissions from an internal combustion engine. A catalytic converter works by using a catalyst to stimulate a chemical reaction in which toxic by-products of combustion are converted to less-toxic substances.

First widely introduced on series-production automobiles in the United States market for the 1975 model year to comply with tightening U.S. Environmental Protection Agency regulations on auto exhaust, catalytic converters are still most commonly used in motor vehicle exhaust systems. Catalytic converters are also used on generator sets, forklifts, mining equipment, trucks, buses, trains, airplanes and other engine-equipped machines.

History

The catalytic converter was invented by Eugene Houdry, a French mechanical engineer and expert in catalytic oil refining who lived in the U.S. Around 1950, when the results of early studies of smog in Los Angeles were published, Houdry became concerned about the role of automobile exhaust in air pollution and founded a special company, Oxy-Catalyst, to develop catalytic converters for gasoline engines — an idea ahead of its time for which he was awarded a patent (US2742437). Widespread adoption had to wait until the extremely effective anti-knock agent tetra-ethyl lead was eliminated from most gasoline over environmental concerns, as the agent would "foul" the converter by forming a coating on the catalyst's surface, effectively disabling it.

The catalytic converter was further developed by John J. Mooney and Carl D. Keith at the Engelhard Corporation, creating the first production catalytic converter in 1973.

Construction

Metal-core converter

Ceramic-core converter

The catalytic converter consists of several components:

1. The core, or substrate. The core is often a ceramic honeycomb in modern catalytic converters, but stainless steel foil honeycombs are also used. The honeycomb surface increases the amount of surface area available to support the catalyst, and therefore is often called a "catalyst support". The ceramic substrate was invented by Rodney Bagley, Irwin Lachman and Ronald Lewis at Corning Glass, for which they were inducted into the National Inventors Hall of Fame in 2002.
2. The washcoat. A washcoat is used to make converters more efficient, often as a mixture of silica and alumina. The washcoat, when added to the core, forms a rough, irregular surface, which has a far-greater surface area than the flat-core surfaces do, which then gives the converter core a larger surface area, and therefore more places for active precious-metal sites. The catalyst is added to the washcoat (in suspension) before being applied to the core.
3. The catalyst itself is most often a precious metal. Platinum is the most-active catalyst and is widely used. It is not suitable for all applications, however, because of unwanted additional reactions and/or cost. Palladium and rhodium are two other precious metals used. Platinum and rhodium are used as a reduction catalyst, while platinum and palladium are used as an oxidation catalyst. Cerium, iron, manganese and nickel are also used, although each has its own limitations. Nickel is not legal for use in the European Union (because of its reaction with carbon monoxide). Copper can be used everywhere except North America, where its use is illegal because of the formation of dioxin.

Types

Two-way

A two-way catalytic converter has two simultaneous tasks:

1. Oxidation of carbon monoxide to carbon dioxide: $2CO + O_2 \rightarrow 2CO_2$
2. Oxidation of unburnt hydrocarbons (unburnt and partially-burnt fuel) to carbon dioxide and water: $C_xH_{2x+2} + [(3x+1)/2]\,O_2 \rightarrow xCO_2 + (x+1)\,H_2O$ (a combustion reaction)

This type of catalytic converter is widely used on diesel engines to reduce hydrocarbon and carbon-monoxide emissions. They were also used on gasoline engines in U.S. market automobiles until 1981. Because of their inability to control nitrous oxide NO_x, they were superseded by three-way converters.

Three-way

Since 1981, three-way catalytic converters have been used in vehicle emission control systems in North America and many other countries on road-going vehicles. A three-way catalytic converter has three simultaneous tasks:

1. Reduction of nitrogen oxides to nitrogen and oxygen: $2NO_x \rightarrow xO_2 + N_2$
2. Oxidation of carbon monoxide to carbon dioxide: $2CO + O_2 \rightarrow 2CO_2$
3. Oxidation of unburnt hydrocarbons (HC) to carbon dioxide and water: $C_xH_{2x+2} + [(3x+1)/2]O_2 \rightarrow xCO_2 + (x+1)H_2O$

These three reactions occur most efficiently when the catalytic converter receives exhaust from an engine running slightly above the stoichiometric point. This point is between 14.6 and 14.8 parts air to 1 part fuel, by weight, for gasoline. The ratio for Autogas (or liquefied petroleum gas (LPG)), natural gas and ethanol fuels is slightly different, requiring modified fuel system settings when using those fuels. Generally, engines fitted with 3-way catalytic converters are equipped with a computerized closed-loop feedback fuel injection system using one or more oxygen sensors, though early in the deployment of three-way converters, carburetors equipped for feedback mixture control were used.

While a three-way catalyst can be used in an open-loop system, NO_x reduction efficiency is low. Within a narrow fuel/air ratio band surrounding stoichiometry, conversion of all three pollutants is nearly complete. However, outside that band, conversion efficiency falls very rapidly. When there is more oxygen than required, the system is said to be running lean(as all the fuel got burnt,the emission of CO and hydrocarbons are minimized)and thereby, the reduction of NO_x is favored, at the expense of CO and hydrocarbons. When there is excessive fuel, the engine is running rich; the reduction of CO and hydrocarbons is favored, at the expense of NO_x.

Oxygen storage

Three-way catalytic converters can store oxygen from the exhaust gas stream, usually when the air-fuel ratio goes lean. When insufficient oxygen is available from the exhaust stream, the stored oxygen is released and consumed. This leanness occurs either when oxygen derived from NO_x reduction is unavailable or certain maneuvers such as hard acceleration enrich the mixture beyond the ability of the converter to supply oxygen.

Unwanted reactions

Unwanted reactions can occur in the three-way catalyst, such as the formation of odiferous hydrogen sulfide and ammonia. Formation of each can be limited by modifications to the washcoat and precious metals used. It is difficult to eliminate these byproducts entirely. Sulfur-free or low-sulfur fuels eliminate or reduce hydrogen sulfide.

For example, when control of hydrogen-sulfide emissions is desired, nickel or manganese is added to the washcoat. Both substances act to block the adsorption of sulfur by the washcoat. Hydrogen sulfide is formed when the washcoat has adsorbed sulfur during a low temperature part of the operating cycle, which is then released during the high-temperature part of the cycle and the sulfur combines with HC.

For diesel engines

For compression-ignition (i.e., diesel engines), the most-commonly-used catalytic converter is the diesel oxidation catalyst. This catalyst uses O_2 (oxygen) in the exhaust gas stream to convert CO (carbon monoxide) to CO_2 (carbon dioxide) and HC (hydrocarbons) to H_2O (water) and CO_2. These converters often operate at 90 percent efficiency, virtually eliminating diesel odor and helping to reduce visible particulates (soot). But they cannot reduce NO_x because chemical reactions always occur in the simplest possible way, and the existing O_2 in the exhaust gas stream would react first.

To reduce NO_x on a compression-ignition engine, the chemical composition of the exhaust must first be changed. Two main techniques are used: exhaust gas recirculation (EGR) and selective catalytic reduction (SCR). NO_x trapping (with NOx absorbers) is a third method, but as of yet (2010), is not widely used.

Diesel-engine exhaust contains relatively high levels of particulate matter (soot), consisting in large part of elemental carbon. Catalytic converters cannot clean up elemental carbon, though they do remove up to 90 percent of the soluble organic fraction, so particulates are cleaned up by a soot trap or diesel particulate filter (DPF). In the U.S., all on-road heavy-duty vehicles powered by diesel and built after January 1, 2007, must be equipped with a catalytic converter and a diesel particulate filter.

Instead of catalysis, a reagent such as ammonia pyrolyzed *in situ* from urea, is sometimes used to reduce the NO_x into nitrogen. One trademark product to do this is AdBlue.

For lean-burn engines

For lean-burn, spark-ignition engines, an oxidation catalyst is used in the same manner as in a diesel engine.

Installation

Many vehicles have a pre-catalyst located close to the engine's exhaust manifold. This unit heats up quickly due to its proximity to the engine, and reduces cold-engine emissions by burning off hydrocarbons from the extra-rich mixture used in a cold engine.

Many three-way catalytic converters use an air-injection tube between the first (NO_x reduction) and second (HC and CO oxidation) stages of the converter. This tube is fed by a secondary air-injection system. The injected air provides oxygen for the catalyst's oxidizing reaction. These systems also sometimes include an upstream air injector to admit oxygen to the exhaust system before it reaches the catalytic converter. This precleans the extra-rich exhaust from a cold engine, and helps bring the catalytic converter quickly up to operating temperature.

Some newer systems do not employ air injection. Instead, they provide a constantly varying mixture that quickly and continually cycles between lean and rich to keep the first catalyst (NO_x reduction) from becoming oxygen-loaded, and to keep the second catalyst (CO oxidization) sufficiently oxygen-saturated. They also use several oxygen sensors to monitor the exhaust, including at least one before the catalytic converter for each bank of cylinders, and one after the converter. Some systems contain the reduction and oxidation functions separately rather than in a common housing.

Damage

Poisoning

Catalyst poisoning occurs when the catalytic converter is exposed to exhaust containing substances that coat the working surfaces, encapsulating the catalyst so that it cannot contact and treat the exhaust. The most-notable contaminant is lead, so vehicles equipped with catalytic converters can only be run on unleaded gasoline. Other common catalyst poisons include manganese (originating primarily from the gasoline additive MMT), and silicone, which can enter the exhaust stream if the engine has a leak, allowing coolant into the combustion chamber. Phosphorus is another catalyst contaminant. Although phosphorus is no longer used in gasoline, it (and zinc, another low-level catalyst contaminant) was until recently widely used in engine oil antiwear additives such as zinc dithiophosphate (ZDDP). Beginning in 2006, a rapid phaseout of ZDDP in engine oils began.

Depending on the contaminant, catalyst poisoning can sometimes be reversed by running the engine under a very heavy load for an extended period of time. The increased exhaust

temperature can sometimes liquefy or sublimate the contaminant, removing it from the catalytic surface. However, removal of lead deposits in this manner is usually not possible because of lead's high boiling point.

Meltdown

Any condition that causes abnormally high levels of unburned hydrocarbons — raw or partially burnt fuel — to reach the converter will tend to significantly elevate its temperature, bringing the risk of a meltdown of the substrate and resultant catalytic deactivation and severe exhaust restriction. Vehicles equipped with OBD-II diagnostic systems are designed to alert the driver to a misfire condition, along with other malfunctions, by means of the "check engine" light on the dashboard.

Regulations

Emissions regulations vary considerably from jurisdiction to jurisdiction. In North America, most spark-ignition engines of over 25 brake horsepower (19 kW) output built after January 1, 2004, are equipped with three-way catalytic converters. In Japan, a similar set of regulations came into effect January 1, 2007, while the European Union has not yet enacted analogous regulations. Most automobile spark-ignition engines in North America have been fitted with catalytic converters since the mid-1970s, and the technology used in non-automotive applications is generally based on automotive technology.

Regulations for diesel engines are similarly varied, with some jurisdictions focusing on NO_x (nitric oxide and nitrogen dioxide) emissions and others focusing on particulate (soot) emissions. This regulatory diversity is challenging for manufacturers of engines, as it may not be economical to design an engine to meet two sets of regulations.

Regulations of fuel quality vary across jurisdictions. In North America, Europe, Japan and Hong Kong, gasoline and diesel fuel are highly regulated, and compressed natural gas and LPG (Autogas) are being reviewed for regulation. In most of Asia and Africa, the regulations are often lax — in some places sulfur content of the fuel can reach 20,000 parts per million (2%). Any sulfur in the fuel can be oxidized to SO_2 (sulfur dioxide) or even SO_3 (sulfur trioxide) in the combustion chamber. If sulfur passes over a catalyst, it may be further oxidized in the catalyst, i.e., SO_2 may be further oxidized to SO_3. Sulfur oxides are precursors to sulfuric acid, a major component of acid rain. While it is possible to add substances such as vanadium to the catalyst washcoat to combat sulfur-oxide formation, such addition will reduce the effectiveness of the catalyst. The most effective solution is to further refine fuel at the refinery to produce ultra-low sulfur diesel. Regulations in Japan, Europe and North America tightly restrict the amount of sulfur permitted in motor fuels. However, the expense of producing such clean fuel makes it impractical for use in many developing countries. As a result, cities in these countries with high levels of vehicular traffic suffer from acid rain, which damages stone and woodwork of buildings and damages local ecosystems.

Negative aspects

Some early converter designs greatly restricted the flow of exhaust, which negatively affected vehicle performance, driveability, and fuel economy. Because they were used with carburetors incapable of precise fuel-air mixture control, they could overheat and set fire to flammable materials under the car. Removing a modern catalytic converter in new condition will only slightly increase vehicle performance without retuning, but their removal or "gutting" continues. The exhaust section where the converter was may be replaced with a welded-in section of straight pipe, or a flanged section of "test pipe" legal for off-road use that can then be replaced with a similarly fitted converter-choked section for legal on-road use, or emissions testing. In the U.S. and many other jurisdictions, it is illegal to remove or disable a catalytic converter for any reason other than its immediate replacement; vehicles without functioning catalytic converters generally fail emission inspections. The automotive aftermarket supplies high-flow converters for vehicles with upgraded engines, or whose owners prefer an exhaust system with larger-than-stock capacity.

Warm-up period

Most of the pollution put out by a car occurs during the first five minutes before the catalytic converter has warmed up sufficiently.

In 1999, BMW introduced the Electric Catalytic Convert, or "E-CAT", in their flagship E38 750iL sedan. Coils inside the catalytic converter assemblies are heated electrically just after engine start, bringing the catalyst up to operating temperature much faster than traditional catalytic converters can, providing cleaner cold starts and low emission vehicle (LEV) compliance.

Environmental impact

Catalytic converters have proven to be reliable and effective in reducing noxious tailpipe emissions. However, they may have some adverse environmental impacts in use:

- The requirement for a rich-burn engine to run at the stoichiometric point means it uses more fuel than a lean-burn engine running at a mixture of 20:1 or less. This increases the amount of fossil fuel consumed and the carbon-dioxide emissions of the vehicle. However, NO_x control on lean-burn engines is problematic.
- Although catalytic converters are effective at removing hydrocarbons and other harmful emissions, they do not solve the fundamental problem created by burning a fossil fuel. In addition to water, the main combustion product in exhaust gas leaving the engine — through a catalytic converter or not — is carbon dioxide (CO_2). Carbon dioxide produced from fossil fuels is one of the greenhouse gases indicated by the Intergovernmental Panel on Climate Change (IPCC) to be a "most likely" cause of global warming. Additionally, the U.S. EPA has stated catalytic converters are a significant and growing cause of global warming,

because of their release of nitrous oxide (N$_2$O), a greenhouse gas over three hundred times more potent than carbon dioxide.

- Catalytic converter production requires palladium or platinum; part of the world supply of these precious metals is produced near Norilsk, Russia, where the industry (among others) has caused Norilsk to be added to *Time* magazine's list of most-polluted places.

Theft

Because of the external location and the use of valuable precious metals including platinum, palladium, and rhodium, converters are a target for thieves. The problem is especially common among late-model Toyota trucks and SUVs, because of their high ground clearance and easily removed bolt-on catalytic converters. Welded-in converters are also at risk of theft from SUVs and trucks, as they can be easily removed. Theft removal of the converter can often inadvertently damage the car's wiring or fuel line resulting in dangerous consequences. Rises in metal costs in the U.S. during recent years have led to a large increase in theft incidents of the converter, which can then cost as much as $1,000 to replace.

Diagnostics

Various jurisdictions now legislate on-board diagnostics to monitor the function and condition of the emissions-control system, including the catalytic converter. On-board diagnostic systems take several forms.

Temperature sensors

Temperature sensors are used for two purposes. The first is as a warning system, typically on two-way catalytic converters such as are still sometimes used on LPG forklifts. The function of the sensor is to warn of catalytic converter temperature above the safe limit of 750 °C (1,380 °F). More-recent catalytic-converter designs are not as susceptible to temperature damage and can withstand sustained temperatures of 900 °C (1,650 °F). Temperature sensors are also used to monitor catalyst functioning — usually two sensors will be fitted, with one before the catalyst and one after to monitor the temperature rise over the catalytic-converter core. For every one percent of CO in the exhaust gas stream, the exhaust gas temperature will rise by 100°C.

Oxygen sensors

The oxygen sensor is the basis of the closed-loop control system on a spark-ignited rich-burn engine; however, it is also used for diagnostics. In vehicles with OBD II, a second oxygen sensor is fitted after the catalytic converter to monitor the O$_2$ levels. The on-board computer makes comparisons between the readings of the two sensors. If both sensors show the same output, the computer recognizes that the catalytic converter is either not functioning or has been removed, and will operate a "check engine" light and retard

engine performance. Simple "oxygen sensor simulators" have been developed to circumvent this problem by simulating the change across the catalytic converter with plans and pre-assembled devices available on the internet, although these are not legal for on-road use. Similar devices apply an offset to the sensor signals, allowing the engine to run a more fuel-economical lean burn that may, however, damage the engine or the catalytic converter.

NO_x sensors

NO_x sensors are extremely expensive and are generally only used when a compression-ignition engine is fitted with a selective catalytic-reduction (SCR) converter, or a NO_x absorber catalyst in a feedback system. When fitted to an SCR system, there may be one or two sensors. When one sensor is fitted it will be pre-catalyst; when two are fitted the second one will be post-catalyst. They are used for the same reasons and in the same manner as an oxygen sensor — the only difference is the substance being monitored.

Exhaust gas recirculation

n internal combustion engines, **exhaust gas recirculation** (**EGR**) is a nitrogen oxide (NOx) emissions reduction technique used in petrol/gasoline and diesel engines.

EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders. In a gasoline engine, this inert exhaust displaces the amount of combustible matter in the cylinder. In a diesel engine, the exhaust gas replaces some of the excess oxygen in the pre-combustion mixture.

Because NOx formation progresses much faster at high temperatures, EGR reduces the amount of NOx the combustion generates. NOx forms primarily when a mixture of nitrogen and oxygen is subjected to high temperature.

EGR valve on top of the inlet manifold of a Saab H engine in a 1987 Saab 90

EGR in spark-ignited engines

The exhaust gas, added to the fuel, oxygen, and combustion products, increases the specific heat capacity of the cylinder contents, which lowers the adiabatic flame temperature.

In a typical automotive spark-ignited (SI) engine, 5 to 15 percent of the exhaust gas is routed back to the intake as EGR. The maximum quantity is limited by the requirement of the mixture to sustain a contiguous flame front during the combustion event; excessive EGR in poorly set up applications can cause misfires and partial burns. Although EGR does measurably slow combustion, this can largely be compensated for by advancing spark timing. The impact of EGR on engine efficiency largely depends on the specific engine design, and sometimes leads to a compromise between efficiency and NOx emissions. A properly operating EGR can theoretically increase the efficiency of gasoline engines via several mechanisms:

- **Reduced throttling losses**. The addition of inert exhaust gas into the intake system means that for a given power output, the throttle plate must be opened

further, resulting in increased inlet manifold pressure and reduced throttling losses.

- **Reduced heat rejection**. Lowered peak combustion temperatures not only reduces NOx formation, it also reduces the loss of thermal energy to combustion chamber surfaces, leaving more available for conversion to mechanical work during the expansion stroke.
- **Reduced chemical dissociation**. The lower peak temperatures result in more of the released energy remaining as sensible energy near TDC, rather than being bound up (early in the expansion stroke) in the dissociation of combustion products. This effect is minor compared to the first two.

It also decreases the efficiency of gasoline engines via at least one more mechanism:

- **Reduced specific heat ratio**. A lean intake charge has a higher specific heat ratio than an EGR mixture. A reduction of specific heat ratio reduces the amount of energy that can be extracted by the piston.

EGR is typically not employed at high loads because it would reduce peak power output. This is because it reduces the intake charge density. EGR is also omitted at idle (low-speed, zero load) because it would cause unstable combustion, resulting in rough idle. The EGR valve also cools the exhaust valves and makes them last far longer (a very important benefit under light cruise conditions)

EGR implementations

Usually, an engine recirculates exhaust gas by piping it from the exhaust manifold to the inlet manifold. This design is called *external* EGR. A control valve (EGR Valve) within the circuit regulates and times the gas flow. Some engine designs perform EGR by trapping exhaust gas within the cylinder by not fully expelling it during the exhaust stroke, which is called *internal* EGR. A form of internal EGR is used in the rotary Atkinson cycle engine.

EGR can also be implemented by using a variable geometry turbocharger (VGT) which uses variable inlet guide vanes to build sufficient backpressure in the exhaust manifold. For EGR to flow, a pressure difference is required across the intake and exhaust manifold and this is created by the VGT.

Another method that has been experimented with, is using a throttle in a turbocharged diesel engine to decrease the intake pressure, thereby initiating EGR flow.

Early (1970s) EGR systems were unsophisticated, utilizing manifold vacuum as the only input to an on/off EGR valve; reduced performance and/or drivability were common side effects. Slightly later (mid 1970s to carbureted 1980s) systems included a coolant temperature sensor which didn't enable the EGR system until the engine had achieved normal operating temperature (presumably off the choke valve and therefore less likely to block the EGR passages with carbon buildups, and a lot less likely to stall due to a cold

engine). Many added systems like "EGR timers" to disable EGR for a few seconds after a full-throttle acceleration. Vacuum reservoirs and "vacuum amplifiers" were sometimes used, adding to the maze of vacuum hoses under the hood. All vacuum-operated systems, especially the EGR due to vacuum lines necessarily close to the hot exhaust manifold, were highly prone to vacuum leaks caused by cracked hoses; a condition that plagued early 1970s EGR-equipped cars with bizarre reliability problems (stalling when warm or cold, stalling or misfiring under partial throttle, etc.). Hoses in these vehicles would be checked by doing a vacuum leak test or pressure smoke test, with a professional smoke generator. When testing, smoke escapes from the hose being tested or the vacuum test gauge indicates a particular hose is leaking.

Modern systems utilizing electronic engine control computers, multiple control inputs, and servo-driven EGR valves typically *improve* performance/efficiency with no impact on drivability.

In the past, a fair number of car owners disconnected their EGR systems in an attempt for better performance and some still do. The belief is either EGR reduces power output, causes a build-up in the intake manifold, or believe that the environmental impact of EGR outweighs the Nitrous Oxide emission reductions. Disconnecting an EGR system is usually as simple as unplugging an electrically operated valve or inserting a ball bearing into the vacuum line in a vacuum-operated EGR valve. In most modern engines, disabling the EGR system will cause the computer to display a check engine light. In most cases, a disabled EGR system will cause the car to fail an emissions test.

Chapter- 7

Thermal Oxidizers and Biofilters

Thermal oxidizer

A **thermal oxidizer** (or **thermal oxidiser**) is a process unit for air pollution control in many chemical plants that decomposes hazardous gases at a high temperature and releases them into the atmosphere.

Principle

Thermal Oxidizers are typically used to destroy Hazardous Air Pollutants (HAPs) and Volatile Organic Compounds (VOCs) from industrial air streams. These pollutants are generally hyrdocarbon based and when destroyed via thermal combustion they are chemically changed to form CO_2 and H_2O.

Regenerative thermal oxidizer (RTO)

One of today's most widely accepted air pollution control technologies across the industry is a Regenerative Thermal Oxidizer, commonly referred to as a RTO. They are very versatile and extremely efficient – energy recovery efficiency can reach 95%. This is achieved through the storage of heat by dense ceramic stoneware. Regenerative Thermal Oxidizers are ideal in low VOC concentrations with larger process requirements. Systems can be used during long continuous 24 hour operations.

There are currently many Regenerative Thermal Oxidizers on the market with the capabitlity of 99+% Volatile Organic Compound (VOC) destruction efficiencies. The ceramic heat exchanger(s) can be designed for thermal efficiencies as high as 97+%. Regenerative Thermal Oxidizers can be designed with multiple hot gas bypass systems, bake-out cycles, re-circulation heat exchangers and O2 monitoring to reduce carbon monoxide and nitrous oxide. Many environmental agencies are requiring 02 continuous monitoing for the control of these secondary gases. Higher VOC streams allow the RTO to operate at reduced or zero fuel usage, which makes these systems ideal for certain plant operations.

Regenerative catalytic oxidizer (RCO)

In some applications, the use of Catalyst with the ceramic media helps allow oxidation at reduced temperatures. This can result in even lower operating costs compared to a Regenerative Thermal Oxidizer. Most systems operate within the 500F to 800F degree range. Some systems are designed to operate both as Regenerative Catalytic Systems and Regenerative Thermal Oxdizers. When these systems are used special design considerations are utilized to reduce the probability of over temperatures, these high temperatures would destroy the washed catalytic structured media.

Ventilation air methane thermal oxidizer (VAMTOX)

Ventilation Air Methane Thermal Oxidizers are used to destroy methane in the exhaust air of underground coal mine shafts. Methane is a greenhouse gas and, when destroyed via thermal combustion, is chemically altered to form CO_2 and H_2O. CO_2 is 25 times less potent than methane when emitted into the atmosphere with regards to global warming. Concentrations of methane in mine ventilation exhaust air of coal and trona mines are very dilute; typically below 1% and often below 0.5%. VAMTOX units have a system of valves and dampers that direct the air flow across one or more ceramic filled bed(s). On start-up, the system preheats by raising the temperature of the heat exchanging ceramic material in the bed(s) at or above the auto-oxidation temperature of methane (1,000°C or 1,832°F), at which time the preheating system is turned off and mine exhaust air is introduced. Then the methane-filled air reaches the preheated bed(s), releasing the heat from combustion. This heat is then transferred back to the bed(s), thereby maintaining the temperature at or above what is necessary to support auto-thermal operation.

Thermal recuperative oxidizer

A less commonly used thermal oxidizer technology is a thermal recuperative oxidizer. Thermal recuperative oxidizers have a primary and/or secondary heat exchanger within the system. A primary heat exchanger preheats the incoming dirty air by recuperating heat from the exiting clean air. This is done by a shell and tube heat exchanger or a plate-type exchanger. As the incoming air passes on one side of the metal tube or plate, hot clean air from the combustion chamber passes on the other side of the tube or plate and heat is transferred to the incoming air through the process of conduction using the metal as the medium of heat transfer. In a secondary heat exchanger the same concept applies for heat transfer, but the air being heated by the outgoing clean process stream is being returned to another part of the plant – perhaps back to the process.

Catalytic oxidizer

Catalytic oxidation occurs through a chemical reaction between the VOC hydrocarbon molecules and a precious-metal catalyst bed that is internal to the oxidizer system. A catalyst is a substance that is used to accelerate the rate of a chemical reaction, allowing the reaction to occur in a normal temperature range of 550°F - 650°F (275°C to 350°C).

Direct fired thermal oxidizer - afterburner

A direct-fired oxidizer is the simplest technology of thermal oxidation. A process stream is introduced into a firing box through or near the burner and enough residence time is provided to get the desired destruction removal efficiency (DRE) of the VOCs. Also called afterburners, these systems are the least capital intensive, but when applied incorrectly, the operating costs can be devastating because there is no form of heat recovery. These are best applied where there is a very high concentration of VOCs to act as the fuel source (instead of natural gas or oil) for complete combustion at the targeted operating temperature.

Biofilter

Biofiltration is a pollution control technique using living material to capture and biologically degrade process pollutants. Common uses include processing waste water, capturing harmful chemicals or silt from surface runoff, and microbiotic oxidation of contaminants in air.

Biofilter installation at a commercial composting facility.

Examples of biofiltration include;

- Bioswales, Biostrips, Biobags, Bioscrubbers, and Trickling filters
- Constructed wetlands and Natural wetlands
- Slow sand filters
- Treatment ponds
- Green belts
- Living walls
- Riparian zones, Riparian forests, Bosques

Control of air pollution

When applied to air filtration and purification, biofilters use microorganisms to remove air pollution. The air flows through a packed bed and the pollutant transfers into a thin biofilm on the surface of the packing material. Microorganisms, including bacteria and fungi are immobilized in the biofilm and degrade the pollutant. Trickling filters and bioscrubbers rely on a biofilm and the bacterial action in their recirculating waters.

The technology finds greatest application in treating malodorous compounds and water-soluble volatile organic compounds (VOCs). Industries employing the technology include food and animal products, off-gas from wastewater treatment facilities, pharmaceuticals, wood products manufacturing, paint and coatings application and manufacturing and resin manufacturing and application, etc. Compounds treated are typically mixed VOCs and various sulfur compounds, including hydrogen sulfide. Very large airflows may be treated and although a large area (footprint) has typically been required -- a large biofilter (>200,000 acfm) may occupy as much or more land than a football field -- this has been one of the principal drawbacks of the technology. Engineered biofilters, designed and built since the early 1990s, have provided significant footprint reductions over the conventional flat-bed, organic media type.

Air cycle system at biosolids composting plant. Large duct in foreground is exhaust air into biofilter shown in next photo

Biosolids composting plant biofilter mound - note sprinkler visible front right to maintain proper moisture level for optimum functioning

One of the main challenges to optimum biofilter operation is maintaining proper moisture throughout the system. The air is normally humidified before it enters the bed with a watering (spray) system, humidification chamber, bioscrubber, or biotrickling filter. Properly maintained, a natural, organic packing media like peat, vegetable mulch, bark or wood chips may last for several years but engineered, combined natural organic and synthetic component packing materials will generally last much longer, up to 10 years. A number of companies offer these types or proprietary packing materials and multi-year guarantees, not usually provided with a conventional compost or wood chip bed biofilter.

Although widely employed, the scientific community is still unsure of the physical phenomena underpinning biofilter operation, and information about the microorganisms involved continues to be developed. A biofilter/bio-oxidation system is a fairly simple device to construct and operate and offers a cost-effective solution provided the pollutant is biodegradable within a moderate time frame (increasing residence time = increased size and capital costs), at reasonable concentrations (and lb/hr loading rates) and that the airstream is at an organism-viable temperature. For large volumes of air, a biofilter may be the only cost-effective solution. There is no secondary pollution (unlike the case of incineration where additional CO_2 and NO_x are produced from burning fuels) and degradation products form additional biomass, carbon dioxide and water. Media irrigation water, although many systems recycle part of it to reduce operating costs, has a moderately high biochemical oxygen demand (BOD) and may require treatment before disposal. However, this "blowdown water", necessary for proper maintenance of any bio-oxidation system, is generally accepted by municipal POTWs without any pretreatment.

Biofilters are being utilized in Columbia Falls, Montana at Plum Creek Timber Company's fiberboard plant. The biofilters decrease the pollution emitted by the manufacturing process and the exhaust emitted is 98% clean. The newest, and largest, biofilter addition to Plum Creek cost $9.5 million, yet even though this new technology is expensive, in the long run it will cost less overtime than the alternative exhaust-cleaning incinerators fueled by natural gas (which are not as environmentally friendly). The biofilters use trillions of microscopic bacteria that cleanse the air being released from the plant.

Water treatment
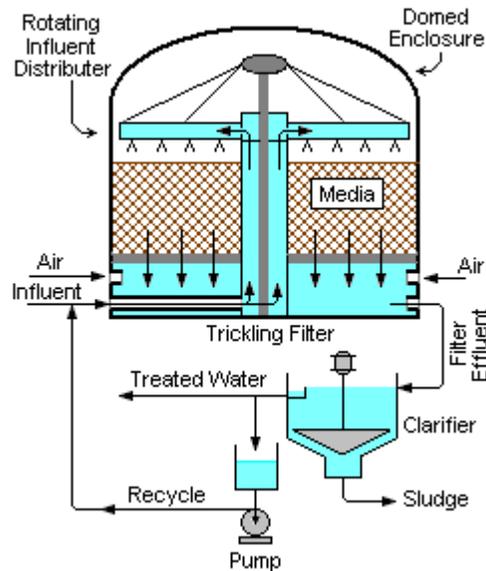
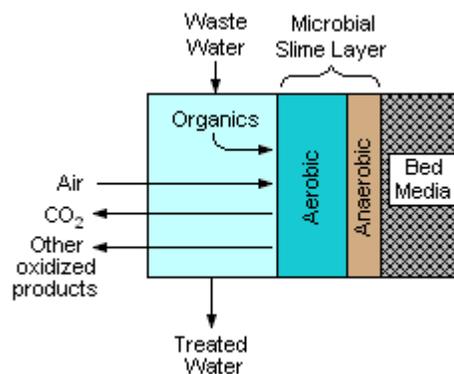A typical complete trickling filter system for treating wastewaters.

Image 1: A schematic cross-section of the contact face of the bed media in a trickling filter.

Trickling filters have been used to filter water for various end uses for almost two centuries. Biological treatment has been used in Europe to filter surface water for drinking purposes since the early 1900s and is now receiving more interest worldwide. Biological treatment methods are also common in wastewater treatment, aquaculture and greywater recycling as a way to minimize water replacement while increasing water quality.

For drinking water, biological water treatment involves the use of naturally occurring micro-organisms in the surface water to improve water quality. Under optimum conditions, including relatively low turbidity and high oxygen content, the organisms break down material in the water and thus improve water quality. Slow sand filters or carbon filters are used to provide a place on which these micro-organisms grow. These biological treatment systems effectively reduce water-borne diseases, dissolved organic carbon, turbidity and colour in surface water, improving overall water quality.

Use in aquaculture

The use of biofilters are commonly used on closed aquaculture systems, such as recirculating aquaculture systems (RAS). Many designs are used, with different benefits and drawbacks, however the function is the same: reducing water exchanges by converting ammonia to nitrate. Ammonia (NH_4^+ and NH_3) originates from the brachial excretion from the gills of aquatic animals and from the decomposition of organic matter. As ammonia-N is highly toxic, this is converted to a less toxic form of nitrite (by *Nitrosomonas* sp.) and then to an even less toxic form of nitrate (by *Nitrobacter* sp.). This "nitrification" process requires oxygen (aerobic conditions), without which the biofilter can crash. Furthermore, as this nitrification cycle produces H^+, the pH can decrease which necessitates the use of buffers such as lime.

Chapter- 8

Flue-Gas Desulfurization

Before flue gas desulfurization was installed, the emissions from this power plant in New Mexico contained a significant amount of sulfur dioxide.

Flue gas desulfurization (FGD) is a technology used to remove sulfur dioxide (SO_2) from the exhaust flue gases of fossil fuel power plants. Fossil fuel power plants burn coal or oil to produce steam for steam turbines, which in turn drive electricity generators.

Sulfur dioxide is one of the elements forming acid rain. Tall flue gas stacks disperse emissions by diluting the pollutants in ambient air and transporting them to other regions.

As stringent environmental regulations regarding SO_2 emissions have been enacted in many countries, SO_2 is now being removed from flue gases by a variety of methods. The below is among the common methods used:

- Wet scrubbing using a slurry of alkaline sorbent, usually limestone or lime, or seawater to scrub gases;
- Spray-dry scrubbing using similar sorbent slurries;
- Wet sulfuric acid process recovering sulfur in the form of commercial quality sulfuric acid;
- SNOX Flue gas desulfurization removes sulfur dioxide, nitrogen oxides and particulates from flue gases;
- Dry sorbent injection systems.

For a typical coal-fired power station, FGD will remove 95 percent or more of the SO_2 in the flue gases.

History

Methods of removing sulfur dioxide from boiler and furnace exhaust gases have been studied for over 150 years. Early ideas for flue gas desulfurization were established in England around 1850.

With the construction of large scale power plants in England in the 1920s, the problems associated with large volumes of SO_2 from a single site began to concern the public. The SO_2 emissions problem did not receive much attention until 1929, when the House of Lords upheld the claim of a landowner against the Barton Electricity Works of the Manchester Corporation for damages to his land resulting from SO_2 emissions. Shortly thereafter, a press campaign was launched against the erection of power plants within the confines of London. This outcry led to the imposition of SO_2 controls on all such power plants.

The first major FGD unit at a utility was installed in 1931 at Battersea Station, owned by London Power Company. In 1935, an FGD system similar to that installed at Battersea went into service at Swansea Power Station. The third major FGD system was installed in 1938 at Fulham Power Station. These three early large-scale FGD installations were abandoned during World War II. Large-scale FGD units did not reappear at utilities until the 1970s, where most of the installations occurred in the United States and Japan.

As of June 1973, there were 42 FGD units in operation, 36 in Japan and 6 in the United States, ranging in capacity from 5 MW to 250 MW. As of around 1999 and 2000, FGD units were being used in 27 countries, and there were 678 FGD units operating at a total power plant capacity of about 229 gigawatts. About 45% of the FGD capacity was in the U.S., 24% in Germany, 11% in Japan, and 20% in various other countries. Approximately 79% of the units, representing about 199 gigawatts of capacity, were using lime or limestone wet scrubbing. About 18% (or 25 gigawatts) utilized spray-dry scrubbers or sorbent injection systems.

Sulfuric acid mist formation

Fossil fuels such as coal and oil contain a significant amount of sulfur. When fossil fuels are burned, about 95 percent or more of the sulfur is generally converted to sulfur dioxide (SO_2). Such conversion happens under normal conditions of temperature and of oxygen present in the flue gas. However, there are circumstances under which such reaction may not occur.

For example, when the flue gas has too much oxygen and the SO_2 is further oxidized to sulfur trioxide (SO_3). Actually, too much oxygen is only one of the ways that SO_3 is formed. Gas temperature is also an important factor. At about 800 °C, formation of SO_3 is favored. Another way that SO_3 can be formed is through catalysis by metals in the fuel. Such reaction is particularly true for heavy fuel oil, where a significant amount of vanadium is present. In whatever way SO_3 is formed, it does not behave like SO_2 in that it forms a liquid aerosol known as sulfuric acid (H_2SO_4) mist that is very difficult to remove. Generally, about 1% of the sulfur dioxide will be converted to SO_3. Sulfuric acid mist is often the cause of the blue haze that often appears as the flue gas plume dissipates. Increasingly, this problem is being addressed by the use of wet electrostatic precipitators.

FGD chemistry

Basic principles

Most FGD systems employ two stages: one for fly ash removal and the other for SO_2 removal. Attempts have been made to remove both the fly ash and SO_2 in one scrubbing vessel. However, these systems experienced severe maintenance problems and low removal efficiency. In wet scrubbing systems, the flue gas normally passes first through a fly ash removal device, either an electrostatic precipitator or a wet scrubber, and then into the SO_2 absorber. However, in dry injection or spray drying operations, the SO_2 is first reacted with the sorbent and then the flue gas passes through a particulate control device.

Another important design consideration associated with wet FGD systems is that the flue gas exiting the absorber is saturated with water and still contains some SO_2. These gases are highly corrosive to any downstream equipment such as fans, ducts, and stacks. Two methods that can minimize corrosion are: (1) reheating the gases to above their dew point, or (2) choosing construction materials and design conditions that allow equipment to withstand the corrosive conditions. Both alternatives are expensive, and engineers designing the system determine which method to use on a site-by-site basis.

Scrubbing with a basic solid or solution
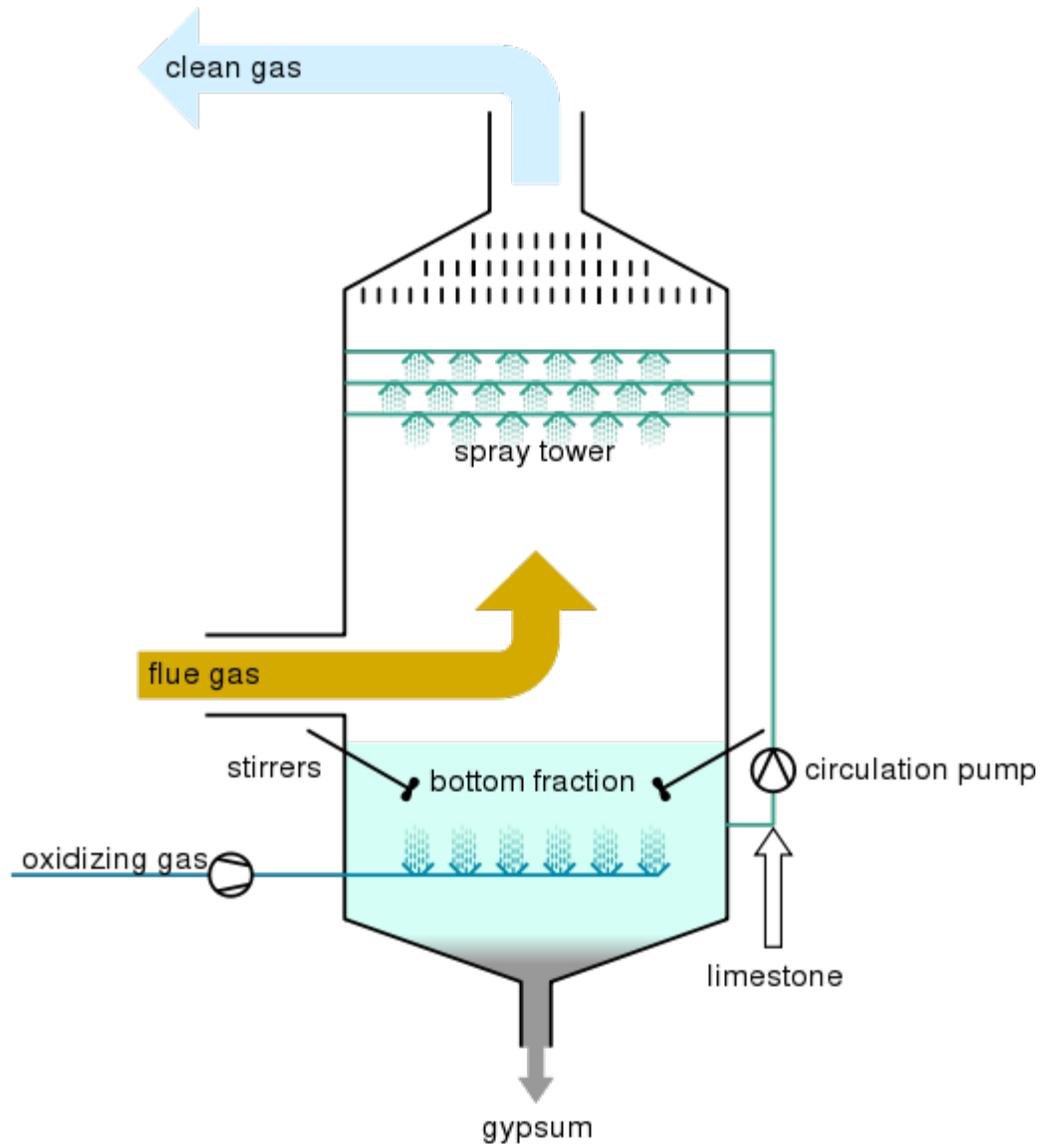
Schematic design of the absorber of an FGD

SO_2 is an acid gas and thus the typical sorbent slurries or other materials used to remove the SO_2 from the flue gases are alkaline. The reaction taking place in wet scrubbing using a $CaCO_3$ (limestone) slurry produces $CaSO_3$ (calcium sulfite) and can be expressed as:

$CaCO_3$ (solid) + SO_2 (gas) → $CaSO_3$ (solid) + CO_2 (gas)
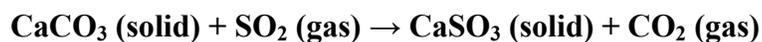
When wet scrubbing with a $Ca(OH)_2$ (lime) slurry, the reaction also produces $CaSO_3$ (calcium sulfite) and can be expressed as:

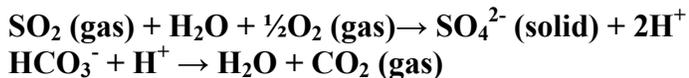**$Ca(OH)_2$ (solid) + SO_2 (gas) → $CaSO_3$ (solid) + H_2O (liquid)**
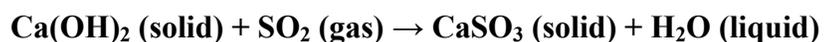
When wet scrubbing with a $Mg(OH)_2$ (magnesium hydroxide) slurry, the reaction produces $MgSO_3$ (magnesium sulfite) and can be expressed as:

$$Mg(OH)_2 \text{ (solid)} + SO_2 \text{ (gas)} \rightarrow MgSO_3 \text{ (solid)} + H_2O \text{ (liquid)}$$

To partially offset the cost of the FGD installation, in some designs, the $CaSO_3$ (calcium sulfite) is further oxidized to produce marketable $CaSO_4 \cdot 2H_2O$ (gypsum). This technique is also known as **forced oxidation**:

$$CaSO_3 \text{ (solid)} + H_2O \text{ (liquid)} + \tfrac{1}{2}O_2 \text{ (gas)} \rightarrow CaSO_4 \text{ (solid)} + H_2O$$
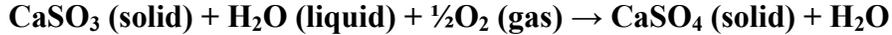
A natural alkaline usable to absorb SO_2 is seawater. The SO_2 is absorbed in the water, and when oxygen is added reacts to form sulfate ions SO_4- and free H^+. The surplus of H^+ is offset by the carbonates in seawater pushing the carbonate equilibrium to release CO_2 gas:

$$SO_2 \text{ (gas)} + H_2O + \tfrac{1}{2}O_2 \text{ (gas)} \rightarrow SO_4^{2-} \text{ (solid)} + 2H^+$$
$$HCO_3^- + H^+ \rightarrow H_2O + CO_2 \text{ (gas)}$$

Types of wet scrubbers used in FGD

To promote maximum gas-liquid surface area and residence time, a number of wet scrubber designs have been used, including spray towers, venturis, plate towers, and mobile packed beds. Because of scale buildup, plugging, or erosion, which affect FGD dependability and absorber efficiency, the trend is to use simple scrubbers such as spray towers instead of more complicated ones. The configuration of the tower may be vertical or horizontal, and flue gas can flow cocurrently, countercurrently, or crosscurrently with respect to the liquid. The chief drawback of spray towers is that they require a higher liquid-to-gas ratio requirement for equivalent SO2 removal than other absorber designs.v

Mobile-bed scrubbers

Venturi-rod scrubbers

A venturi scrubber is a converging/diverging section of duct. The converging section accelerates the gas stream to high velocity. When the liquid stream is injected at the throat, which is the point of maximum velocity, the turbulence caused by the high gas velocity atomizes the liquid into small droplets, which creates the surface area necessary for mass transfer to take place. The higher the pressure drop in the venturi, the smaller the droplets and the higher the surface area. The penalty is in power consumption.

For simultaneous removal of SO_2 and fly ash, venturi scrubbers can be used. In fact, many of the industrial sodium-based throwaway systems are venturi scrubbers originally designed to remove particulate matter. These units were slightly modified to inject a sodium-based scrubbing liquor. Although removal of both particles and SO_2 in one vessel can be economic, the problems of high pressure drops and finding a scrubbing medium to

remove heavy loadings of fly ash must be considered. However, in cases where the particle concentration is low, such as from oil-fired units, it can be more effective to remove particulate and SO_2 simultaneously.

Plate towers

Packed bed scrubbers

A packed scrubber consists of a tower with packing material inside. This packing material can be in the shape of saddles, rings, or some highly specialized shapes designed to maximize contact area between the dirty gas and liquid. Packed towers typically operate at much lower pressure drops than venturi scrubbers and are therefore cheaper to operate. They also typically offer higher SO_2 removal efficiency. The drawback is that they have a greater tendency to plug up if particles are present in excess in the exhaust air stream.

Spray towers

A spray tower is the simplest type of scrubber. It consists of a tower with spray nozzles, which generate the droplets for surface contact. Spray towers are typically used when circulating a slurry (see below). The high speed of a venturi would cause erosion problems, while a packed tower would plug up if it tried to circulate a slurry.

Counter-current packed towers are infrequently used because they have a tendency to become plugged by collected particles or to scale when lime or limestone scrubbing slurries are used.

Scrubbing reagent

As explained above, alkaline sorbents are used for scrubbing flue gases to remove SO_2. Depending on the application, the two most important are lime and sodium hydroxide (also known as caustic soda). Lime is typically used on large coal or oil fired boilers as found in power plants, as it is very much less expensive than caustic soda. The problem is that it results in a slurry being circulated through the scrubber instead of a solution. This makes it harder on the equipment. A spray tower is typically used for this application. The use of lime results in a slurry of calcium sulfite ($CaSO_3$) that must be disposed of. Fortunately, calcium sulfite can be oxidized to produce by-product gypsum ($CaSO_4 \cdot 2H_2O$) which is marketable for use in the building products industry.

Caustic soda is limited to smaller combustion units because it is more expensive than lime, but it has the advantage that it forms a solution rather than a slurry. This makes it easier to operate. It produces a "spent_caustic" solution of sodium sulfite/bisulfite (depending on the pH), or sodium sulfate that must be disposed of. This is not a problem in a kraft pulp mill for example, where this can be a source of makeup chemicals to the recovery cycle.

Scrubbing with sodium sulfite solution

It is possible to scrub sulfur dioxide by using a cold solution of sodium sulfite, this forms a sodium hydrogen sulfite solution. By heating this solution it is possible to reverse the reaction to form sulfur dioxide and the sodium sulfite solution.

In some ways this can be thought of as being similar to the reversible liquid-liquid extraction of an inert gas such as xenon or radon (or some other solute which does not undergo a chemical change during the extraction) from water to another phase. While a chemical change does occur during the extraction of the sulfur dioxide from the gas mixture, it is the case that the extraction equilibrium is shifted by changing the temperature rather than by the use of a chemical reagent.

Gas phase oxidation followed by reaction with ammonia

A new, emerging flue gas desulfurization technology has been described by the IAEA. It is a radiation technology where an intense beam of electrons is fired into the flue gas at the same time as ammonia is added to the gas. The Chendu power plant in China started up such a flue gas desulfurization unit on a 100 MW scale in 1998. The Pomorzany power plant in Poland also started up a similar sized unit in 2003 and that plant removes both sulfur and nitrogen oxides. Both plants are reported to be operating successfully. However, the accelerator design principles and manufacturing quality need further improvement for continuous operation in industrial conditions.

No radioactivity is required or created in the process. The electron beam is generated by a device similar to the electron gun in a TV set. This device is called an accelerator. This is an example of a radiation chemistry process where the physical effects of radiation are used to process a substance.

The action of the electron beam is to promote the oxidation of sulfur dioxide to sulfur(VI) compounds. The ammonia reacts with the sulfur compounds thus formed to produce ammonium sulfate, which can be used as a nitrogenous fertilizer. In addition, it can be used to lower the nitrogen oxide content of the flue gas. This method has attained industrial plant scale.

Facts and statistics

Flue gas desulfurization scrubbers have been applied to combustion units firing coal and oil that range in size from 5 MW to 1500 MW. Scottish Power are spending £400 million installing FGD at Longannet power station which has a capacity of over 2 GW. Dry scrubbers and spray scrubbers have generally been applied to units smaller than 300 MW.

Approximately 85% of the flue gas desulfurization units installed in the US are wet scrubbers, 12% are spray dry systems and 3% are dry injection systems.

The highest SO_2 removal efficiencies (greater than 90%) are achieved by wet scrubbers and the lowest (less than 80%) by dry scrubbers. However, the newer designs for dry scrubbers are capable of achieving efficiencies in the order of 90%.

In spray drying and dry injection systems, the flue gas must first be cooled to about 10-20 °C above adiabatic saturation to avoid wet solids deposition on downstream equipment and plugging of baghouses.

The capital, operating and maintenance costs per short ton of SO_2 removed (in 2001 US dollars) are:

- For wet scrubbers larger than 400 MW, the cost is $200 to $500 per ton
- For wet scrubbers smaller than 400 MW, the cost is $500 to $5,000 per ton
- For spray dry scrubbers larger than 200 MW, the cost is $150 to $300 per ton
- For spray dry scrubbers smaller than 200 MW, the cost is $500 to $4,000 per ton

Alternative methods of reducing sulfur dioxide emissions

An alternative to removing sulfur from the flue gases after burning is to remove the sulfur from the fuel before or during combustion. Hydrodesulfurization of fuel has been used for treating fuel oils before use. Fluidized bed combustion adds lime to the fuel during combustion. The lime reacts with the SO_2 to form sulfates which become part of the ash.

Chapter- 9

Gas Flare

Gas flare at Star Refinery, Map Ta Phut, Thailand

Biogas holder with lightning protection rods and back-up gas vent stack

A gas flare at an oil refinery.

A **gas flare**, alternatively known as a **flare stack**, is an elevated vertical conveyance found accompanying the presence of oil wells, gas wells, rigs, refineries, chemical plants, natural gas plants, and landfills. They are used to eliminate waste gas which is otherwise not feasible to use or transport. They also act as safety systems for non-waste gas and is

released via pressure relief valve when needed to ease the strain on equipment. They protect gas processing equipments from being overpressured. Also in case of an emergency situation, the flare system helps burn out the total reserve gas.

Function

On oil production rigs, in refineries and chemical plants, its primary purpose is to act as a safety device to protect vessels or pipes from over-pressuring due to unplanned upsets. This acts just like the spout on a tea kettle when it starts whistling as the water in it starts boiling. Whenever plant equipment items are over-pressured, the pressure relief valves on the equipment automatically release gases (and sometimes liquids as well) which are routed through large piping runs called **flare headers** to the flare stacks. The released gases and/or liquids are burned as they exit the flare stacks. The size and brightness of the resulting flame depends upon how much flammable material was released. Steam can be injected into the flame to reduce the formation of black smoke. The injected steam does however make the burning of gas sound louder, which can cause complaints from nearby residents. Compared to the emission of black smoke, it can be seen as a valid trade off. In more advanced flare tip designs, if the steam used is too wet it can freeze just below the tip, disrupting operations and causing the formation of large icicles. In order to keep the flare system functional, a small amount of gas is continuously burned, like a pilot light, so that the system is always ready for its primary purpose as an over-pressure safety system. The continuous gas source also helps diluted mixtures achieve complete combustion. Enclosed ground flares are engineered to eliminate smoke, and contain the flame within the stack.

Climatic effects

Flaring and venting of natural gas from oil & gas wells is a significant source of greenhouse gas emissions. Its contribution to greenhouse gases has declined by three-quarters in absolute terms since a peak in the 1970s of approximately 110 million metric tons/year and now accounts for 0.5% of all anthropogenic carbon dioxide emissions.

Recently, under the Kyoto Protocol, garbage collecting companies in some developing nations have received a carbon bonus for installing combustion devices for the methane gas produced at their landfills, preventing methane from reaching the atmosphere. After the burning, this gas is converted to heat, water and CO_2, and according to the Third assessment report of the IPCC, as Methane is 23 times more powerful a greenhouse gas than CO_2 the greenhouse effect is reduced in the same order.

Volume

The World Bank estimates that over 150 billion cubic metres of natural gas are flared or vented annually, an amount worth approximately 30.6 billion dollars, equivalent to 25 percent of the United States' gas consumption or 30 percent of the European Union's gas consumption per year.

This flaring is highly concentrated: 10 countries account for 75% of emissions, and twenty for 90%. The largest flaring operations occur in the Niger Delta region of Nigeria. The leading contributors to gas flaring are (in declining order): Nigeria, Russia, Iran, Algeria, Mexico, Venezuela, Indonesia, and the United States. In spite of a ruling by the Federal High Court of Nigeria (that forbade flaring) in 2005, 43% of the gas retrieval was still being flared in 2006. It will be prohibited by law as of 2008.

Russian flaring

Russia has announced it will stop the practice of **gas flaring** as stated by deputy prime minister Sergei Ivanov on Wednesday September 19, 2007. This step was, at least in part, a response to a recent report by the National Oceanic and Atmospheric Administration (NOAA) that concluded Russia's previous numbers may have been underestimated. The report, which used night time light pollution satellite imagery to estimate flaring, put the estimate for Russia at 50 billion cubic meters while the official numbers are 15 or 20 billion cubic meters. The number for Nigeria is 23 billion cubic meters.
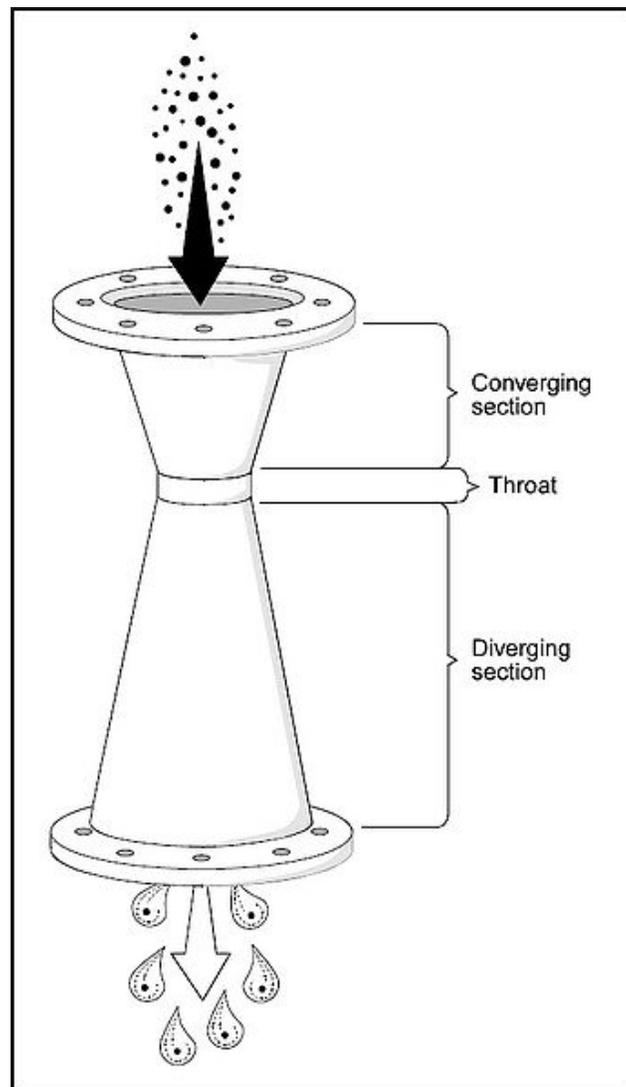
Chapter- 10

Venturi Scrubber

Figure 1 - Venturi scrubber

A **venturi scrubber** is designed to effectively use the energy from the inlet gas stream to atomize the liquid being used to scrub the gas stream. This type of technology is a part of the group of air pollution controls collectively referred to as wet scrubbers.

Venturi devices have also been used for over 100 years to measure fluid flow (Venturi tubes derived their name from Giovanni Battista Venturi, an Italian physicist).

About 35 years ago, *Johnstone (1949)* and other researchers found that they could effectively use the venturi configuration to remove particles from gas streams. **Figure 1** illustrates the classic venturi configuration.

A venturi scrubber consists of three sections: a converging section, a throat section, and a diverging section. The inlet gas stream enters the converging section and, as the area decreases, gas velocity increases (in accordance with the Bernoulli equation). Liquid is introduced either at the throat or at the entrance to the converging section.

The inlet gas, forced to move at extremely high velocities in the small throat section, shears the liquid from its walls, producing an enormous number of very tiny droplets.

Particle and gas removal occur in the throat section as the inlet gas stream mixes with the fog of tiny liquid droplets. The inlet stream then exits through the diverging section, where it is forced to slow down.

Venturis can be used to collect both particulate and gaseous pollutants, but they are more effective in removing particles than gaseous pollutants.
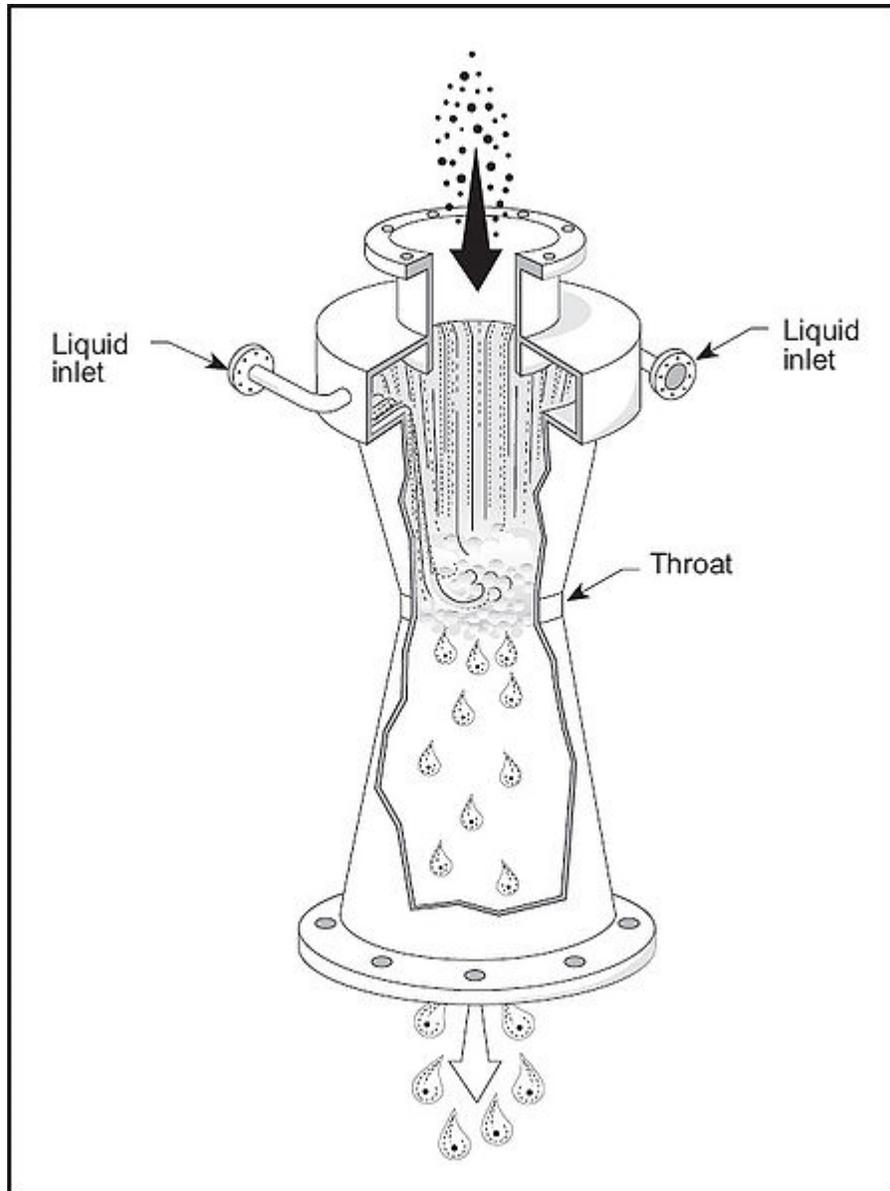
Figure 2 - Wetted throat venturi scrubber

Liquid can be injected at the converging section or at the throat. **Figure 2** shows liquid injected at the converging section. Thus, the liquid coats the venturi throat making it very effective for handling hot, dry inlet gas that contains dust. Otherwise, the dust would have a tendency to cake on or abrade a dry throat. These venturis are sometimes referred to as having a wetted approach.

Figure 3 shows liquid injected at the venturi throat. Since it is sprayed at or just before the throat, it does not actually coat the throat surface. These throats are susceptible to solids buildup when the throat is dry. They are also susceptible to abrasion by dust particles. These venturis are best used when the inlet stream is cool and moist. These venturis are referred to as having a non-wetted approach.

Venturis with round throats (**Figures 2** and **3**) can handle inlet flows as large as 88,000 m³/h (40,000 cfm) (*Brady and Legatski 1977*). At inlet flow rates greater than this, achieving uniform liquid distribution is difficult, unless additional weirs or baffles are used. To handle large inlet flows, scrubbers designed with long, narrow, rectangular throats (**Figure 4**) have been used.
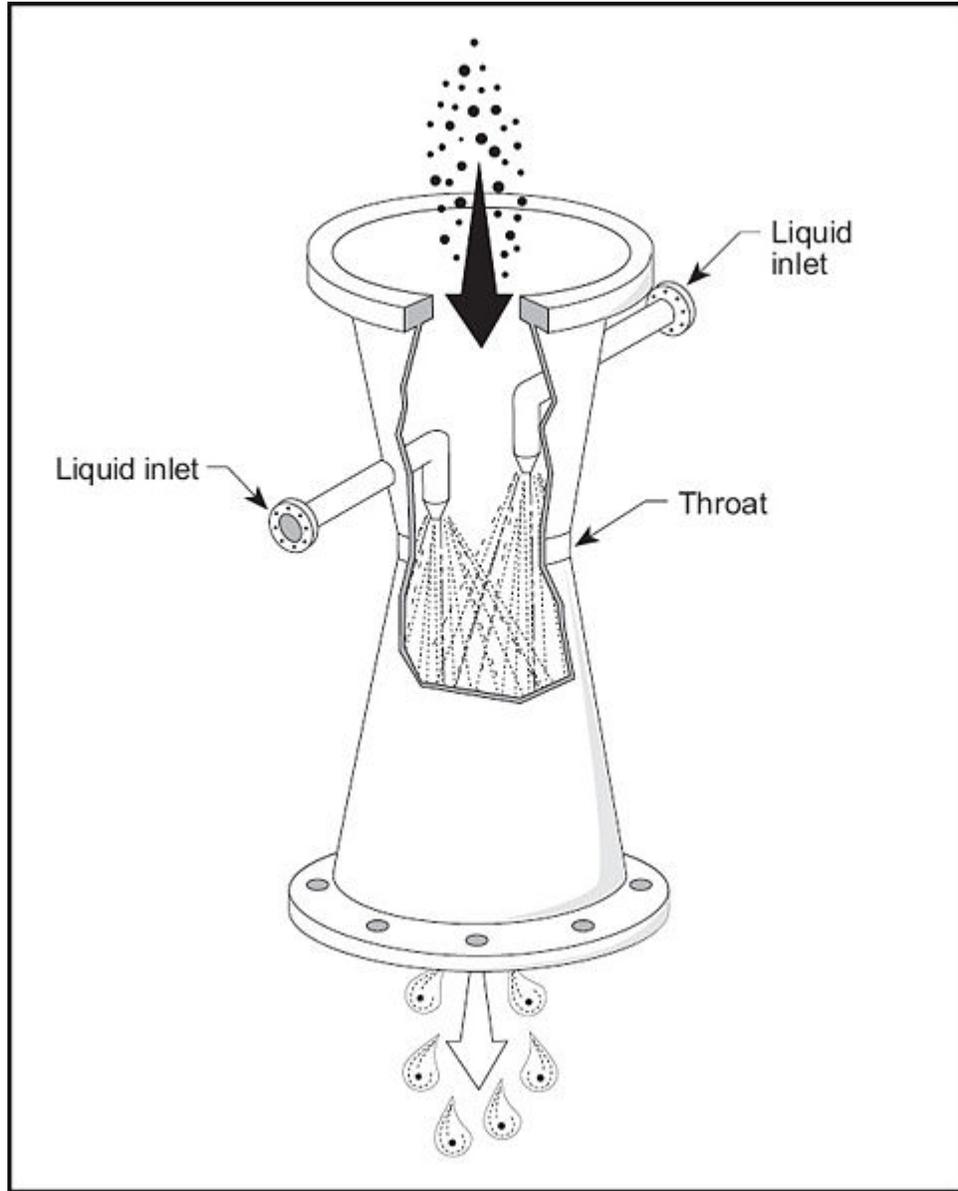

Figure 3 - Non-wetted throat venturi scrubber

Simple venturis have fixed throat areas and cannot be used over a wide range of gas flow rates. Manufacturers have developed other modifications to the basic venturi design to maintain scrubber efficiency by changing the throat area for varying inlet gas rates.

Certain types of orifices (throat areas) that create more turbulence than a true venturi were found to be equally efficient for a given unit of energy consumed (*McIlvaine Company 1974*).

Results of these findings led to the development of the annular-orifice, or adjustable-throat, venturi scrubber (**Figure 5**). The size of the throat area is varied by moving a plunger, or adjustable disk, up or down in the throat, thereby decreasing or increasing the annular opening. Gas flows through the annular opening and atomizes liquid that is sprayed onto the plunger or swirled in from the top.

Another adjustable-throat venturi is shown in **Figure 6**. In this scrubber, the throat area is varied by using a movable plate. A water-wash spray is used to continually wash collected material from the plate.

Another modification can be seen in the venturi-rod or rod deck scrubber. By placing a number of pipes parallel to each other, a series of longitudinal venturi openings can be created as shown in **Figure 7**. The area between adjacent rods is a small venturi throat.
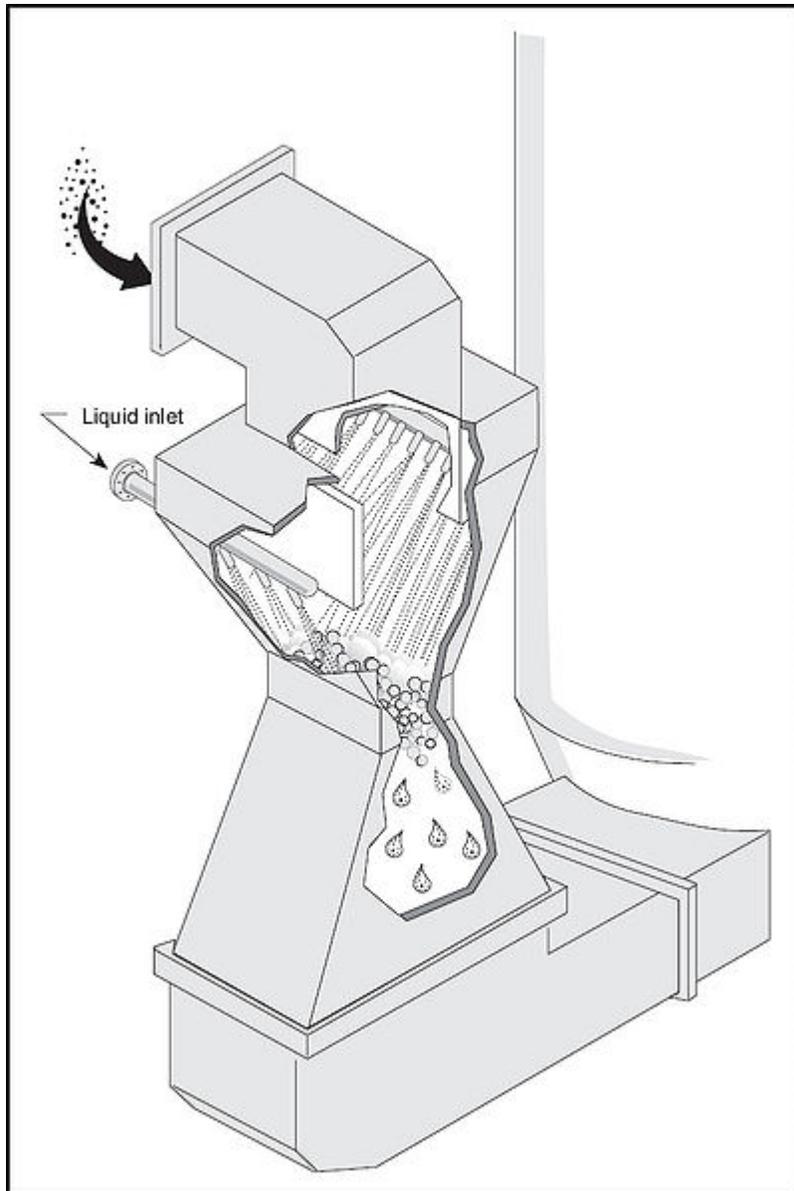
Figure 4 - Rectangular throat venturi scrubber

Water sprays help prevent solids buildup. The principal atomization of the liquid occurs at the rods, where the high-velocity gas moving through spacings creates the small droplets necessary for fine particle collection. These rods must be made of abrasion-resistant material due to the high velocities present.

All venturi scrubbers require an entrainment separator because the high velocity of gas through the scrubber will have a tendency to entrain the droplets with the outlet clean gas stream.

Cyclonic, mesh-pad, and blade separators are all used to remove liquid droplets from the flue gas and return the liquid to the scrubber water. Cyclonic separators, the most popular

for use with venturi scrubbers, are connected to the venturi vessel by a flooded elbow (**Figure 8**). The liquid reduces abrasion of the elbow as the outlet gas flows at high velocities from the venturi into the separator.
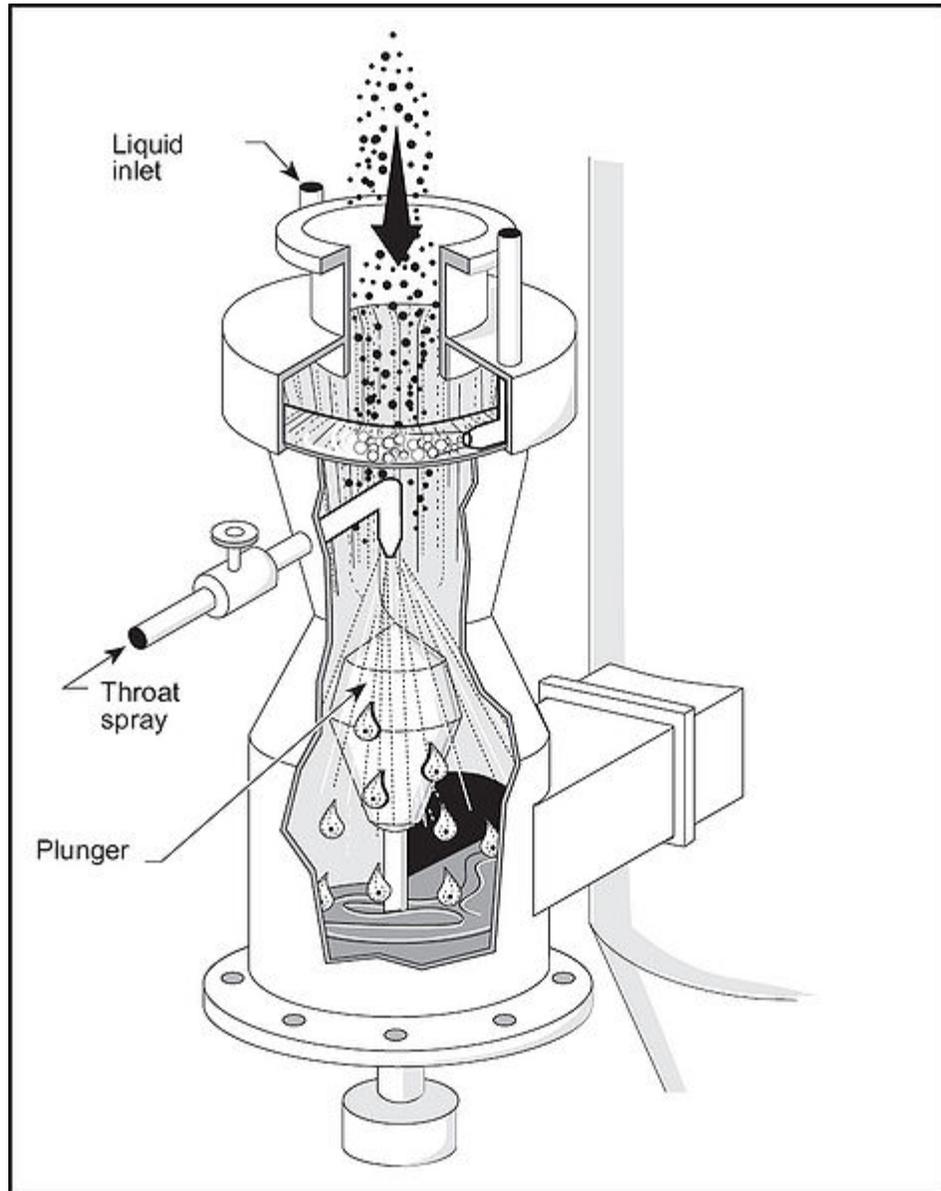
Particle collection

Figure 5 - Adjustable-throat venturi scrubber with plunger

Venturis are the most commonly used scrubber for particle collection and are capable of achieving the highest particle collection efficiency of any wet scrubbing system. As the inlet stream enters the throat, its velocity increases greatly, atomizing and turbulently mixing with any liquid present.

The atomized liquid provides an enormous number of tiny droplets for the dust particles to impact on. These liquid droplets incorporating the particles must be removed from the scrubber outlet stream, generally by cyclonic separators.

Particle removal efficiency increases with increasing pressure drop because of increased turbulence due to high gas velocity in the throat. Venturis can be operated with pressure drops ranging from 12 to 250 cm (5 to 100 in) of water.

Most venturis normally operate with pressure drops in the range of 50 to 150 cm (20 to 60 in) of water. At these pressure drops, the gas velocity in the throat section is usually between 30 and 120 m/s (100 to 400 ft/s), or approximately 270 mph at the high end. These high pressure drops result in high operating costs.

The liquid-injection rate, or liquid-to-gas ratio (L/G), also affects particle collection. The proper amount of liquid must be injected to provide adequate liquid coverage over the throat area and make up for any evaporation losses. If there is insufficient liquid, then there will not be enough liquid targets to provide the required capture efficiency.

Most venturi systems operate with an L/G ratio of 0.4 to 1.3 l/m^3 (3 to 10 gal/1000 ft^3) (*Brady and Legatski 1977*). L/G ratios less than 0.4 l/m^3 (3 gal/1000 ft^3) are usually not sufficient to cover the throat, and adding more than 1.3 l/m^3 (10 gal/1000 ft^3) does not usually significantly improve particle collection efficiency.
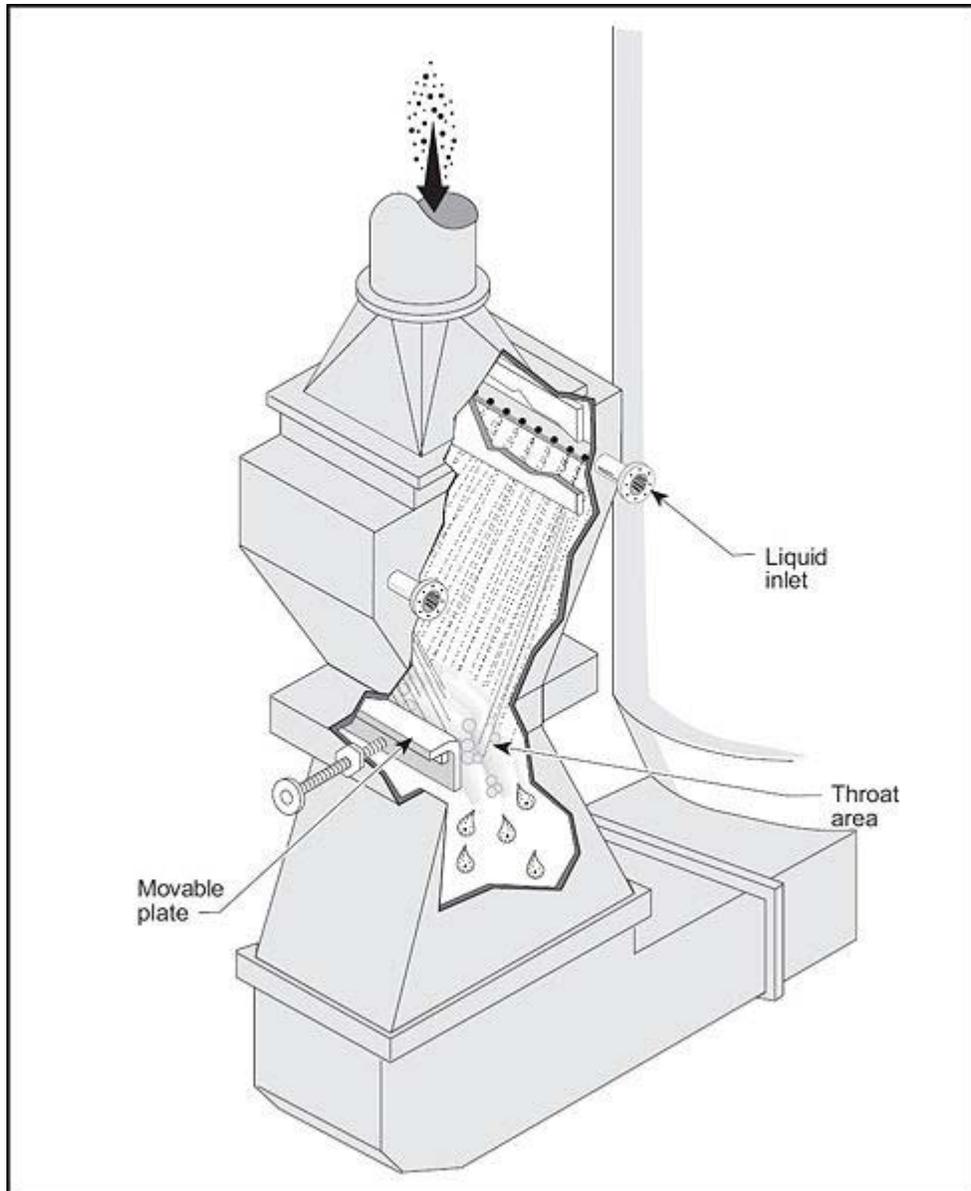
Gas collection

Figure 6 - Adjustable-throat venturi scrubber with movable plate

Venturi scrubbers can be used for removing gaseous pollutants; however, they are not used when removal of gaseous pollutants is the only concern.

The high inlet gas velocities in a venturi scrubber result in a very short contact time between the liquid and gas phases. This short contact time limits gas absorption. However, because venturis have a relatively open design compared to other scrubbers, they are very useful for simultaneous gaseous and particulate pollutant removal, especially when:

- Scaling could be a problem
- A high concentration of dust is in the inlet stream

- The dust is sticky or has a tendency to plug openings
- The gaseous contaminant is very soluble or chemically reactive with the liquid

To maximize the absorption of gases, venturis are designed to operate at a different set of conditions from those used to collect particles. The gas velocities are lower and the liquid-to-gas ratios are higher for absorption.

For a given venturi design, if the gas velocity is decreased, then the pressure drop (resistance to flow) will also decrease and vice versa. Therefore, by reducing pressure drop, the gas velocity is decreased and the corresponding residence time is increased. Liquid-to-gas ratios for these gas absorption applications are approximately 2.7 to 5.3 l/m^3 (20 to 40 gal/1000 ft^3). The reduction in gas velocity allows for a longer contact time between phases and better absorption.

Increasing the liquid-to-gas ratio will increase the potential solubility of the pollutant in the liquid.

Though capable of some incidental control of volatile organic compounds (VOC), generally venturi scrubbers are limited to control PM (particulate matter) and high solubility gases (*EPA, 1992; EPA, 1996*).
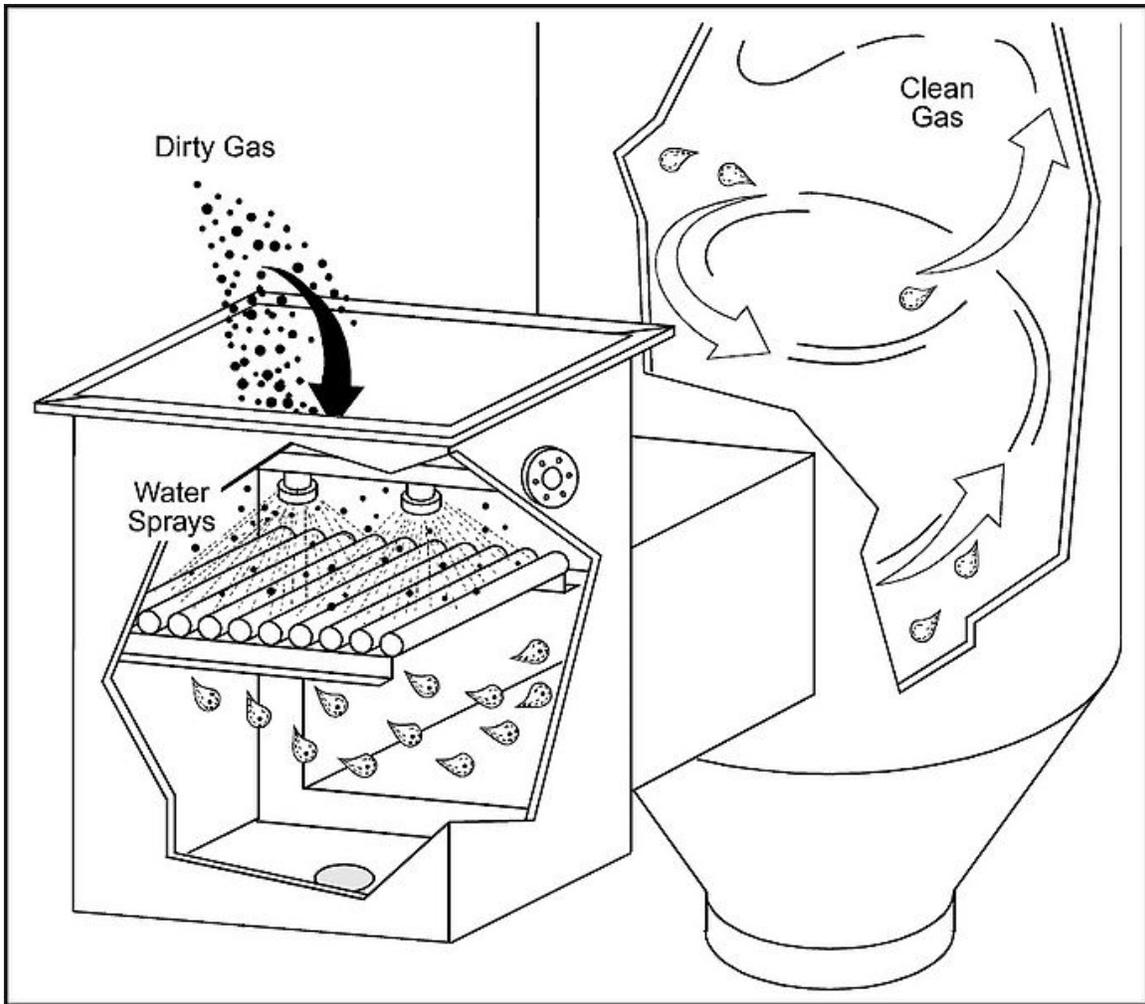
Maintenance problems

Figure 7 - Venturi rod scrubber

The primary maintenance problem for venturi scrubbers is wear, or abrasion, of the scrubber shell because of high gas velocities. Gas velocities in the throat can reach speeds of 430 km/h (270 mph). Particles and liquid droplets traveling at these speeds can rapidly erode the scrubber shell.

Abrasion can be reduced by lining the throat with silicon carbide brick or fitting it with a replaceable liner. Abrasion can also occur downstream of the throat section. To reduce abrasion here, the elbow at the bottom of the scrubber (leading into the separator) can be flooded (i.e. filled with a pool of scrubbing liquid). Particles and droplets impact on the pool of liquid, reducing wear on the scrubber shell.

Another technique to help reduce abrasion is to use a precleaner (i.e., quench sprays or cyclone) to remove the larger particles.

The method of liquid injection at the venturi throat can also cause problems. Spray nozzles are used for liquid distribution because they are more efficient (have a more

effective spray pattern) for liquid injection than weirs. However, spray nozzles can easily plug when liquid is recirculated. Automatic or manual reamers can be used to correct this problem. However, when heavy liquid slurries (either viscous or particle-loaded) are recirculated, open-weir injection is often necessary.
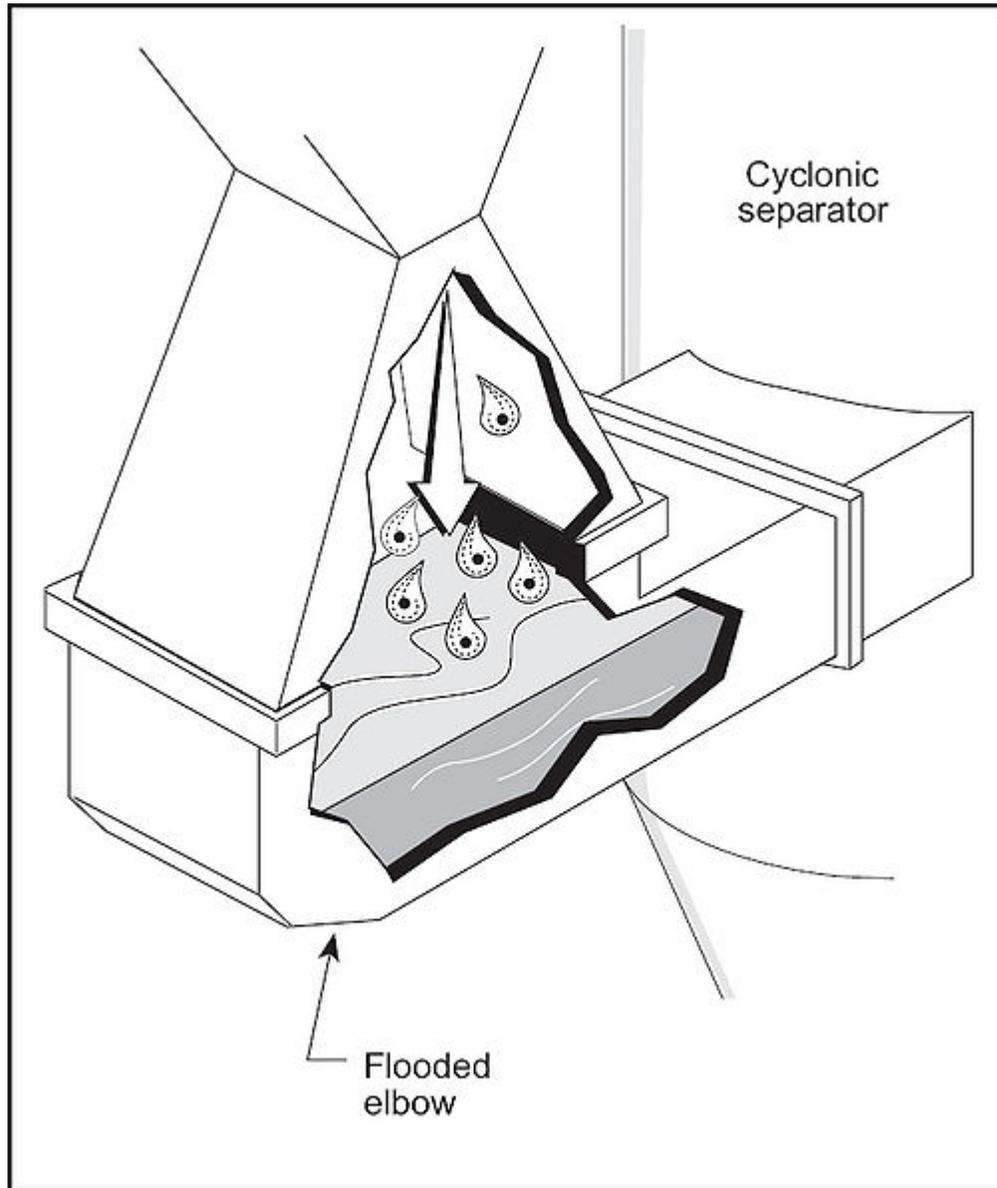
Summary

Figure 8 - Flooded elbow

Venturi scrubbers can have the highest particle collection efficiencies (especially for very small particles) of any wet scrubbing system.

They are the most widely used scrubbers because their open construction enables them to remove most particles without plugging or scaling. Venturis can also be used to absorb pollutant gases; however, they are not as efficient for this as are packed or plate towers.

Venturi scrubbers have been designed to collect particles at very high collection efficiencies, sometimes exceeding 99%. The ability of venturis to handle large inlet volumes at high temperatures makes them very attractive to many industries; consequently, they are used to reduce particulate emissions in a number of industrial applications.

This ability is particularly desirable for cement kiln emission reduction and for control of emissions from basic oxygen furnaces in the steel industry, where the inlet gas enters the scrubber at temperatures greater than 350 °C (660 °F).

Venturis are also used to control fly ash and sulfur dioxide emissions from industrial and utility boilers.
The operating characteristics of venturi scrubbers are listed in **Table 1**.

Table 1. Operating characteristics of venturi scrubbers

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p_L)	Removal efficiency
Gases	13-250 cm of water (5-100 in of water)	2.7-5.3 l/m^3 (20-40 gal/1,000 ft^3)		30-60% per venturi, depending on pollutant solubility
Particles	50-250 cm of water (50-150 cm of water is common) 20-100 in of water (20-60 in. of water is common)	0.67-1.34 l/m^3(5-10 gal/1,000 ft^3)	< 7-100 kPa (< 1-15 psig)	90-99% is typical