Wet scrubbers use a liquid to remove solid, liquid, or gaseous contaminants from a gas stream. The scrubbing liquid performs this separation by dissolving, trapping, or chemically reacting with the contaminant.

Scrubbers are used extensively to control air polluting emissions. So many different scrubber configurations have been used that there is some confusion as to whether they all belong in the same category. In some references, for example, the definition of a scrubber may be restricted to certain design criteria, such as whether the units are open or packed. In this text, any device fitting the definition of the first sentence is a wet scrubber.

Scrubber systems can be designed to remove entrained particulate materials such as dust, fly ash, or metal oxides, or to remove gases, such as oxides of sulfur (SO\textsubscript{x}), from a flue gas stream to meet air emission standards.

**PARTICLE COLLECTION CONCEPTS**

In scrubbing particulate matter from gases, the principal concern is usually removal of particles smaller than than 10 \(\mu\text{m}\). Larger particles are relatively easy to separate. The successful design and operation of wet scrubbers depends on knowing the size, composition, and derivation of the particles to be collected.

Figure 41.1 shows estimated size for some common pollutants. Just as fine particles in water (colloids) carry a charge of static electricity, so do colloidal particles in the fumes and dust, defined as aerosols. If these particles carry no charge, they may be deliberately charged to assist removal by special separators called electrostatic precipitators.

Among the particulates (term for the suspended solid materials) collected by wet scrubbers are dispersion aerosols from processes such as grinding, solid and liquid atomization, and transport of suspended powders by air currents or vibration. Dispersion aerosols are usually coarse and contain a wide range of particle sizes. Dispersion aerosols consisting of individual or slightly aggregated, irregularly formed particles are called dusts.

Condensation aerosols are formed when supersaturated vapors condense or when gases react chemically, forming a nonvolatile product. These aerosols are usually smaller than 1 \(\mu\text{m}\). In condensed aerosols, solid particles are often loose aggregates of a large number of primary particles of crystalline or spherical form. Condensation aerosols with a solid dispersed phase or a solid-liquid dispersion phase are classed as smokes or fumes. Aerosols which include a liquid dispersion...
Meters

FIG. 41.1 A comparison of the size of particles present in air emissions.

phase are called mists. This classification usually applies regardless of particle size, and differentiation is sometimes difficult.

In practice, a combination of dispersion and condensation aerosols is encountered. Different size particles behave differently because of such physical properties as light scattering, evaporation rates, and particle movement. The choice of the best device for particle removal from gas is affected by these differences. Particle sizes, volumes, and weights may be obtained by microscopic sizing and density estimation.

PARTICULATE EMISSIONS

Limits on particulate emissions (smoke, mist, dust) are usually established in four ways:

1. **Emission rate:** The maximum weight that can be legally emitted in pounds per hour (kg/h). This may be expressed as the rate for a specific industry in production terms, e.g., pounds per hour per ton (kg/h/kkg) of pulp.

2. **Maximum concentration:** Maximum amount of particulate matter in the gas stream released, e.g., g/m³, grains/cubic foot, or lb/1000 lb gas.

3. **Maximum opacity:** Maximum opacity of the gas stream emitted, usually measured by observation and comparison to empirical standards (Ringlemann numbers).

4. **Corrected emission rate.** Corrected emission rate is tied to an air quality standard by a formula based on atmospheric dispersion considerations.

Often, several particular emission regulations are enforced simultaneously. If all four types of restrictions are employed, a plant might pass on emission rate and concentration, but fail on opacity. This is an understandable situation, since large particles are the major contributors to weight while smaller particles, in the 0.1 to 2.0 μm range, are the major contributors to opacity.

The addition of chemical additives to the scrubber water to capture particles in the 0.1 to 2.0 μm range is often an economical way to meet air quality standards, particularly when compared to the cost of modifications and additions to equipment.
The wet scrubbers discussed in this chapter use water to remove particulates, gases, or both from industrial gas streams or stacks. Water chemistry is often extremely complicated in these scrubber systems because of the variety of operations occurring simultaneously in the scrubber environment.

1. **Heat transfer:** The gas and water are often at different temperatures, so heat will be transferred in the scrubbing process.

2. **Evaporation/condensation:** The gas may be hot and saturated with water vapor. Contact with colder water will dehumidify the gas, and the scrubbing water will be diluted with condensate. If the stack gas is hot and dry, the scrubber water will evaporate, as in a cooling tower, and become concentrated.

3. **Mass transfer:** The gas may contain water-soluble solids or gases that will dissolve in the scrubber water. The water may transfer gases to the gas stream also. For example, the water may be recycled over a cooling tower becoming saturated with O\(_2\) and N\(_2\), later releasing them to the gas stream.

4. **Scaling:** As the scrubber water is heated or increases in pH, alkalinity, or sulfate-sulfite content, precipitation of CaCO\(_3\), CaSO\(_4\), or CaSO\(_3\) may occur and the scrubber may become scaled.

5. **Corrosion:** A common and troublesome problem encountered in most wet scrubbers.

6. **Fouling:** Fouling may occur from the coagulation of the particulate being removed or from microbial activity. Many industrial gas streams contain organics that supply food to microbes.

**PRINCIPLES OF OPERATION**

Scrubber manufacturers offer a bewildering array of products. Scrubbers are available in a wide range of designs, sizes, and performance capabilities. Some are designed primarily for collection of particles and others for mass transfer (gas removal by a chemical reaction). As good liquid-gas contact is needed for both operations, all scrubbers can collect both particles and gases to some extent. The degree to which the particle collection and mass transfer characteristics of a scrubber can be utilized determines the applicability of the scrubber for each specific purification problem. Figure 41.2 shows the commonly accepted domain of wet
scrubbers, based on particle size, relative to other competitive devices. Figure 41.3 shows the relative particulate removal efficiency of the more common types.

Particle size is one of the most important factors affecting removal efficiency, larger particles being much more easily removed. Submicron particles (1 μm = 10⁻⁶ m) are the most difficult to remove.

All wet particle scrubbers operate on the same basic aerodynamic principle. A simple analogy: If water droplets of basketball size were projected to collide with gas-stream particles the size of BBs, the statistical chances of collision would be small. As the size of the droplets is reduced to more nearly the size of the particles, the chances of collision improve. Studies have shown that a surface film surrounding a water droplet has an approximate thickness of 1/200 of its diameter. A BB (the particle in flight) having a diameter less than 1/200 the diameter of the basketball will flow through the streamline film around the basketball without collision (Figure 41.4). But if the droplet were a baseball instead of basketball, collision would occur. A 0.5-μm fume particle requires water droplets smaller than 100 μm (200 × 0.5) for adequate collection. Efficient scrubbing, therefore, requires atomizing the liquid to a fineness related to particle size to afford maximum contact with the particles to be captured.

The probability of a droplet hitting the dust particles is proportional to the dust concentration; a ball would be less likely to hit a single BB than a swarm of them.
To equalize these factors, scrubbers are regulated as to the volume of gas to be scrubbed (measured by pressure drop of the gas stream), and water to be sprayed (measured by hydraulic pressure at the spray nozzles).

The scrubbing chamber's height and diameter are also tailored to the known characteristics of the gas.

**CATEGORIZING WET SCRUBBERS**

Wet scrubbers differ principally in their methods of effecting contact between the recirculating liquid and the gas stream. Techniques employed include injecting the liquid into collection chambers as a spray, flowing the liquid into chambers over weirs, bubbling gas through trays or beds containing the liquid, and atomization of the liquid by injection into a rapidly moving gas stream.

One way of categorizing wet scrubbers is by their energy requirements. Some require high energy to perform their task while others require very little. Generally speaking, low-energy scrubbers are used for removal of large particulate matter and gaseous contaminants. They rely on high liquid/gas ratios and contact time in the scrubber to increase removal efficiency. High-energy scrubbers are used for the removal of very small particulates (1 μm and less). They depend on high gas velocity for atomization to form small liquid droplets, with maximum impact between water droplets and particulate matter.

A second way of categorizing wet scrubbers is based on their selectivity toward either gaseous contaminants or particulate matter. Scrubbers designed primarily for removal of gas are called mass transfer scrubbers or gas absorbers; those designed for removal of particulate are called wet particle scrubbers.

**GAS ABSORPTION SCRUBBERS**

Gas absorbers, the first category, are designed to maximize contact time and surface area between the scrubbing liquid and the gas. This provides maximum opportunity for liquid/gas chemical reactions to occur. Absorption scrubbers usually have low energy requirements. The types most commonly used are the packed bed, moving bed, impingement, and plate-type scrubbers. Although wet particle scrubbers will also provide mass transfer removal of some gases, these four types of absorption scrubbers will do the job more completely and with greater efficiency.

Mass transfer (gas absorption) reactions require long residence times because the contaminants must first be absorbed by the scrubbing liquor and then react chemically to form a product that remains in the liquid phase.

**PACKED TOWER**

The packed tower (packed bed) consists of a vertical vessel containing packing materials such as rings, saddles, or tellerettes (Figure 41.5). Water is sprayed across the top of the bed and trickles through the packing material. Gas enters
near the bottom and contaminants are removed as the gas stream moves upward through the water-washed packing.

The cleaned gas stream passes through a mist eliminator near the top where entrained moisture is removed prior to discharge. Scrubbing liquor is collected at the bottom. A portion is usually recycled to the inlet, and the balance discharged to the sewer.

Although flows can also be cocurrent or crosscurrent, the countercurrent type is most widely used. Packed beds have long been used for gas absorption operations because they are able to reduce odor and pollutant gases to low residual concentrations. The limiting factor is economics. As better separation is called for, beds require greater packing depth and operate with higher pressure drops. Gases entering a packed bed should not be heavily laden with solid particles as these cause clogging of the packing material. Pressure drop is typically 0.5 in of H$_2$O per foot of packing (4 cm H$_2$O/m).

Typical applications include rendering plants, food-processing plants, sewage treatment plants, and metal pickling plants.

**MOVING BED SCRUBBERS**

The moving bed wet scrubbers are well suited for high heat transfer and mass transfer rates (Figure 41.6). They are able to handle viscous liquids and heavy slurries without plugging. They accomplish this by using lightweight sphere packing that is free to move between upper and lower retaining grids. Countercurrent gas and liquid flows cause the spheres to move in a random, turbulent motion, causing intimate mixing of the liquid and gas.

In addition to excellent gas/liquid contact, the turbulence provides continuous cleaning of the moving spheres to minimize plugging or channeling of the bed.
Moving bed scrubbers are useful for absorbing gas and removing particulates simultaneously. This type of scrubber is especially suited for use with gases containing viscous or gummy substances, which would result in plugging of conventional packed bed scrubbers.

Efficiency is good for collection of particles larger than 1 \( \mu m \). Both particle collection and gas absorption efficiency may be increased by employing several stages in series. Pressure drop is typically 0.2 to 0.5 in \( H_2O \) per stage.

**TURBULENT CONTACT ABSORBER (TCA)**

The turbulent contact absorber was developed as an extension of the moving bed scrubber, the difference being the increased turbulence of the TCA unit, resulting from using fewer spheres per unit volume. The TCA enhances the beneficial characteristics of the moving bed scrubber and permits high liquid and gas flows.

**Plate Scrubbers**

A plate scrubber consists of a tower having plates (trays) mounted inside (Figure 41.7). Liquid introduced at the top flows successively across each plate as it moves downward. Gas passing upward through the openings in each plate mixes with the liquid flowing over it. The gas/liquid contact causes gas absorption or particle
FIG. 41.7 The plate scrubber provides intimate gas/liquid contact. The flat plates are kept relatively free of deposits in most applications by turbulence. (Courtesy of Koch Engineering Company, Inc.)

removal. A plate scrubber is named for the type of plates it contains: if the plates are sieves, it is called a sieve plate tower.

Impingement Scrubbers

In some designs, impingement baffles are placed a short distance above each perforation on a sieve plate to form an impingement plate to increase turbulence and enhance gas/particle/liquid interaction (Figure 41.8). The impingement baffles are below the liquid level. Pressure drop is about 1 to 2 in H₂O for each plate.

**WET PARTICLE SCRUBBERS**

The four basic factors determining the efficiency of wet particle scrubbers are:

1. Water surface area
2. Liquid/gas ratio
3. Particle size and scrubber energy
4. Particulate affinity for water (wettability)

Anything mechanical or chemical that causes the water spray nozzles to form smaller water droplets with a larger surface area increases the collision rate
between the particulate in the gas phase and the water, resulting in increased particulate removal.

The second way to increase the collision rate is to pump more water through the scrubber. Increasing the liquid/gas ratio is an inefficient means of increasing the surface area of water. Usually, it is more economical to increase the effective liquid/gas ratio by causing smaller droplets to form mechanically or chemically.

The force with which particulate matter strikes the water is a third factor in scrubber performance. Since a liquid film barrier separates particulate in the gas phase from the water, a particle must have enough energy to force its way into the water droplet to be captured. Smaller particles require more energy than larger ones because they have a lower mass and strike the barrier with less momentum than larger particles moving at the same velocity. So, higher energy is required for scrubbing small particles than for large particles.

A higher energy must also be expended to scrub a particle that is hydrophobic (repelled by water) than a similar size particle that is attracted to water—and most particulates in the gas stream are hydrophobic. Increasing the mechanical energy of a wet scrubber increases its ability to remove smaller, and more hydrophobic, particulates.

Another means for increasing the removal of these particles is chemical reduction of surface tension, increasing the wetting power of the water.
Either a high-energy or low-energy scrubber may be used for removal of particulates from gas streams, the choice depending on the size of the particles. Low-energy scrubbers, such as the spray tower and wet cyclone, may be used for particles over 5 μm. For particles smaller than 5 μm, a high-energy scrubber such as a venturi or a venturi ejector provides more complete removal. Many wet scrubbing systems, such as those cleaning steel mill blast furnace gas, employ a low-energy scrubber followed by a high-energy scrubber. The function of the low-energy scrubber is to cool the gas (reduce volume) and remove large particles, thereby reducing the load on the high-energy venturi scrubber. This also reduces the size and power of the induced draft fan, because the cooling effect reduces gas volume.

Spray Towers

The spray tower collects particles or gases on liquid droplets produced by spray nozzle atomization. The characteristics of the droplets are determined by the design of the nozzle. The sprays are directed into a chamber shaped to conduct the gas to the atomized droplets. Spray towers can be used for both mass transfer and particle collection. Their low pressure drop, 1 to 2 in H₂O, and high water rate make them the least expensive of the mass transfer scrubbers. Spray chambers are most applicable for removal of large particles, gas cooling, humidification or dehumidification, and the removal of gases with high liquid solubilities.

Wet Cyclones

Wet cyclone scrubbers (Figure 41.9) are effective for removing dusts and liquid aerosols. A finely atomized water spray contacts the gas stream, which enters tangentially at the bottom to pursue a spiral path upward. The atomized droplets are

![Diagram of wet cyclone scrubber](image-url)
caught in the spinning gas stream and swept by centrifugal force across to the walls of the cylinder, colliding with, absorbing, and collecting the dust or fume particles en route. The scrubbing liquid and particles drain down the wall to the bottom, and clean gas leaves through the top. The higher pressure drop, 6 to 8 in of H\textsubscript{2}O, increases energy costs over those for a spray tower.

**Venturi Scrubbers**

Venturi scrubbers (Figure 41.10) are best suited for removal of 0.05 to 5 \(\mu\)m particulates such as those created by condensation of a liquid or metallic vapor or by a chemical reaction forming a mist or fume. Typical examples are ammonium chloride fumes from steel galvanizing, phosphorus pentoxide fumes from phosphoric acid concentration, mists from dry ice plants, and zinc oxide fumes from reverberatory furnaces.

![Figure 41.10](image.png)

**FIG. 41.10** A venturi scrubber with a variable throat to accommodate changes in gas flow. *(Courtesy of FMC Corporation.)*

These aerosols are removed by passing the gas and water streams cocurrently through the extremely small throat section of a venturi. As the velocity is accelerated in the throat, the liquid breaks up into extremely fine drops. High gas velocities, ranging from 200 to 400 ft/s, make the relative velocity between gas and liquid high enough to cause good liquid atomization and particle collection.
The liquid drops collide with and remove the particles in the gas stream and the drops then agglomerate for separation from the gas. The cleaned gas stream then passes through a separator to eliminate entrained liquid.

Venturi scrubbers require high pressure drops (5 to 100 in H$_2$O). Pressure drop must be increased as the particle size becomes smaller to ensure adequate removal.

Venturi scrubbers can also be used for removing soluble gases. However, such applications are limited to situations where small particulates are also present, because the high energy requirements for operating venturi scrubbers make them costly for controlling gaseous pollutants.

Several modifications of the basic venturi scrubber are available to meet specific requirements of the size and type of particle to be removed. Low-, medium-, or high-energy venturi scrubbers are available, with energy requirements directly related to the pressure drop needed for removal of submicron particulates.

Many venturi scrubbers have a variable throat to allow for change in load. Also, at a fixed load, as the throat is decreased in size, velocity increases, resulting in increased pressure drop and better efficiency in removing submicron particles.

Venturi scrubbers use several methods to atomize the scrubbing water. In the most common, liquid is sprayed through jets across the venturi throat (Figure 41.10). This provides effective removal of submicron dust, fume, and mist particles, and is the first choice for the majority of applications. In another common venturi, the flooded-wall-type, the scrubbing liquid is introduced tangentially at the top, as shown in Figure 41.11. It spirals down the converging walls to the throat in a continuous film. At the entrance of the throat, it forms a curtain of liquid in the gas stream. The impaction of the gas into this curtain atomizes the liquid. Further impaction and agglomeration occur in the diverging section.

This type of venturi scrubber is recommended for hard-to-handle situations:

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**FIG. 41.11** In this venturi scrubber design, the water is atomized and it flows down a spiral path toward the venturi throat.
removal of "sticky" solids from gases; recycling of dirty water where water supplies are limited; and recovery of process materials in concentrated form.

Another common type is the flooded disk scrubber, in which liquid is introduced to a disk slightly upstream of the venturi throat. This liquid flows to the edge of the disk and is atomized by the high-velocity gas stream.

Figure 41.12 shows an ejector venturi which uses high-pressure spray nozzles to collect particulates, absorb gases, and move the gas. It derives its energy from the high-pressure liquid, while the regular venturi derives most of its energy from the high gas velocity produced by the induced draft fan. An induced draft fan may or may not be required, depending on the ejector venturi being used.

There is a high velocity difference between the liquid droplets and the gas; this affects particle separation. Collection efficiency is generally high for solid particles larger than 1 µm. Mass transfer is affected by the cocurrent flow of the gas-liquid. Energy consumption is relatively high because of pumping costs.

Ejector venturis may be used alone or as the first stage of a more complex system. The principal collection mechanism in this type of scrubber is inertial impaction, which is effected by liquid drops. Particle adherence upon striking the droplets is dependent upon the wettability of the particles. Because scrubbing liquid is usually recirculated, nozzles must be capable of handling a high solids concentration.

**WET ELECTROSTATIC PRECIPITATORS**

Water can also be used with electrostatic precipitation to improve removal of particulates. In this type of system, water is continually recirculated over the plates and discharged to an ash sluice pond or thickener to be clarified for reuse.

**WATERSIDE PROBLEMS**

Operating conditions in the scrubber may produce a severely corrosive or scaling water, depending on the gas stream being scrubbed and on the nature of any chemicals being added to the water. Many systems use lime/limestone slurries to react with SO$_2$, forming insoluble compounds to be removed in a thickener. The problems encountered in wet scrubber operation parallel those found in an open recirculating cooling water system, but the scrubber water is often more saline.
Chemical treatment programs for wet scrubber systems are designed to:

1. Maintain clean nozzles and collection surfaces, preventing deposit or scale buildup, thus helping to maintain unit efficiency.
2. Improve particulate capture or, for gas removal, mass transfer.
3. Control corrosion in the scrubber and recirculating water system.

Water problems in scrubbers range from scale and deposits to corrosion and waste disposal. Depending on the moisture level or dewpoint of the gas stream, gas cooling can result in evaporation or condensation, leading to concentration or dilution of scrubber water.

If the gas stream is above the dewpoint, recycling water for wet scrubbing results in evaporation and concentration of the scrubber water, adding to corrosion and scale problems inherent with the gases or particulates removed from the gas stream. However, in some systems the gas contains substantial water vapor, so condensation with resultant dilution of the recycle water may occur. This tends to lessen the potential for scale, deposits, and corrosion. Dilution is less common than concentration.

Each scrubbing system must be considered individually because of the wide variety of construction materials available, including mild and stainless steels, copper and nickel alloys, fiberglass, PVC, ceramics, lead, and refractories, to name a few. Many manufacturers construct scrubbers of alloyed metals and nonmetallic materials to avoid corrosion problems but still encounter the problems of scale and deposition. The same techniques and principles used for corrosion and deposit control in cooling systems apply to scrubbers.

Scrubber systems that operate under low pH conditions usually have deposits

### Table 41.1 Typical Deposit Analyses*

<table>
<thead>
<tr>
<th>Sugar mill scrubber supply line</th>
<th>Electric utility demister scrubber</th>
<th>Process scrubber—calcium carbide</th>
<th>Coke gas scrubber—calcium carbide</th>
<th>Blast furnace scrubber—return to furnace</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium (as CaO)</td>
<td>60</td>
<td>49</td>
<td>36.4</td>
<td>33</td>
</tr>
<tr>
<td>Iron (as Fe₂O₃)</td>
<td>1</td>
<td>2.6</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Carbonate (as CO₂)</td>
<td>2</td>
<td>16</td>
<td>0</td>
<td>21</td>
</tr>
<tr>
<td>Sulfur (as SO₂)</td>
<td>36</td>
<td>32</td>
<td>44</td>
<td>4</td>
</tr>
<tr>
<td>Silicon (as SiO₂)</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Aluminum (as Al₂O₃)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Chlorine (as Cl)</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Sodium (as Na₂O)</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Magnesium (as MgO)</td>
<td>0</td>
<td>0</td>
<td>58.5</td>
<td>5</td>
</tr>
<tr>
<td>Loss at 800°C</td>
<td>14</td>
<td>16</td>
<td>60</td>
<td>67</td>
</tr>
<tr>
<td>Carbon</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>62</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>0</td>
<td>0</td>
<td>19</td>
<td></td>
</tr>
</tbody>
</table>

* Inorganics in dried sample scaled to 100%.
+ All figures in %.
that are primarily particulates removed from the gas. Those systems that operate at a pH greater than 7.0 will normally yield scale deposits produced from water reactions, or scale and suspended solids combined.

However, even high-pH systems of this type will sometimes yield deposits that are primarily particulates removed from the gas. It is difficult to generalize regarding composition of deposits because of the wide variability of scrubber designs, process gases, and water characteristics. The most commonly encountered deposits are calcium carbonate, calcium sulfate, lime \([\text{Ca(OH)}_2]\), iron oxide, carbon black (soot), oils and greases, aluminosilicates (clays), and metal sulfides. Deposits, like corrosion, can plague virtually every section of the scrubber system—from the inlet gas ports to the induced draft fan and stack. Deposits usually form at the venturi throat, trays, and packing in gas absorbers, liquid recycle lines and pumps, mist eliminators, induced draft fans, and clarifier supply lines.

The deposit analyses shown in Table 41.1 illustrate the primary components of deposits removed from different types of scrubbers to illustrate the wide diversity from one industry to another. These analyses show that deposit compositions vary widely, with calcium occurring most frequently.

Chemical treatment for scale and deposit control is effective in controlling the majority of deposits, but it must be individualized for each scrubbing system owing to variation in deposition problems.

**Waste Treatment**

Since the basic function of the wet scrubber is to remove contaminants from process and combustion gases, once the scrubber liquid has done its job, the disposal of contaminants transferred to the water must be considered. For the small plant, this may entail merely discharging a bleed-off of recycle water to the sanitary sewer. The larger plant may be required to install an in-plant clarification system. There are two basic types: The first is the full-flow, inline clarifier which clarifies all scrubber water after it has made one pass through the scrubber. Water is recycled from the clarifier to the scrubber for further reuse. Problems are usually less severe with this type of unit because suspended solids are usually maintained at a fairly low level. This type of system is in many respects comparable to a once-through system.

The second basic type of clarifier is that used for clarification of a blowdown sidestream from the recycle system prior to discharge. Problems are normally more severe with this type of system.

Scrubbing liquid that contains high BOD, heavy metals, or toxic matter may require additional treatment, such as biological oxidation, prior to discharge.

**Auxiliary Equipment**

Although the wet scrubber is the heart of the gas cleaning system, auxiliary equipment is required to help the scrubber work efficiently. Auxiliary equipment may be categorized as follows:

1. *Dust catchers* remove gross solids to prevent overloading the scrubber.
2. *Gas quenchers* cool high-temperature (over 1000°F) gas and reduce evaporation in the scrubber.
3. **Entrainment separators** (demisters) reduce water droplets in the exit gas.
4. **Gas cooling towers** reduce plume discharge.
5. **Water cooling towers, cooling ponds, or spray ponds** facilitate optimum water recycle and minimize makeup.
6. **Induced draft fan** moves gas from the scrubber to the discharge vent or stack.
7. **Forced draft fans** move gas to the scrubber and through to the vent or stack.
8. **Gas reheat system** reduces plume discharge by raising the dewpoint of the gas.
9. **Clarifiers, thickeners, and settling ponds** facilitate recycle and recover solids for disposal or reuse.
10. **Sludge dewatering devices** consolidate recovered solids.

**SELECTED GAS SCRUBBING SYSTEMS**

This section presents examples of gas scrubbing systems used in the electric utility, steel, and paper industries, including the basic types of scrubbers and auxiliary systems used in these applications and the nature of the waterside problems.

**Removal of Particulate (Fly Ash) and SO$_2$ from Flue Gas**

Although several different scrubbing systems are available for this application in the utility industry, the process using limestone has been selected to illustrate many of the aspects of wet scrubbing previously discussed.

Figure 41.13 shows the limestone scrubbing process for removal of SO$_2$ from boiler flue gas. Two venturi/absorber scrubber modules, the heart of the system, are used to treat the entire flow of flue gas. This system is designed to be added to an existing conventional stack-gas cleaning system.

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**FIG. 41.13** Utility stack gas scrubbing system. *From Power, September 1974.*
Limestone stored in silos discharges through a gravimetric feeder, a wet ball mill, and classification system. Limestone slurry at 20% solids leaves the milling system and is stored for transfer to the scrubber modules as needed.

Each scrubber unit consists of (1) a variable-throat venturi that removes fly ash and provides an initial stage of SO$_2$ removal, followed by (2) a countercurrent tray absorber. Sprays in the venturi and the absorber drain into separate reaction tanks, where chemical reactions are allowed to go to completion before the slurry is returned to the scrubber.

Spent slurry from the scrubber, principally calcium sulfite (CaSO$_3$), is pumped to a thickener. Clarified water from this unit is discharged to a pond and returned to the reaction tanks. Thickener underflow is pumped to a sludge-treatment plant, where fly ash and other dry additives are blended to modify the gell-like sludge to produce a stable landfill.

Cleaned flue gases leaving each absorber pass through a bare-tube steam-coil reheater and then to a booster fan. Both booster fans discharge into ID fan inlets. An electrostatic precipitator ahead of the scrubbers serves to remove the bulk of fly ash initially. In case of scrubber system malfunction, a bypass of the precipitator discharge goes directly to the stack.

Major control functions, including limestone feed rate, venturi spray liquor rate, venturi differential pressure, slurry solids concentration, and milling system operation, are handled automatically from the boiler control room.

Primary waterside problems are scale and deposits in the venturi scrubber, gas absorbers, and venturi and absorber recirculation lines and pumps.

Steel Mill Flue Gas Scrubbers

Wet scrubbers are commonly employed by the steel industry for scrubbing gases produced by the blast furnace and basic oxygen furnace (BOF). A diagram and description of each will be presented to show how the basic scrubber and auxiliary equipment may be combined to meet effluent gas requirements.

Blast furnace gas contains CO and is used for combustion in boilers. This requires the effluent gas to be clean and cooled to reduce gas volumes and moisture content prior to combustion. Prior cooling and reduction in gas volume results in substantial savings in delivery costs through the extensive distribution system throughout the mill. Since the primary objective of cleaning blast furnace gas is to produce dust-free, cooled gas to be used as fuel for the boilers, the scrubbing system is designed as shown in Figure 41.14.

![FIG. 41.14 Blast furnace gas scrubbing system.](image-url)
Effective removal of a mixture of coarse and fine dust from a very dusty gas necessitates the use of a dust catcher and a multiventuri scrubbing system. Effective cooling requires the use of a gas cooling tower prior to effluent gas discharge to the boiler.

The dust catcher is merely a settling chamber to remove large particles and reduce loading on the venturi scrubbers. The gas passes through both a primary venturi (with separator) and a secondary venturi for even more effective particulate removal. Then the gas passes through the entrainment separator/gas cooling tower combination. The cleaned, cooled gas is then sent to furnaces. Adequate cooling is required to reduce the moisture level of the gas to avoid problems in distribution lines and furnaces, especially in winter.

The recycle water collected from the first venturi, containing a high level of particulates, is sent directly to a clarifier-thickener. The recycle water collected from the separator is recirculated to the first venturi scrubber. Makeup water is added at the clarifier, and the combined overflow is recycled to the secondary venturi. So the cleanest water contacts the cleanest gas, and works its way back to the first venturi and then to the clarifier. Water can be recycled from the thickener to the scrubber or may be used for some other purpose such as slag quenching.

A conventional cooling tower is normally used for removal of heat from the gas cooling tower water or scrubber water. The design of the tower makes it possible to keep the cooling water and the venturi scrubber water separate.

The scrubber water generally contains considerable hardness and alkalinity from the lime fines in the burden in the blast furnace. Consequently, scale is frequently encountered. Deposits of iron oxide and unburned carbon are also a concern in many systems. Deposition problems are most frequently encountered in the primary venturi nozzles and throat region, where the gas contains the highest level of particulates, and in the lines and pumps going to and from the thickener. However, deposition can occur in both venturi scrubbers, the separators, the gas

![Diagram of BOF scrubbing systems](image-url)
cooling tower, or the scrubber recycle lines and pumps. Clarification is another major problem area since inadequate liquids/solids separation results in poor water quality of the clarifier overflow.

The objective of BOF gas cleaning is to produce effluent acceptable for discharge into the environment, since the cleaned BOF gas cannot be reused. As a result, the gas scrubber system for a BOF, shown in Figure 41.15, is somewhat different from the system used for blast furnace gas cleaning. The blast furnace dust catcher is replaced by a quenching system and the primary and secondary venturi replaced by a single venturi scrubber.

The function of the quencher is to substantially reduce gas temperatures, by 1000 to 1500°F (560 to 840°C), and to reduce gas volumes and resultant fan size and power requirements. A secondary function is to remove dust and particulates greater than 10 μm. This particulate is collected in the scrubber and sent to the solids removal system and thickener. The humidified, cooled gas then passes through the venturi, flooded elbow, separator, and gas cooler prior to discharge up the stack.

The BOF recycle water from the clarifier is pumped to the venturi scrubber, collected in the separator, pumped to the quencher, collected in the scrubber, and transferred to the thickener system for clarification and reuse. A cooling tower is then used for removal of waste heat from the gas cooling tower water.

Scale is normally the primary problem in most BOF scrubber systems. Calcium and alkalinity levels vary, but are usually not as high as in a blast furnace scrubbing system. Scaling potential is severe in a BOF scrubber because pH occa-
sionally gets as high as 11.0 during lime addition to the converter during a blow. The pH in the thickener is generally more consistent than in the scrubbing water because of equalization in the thickener.

Problem locations in the scrubber system are similar to the blast furnace circuit.

**Pulp/Paper Wet Scrubbers**

The most common applications for wet scrubbers in the pulp and paper industry are for coal-fired, bark-fired (hog fuel), and recovery boiler flue gases, and lime kiln recovery operations. The type of wet scrubber that finds the greatest application is the venturi with cyclonic separator combination, or electrostatic/wet cyclone combination. The recovery boiler flue gas scrubber uses a wet cyclonic separator in combination with an electrostatic precipitator (Figure 41.16), while the other processes use the venturi/cyclone combination.

The venturi/cyclone or cyclone scrubbers are very basic systems that suffer from the standard problems associated with wet scrubbing systems—deposition and scaling. Calcium carbonate scaling potential is most severe in the lime kiln scrubber because of the CaO and CaCO$_3$ particulate in the effluent gas. Problems in thickener operation are similar to those encountered in the utility and steel industries.