5.4 WET SCRUBBERS

Wet scrubbers are PM control devices that rely on direct and irreversible contact of a liquid (droplets, foam, or bubbles) with the PM. The liquid with the collected PM is then easily collected. Scrubbers can be very specialized and designed in many different configurations. Wet scrubbers are generally classified by the method that is used to induce contact between the liquid and the PM, e.g. spray, packed-bed, plate. Scrubbers are also often described as low-, medium-, or high-energy, where energy is often expressed as the pressure drop across the scrubber. This section addresses the basic operating principles, designs, collection efficiency, applicability, and costs of wet scrubbers.

Wet scrubbers have important advantages when compared to other PM collection devices. They can collect flammable and explosive dusts safely, absorb gaseous pollutants, and collect mists. Scrubbers can also cool hot gas streams. There are also some disadvantages associated with wet scrubbers. For example, scrubbers have the potential for corrosion and freezing. Additionally, the use of wet scrubbers can lead to water and solid waste pollution problems.[1] These disadvantages can be minimized or avoided with good scrubber design.

5.4.1 Particle Collection and Penetration Mechanisms

The dominant means of PM capture in most industrial wet scrubbers is inertial impaction of the PM onto liquid droplets. Brownian diffusion also leads to particle collection, but its effects are only significant for particles approximately 0.1 micrometer (:m) in diameter or less.[2] Direct interception is another scrubber collection mechanism. Less important scrubber collection mechanisms utilize gravitation, electrostatics, and condensation.[2]

Inertial impaction in wet scrubbers occurs as a result of a change in velocity between PM suspended in a gas, and the gas itself. As the gas approaches an obstacle, such as a liquid droplet, the gas changes direction and flows around the droplet. The particles in the gas will also accelerate and attempt to change direction to pass around the droplet. Inertial forces will attempt to maintain the forward motion of the particle towards the object, but the fluid force will attempt to drag the particle around the droplet with the gas. The resultant particle motion is a combination of these forces of fluid drag and inertia. This results in impaction for the particles where inertia dominates, and by-pass for those particles overwhelmed by fluid drag.[2] Large particles, particles i.e. greater than 10 µm are more easily collected by inertial impaction because these particles have more inertial momentum to resist changes in the flow of the gas and, therefore, impact the droplet. Small particles (i.e. particles <1 µm) are more difficult to collect by inertial impaction because they remain in the flow lines of the gas due to the predominance of the fluid drag force.

Collection by diffusion occurs as a result of both fluid motion and the Brownian (random) motion of particles. This particle motion in the scrubber chamber results in direct particle-liquid contact. Since this contact is irreversible, collection of the PM by the liquid occurs. Diffusional collection effects are most significant for particles less than 0.1 μm in diameter.[2] Direct interception occurs when the path of a particle comes within one radius of the collection medium, which in a scrubber is a liquid droplet. The path can be the result of inertia, diffusion, or fluid motion.[2]

Gravitational collection as a result of falling droplets colliding with particles is closely related to impaction and interception, and is a minor mechanism in some scrubbers.[2] Gravitational settling of particles is usually not a factor because of high gas velocities and short residence times.[3] Generally, electrostatic attraction is not an important mechanism except in cases where the particles, liquid, or both, are being deliberately charged, or where the scrubber follows an electrostatic precipitator.[3] Some scrubbers are designed to enhance particle capture through condensation. In such cases, the dust-laden stream is supersaturated with liquid (usually water). The particles then act as condensation nuclei, growing in size as more liquid condenses around them and becoming easier to collect by inertial impaction.[2,4]

The collection mechanisms of wet scrubbers are highly dependent on particle size. Inertial impaction is the major collection mechanism for particles greater than approximately 0.1 μm in diameter. The effectiveness of inertial impaction increases with increasing particle size. Diffusion is generally effective only for particles less than 0.1 μm in diameter, with collection efficiency increasing with decreasing particle size. The combination of these two major scrubber collection mechanisms contributes to a minimum collection efficiency for PM approximately 0.1 μm in diameter.[5] The exact minimum efficiency for a specific scrubber will depend on the type of scrubber, operating conditions, and the particle size distribution in the gas stream. Scrubber collection efficiency is discussed in more detail in Section 5.4.3.

5.4.2 Types of Wet Scrubbers

There are a great variety of wet scrubbers that are either commercially available or can be custom designed. While all wet scrubbers are similar to some extent, there are several distinct methods of using the scrubbing liquid to achieve particle collection. Wet scrubbers are usually classified according to the method that is used to contact the gas and the liquid.

The most common scrubber design is the introduction of liquid droplets into a spray chamber, where the liquid is mixed with the gas stream to promote contact with the PM. In a packed-bed scrubber, layers of liquid are used to coat various shapes of packing material that become impaction surfaces for the particle-laden gas. Scrubber collection can also be achieved by forcing the gas at high velocities though a liquid to form jet streams. Liquids are also used to supersaturate the gas stream, leading to particle scrubbing by condensation.

5.4.2.1 Spray Chambers

Spray chambers are very simple, low-energy wet scrubbers. In these scrubbers, the particulate-laden gas stream is introduced into a chamber where it comes into contact with liquid droplets generated by spray nozzles. These scrubbers are also known as pre-formed spray scrubbers, since the liquid is formed into droplets prior to contact with the gas stream. The size of the droplets generated by the spray nozzles is controlled to maximize liquid-particle contact and, consequently, scrubber collection efficiency.

The common types of spray chambers are spray towers and cyclonic chambers. Spray towers are cylindrical or rectangular chambers that can be installed vertically or horizontally. In vertical spray towers, the gas stream flows up through the chamber and encounters several sets of spray nozzles producing liquid droplets. A de-mister at the top of the spray tower removes liquid droplets and wetted PM from the exiting gas stream. Scrubbing liquid and wetted PM also drain from the bottom of the tower in the form of a slurry. Horizontal spray chambers operate in the same manner, except for the fact that the gas flows horizontally through the device. A typical spray tower is shown in Figure 5.4-1.[1,2,5]

A cyclonic spray chamber is similar to a spray tower with one major difference. The gas stream is introduced to produce cyclonic motion inside the chamber. This motion contributes to higher gas velocities, more effective particle and droplet separation, and higher collection efficiency.[1] Tangential inlet or turning vanes are common means of inducing cyclonic motion.[5] Figure 5.4-2 provides an example of a cyclonic spray chamber.

5.4.2.2 Packed-Bed Scrubbers

Packed-bed scrubbers consist of a chamber containing layers of variously-shaped packing material, such as raschig rings, spiral rings, and berl saddles, that provide a large surface area for liquid-particle contact. These and other types of packings are illustrated in Figure 5.4-3.[2,5] The packing is held in place by wire mesh retainers and supported by a plate near the bottom of the scrubber. Scrubbing liquid is evenly introduced above the packing and flows down through the bed. The liquid coats the packing and establishes a thin film. In vertical designs, the gas stream flows up the chamber (countercurrent to the liquid). Some packed beds are designed horizontally for gas flow across the packing (crosscurrent).

In packed-bed scrubbers, the gas stream is forced to follow a circuitous path through the packing, on which much of the PM impacts. The liquid on the packing collects the PM and flows down the chamber towards the drain at the bottom of the tower. A mist eliminator (also called a "de-mister") is typically positioned above/after the packing and scrubbing liquid supply. Any scrubbing liquid and wetted PM entrained in the exiting gas stream will be removed by the mist eliminator and returned to drain through the packed bed. A typical packed-bed scrubber is illustrated in Figure 5.4-4.[2,5]

In a packed-bed scrubber, high PM concentrations can clog the bed, hence, the limitation of these devices to streams with relatively low dust loadings.[5] Plugging is a serious problem for packed-bed scrubbers because the packing is more difficult to access and clean than other scrubber designs.[2] Mobile-bed scrubbers are available that are packed with low-density plastic spheres that are free to move within the packed bed.[5] These scrubbers are less susceptible to plugging because of the increased movement of the packing material. In general, packed-bed scrubbers are more suitable for gas scrubbing than particulate scrubbing because of the high maintenance requirements for control of PM.[1,2]

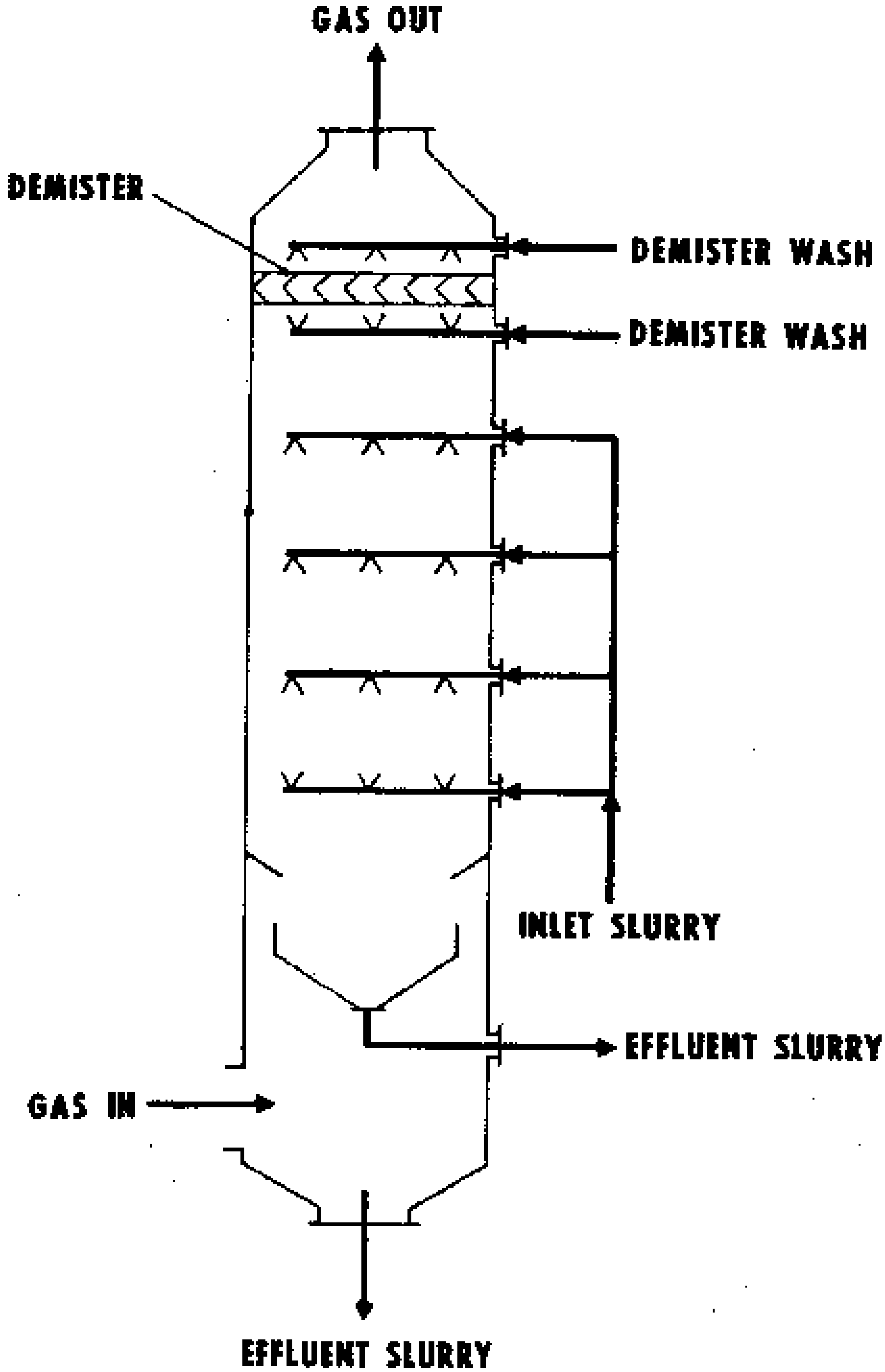


Figure 5.4-1. Schematic Diagram of a Spray Tower Scrubber (Reference 2).

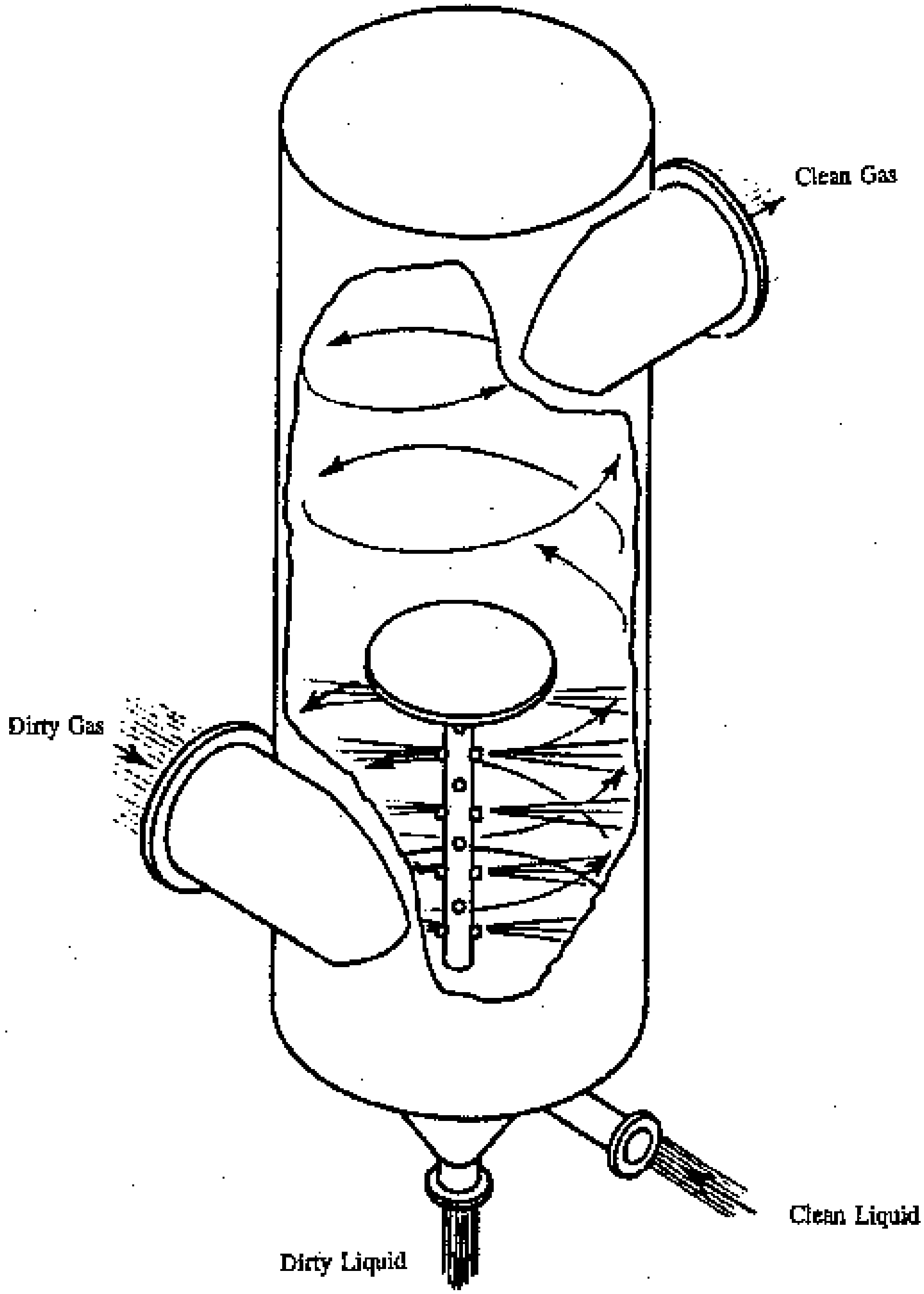


Figure 5.4-2. Schematic Diagram of a Cyclonic Spray Chamber Scrubber (Reference 1).

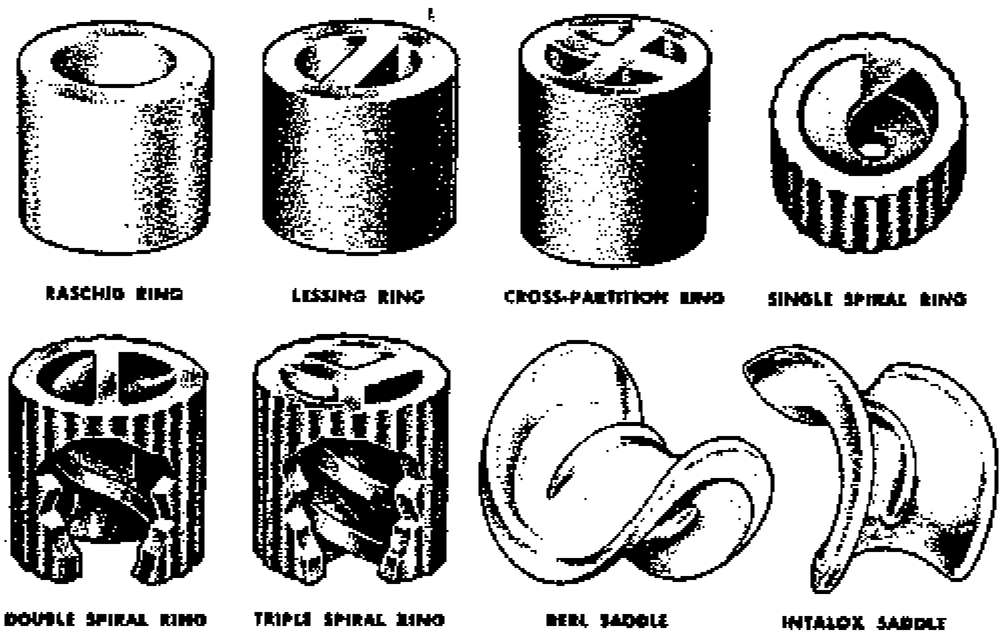


Figure 5.4-3. Typical Packing Materials for Packed Bed Scrubbers (Reference 2).

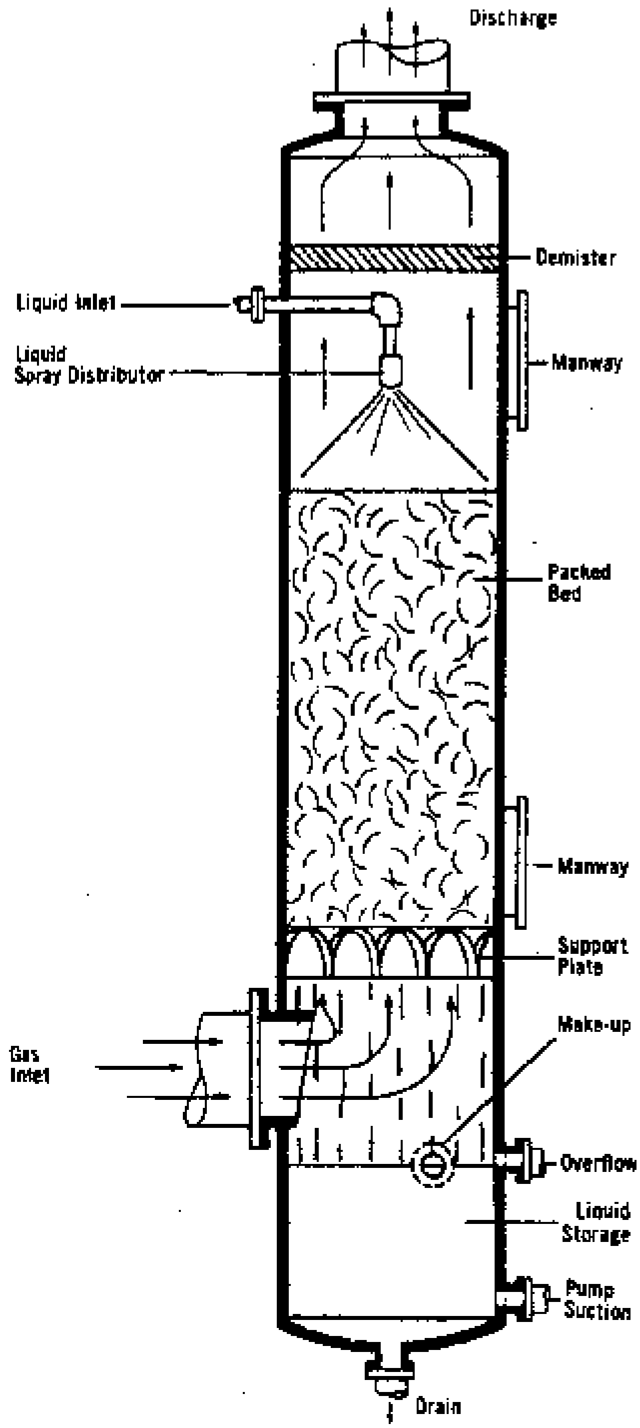


Figure 5.4-4. Schematic Diagram of a Packed Tower Scrubber (Reference 2).

5.4.2.3 Impingement Plate Scrubbers

An impingement plate scrubber is a vertical chamber with plates mounted horizontally inside a hollow shell. Impingement plate scrubbers operate as countercurrent PM collection devices. The scrubbing liquid flows down the tower while the gas stream flows upward. Contact between the liquid and the particle-laden gas occurs on the plates. The plates are equipped with openings that allow the gas to pass through. Some plates are perforated or slotted, while more complex plates have valve-like openings. Figure 5.4-5 shows common plate designs used in impingement plate scrubbers.[2,5]

The simplest impingement plate is the sieve plate, which has round perforations. In this type of scrubber, the scrubbing liquid flows over the plates and the gas flows up through the holes. The gas velocity prevents the liquid from flowing down through the perforations. Gas-liquid-particle contact is achieved within the froth generated by the gas passing through the liquid layer. Complex plates, such as bubble cap or baffle plates, introduce an additional means of collecting PM. The bubble caps and baffles placed above the plate perforations force the gas to turn before escaping the layer of liquid. While the gas turns to avoid the obstacles, most PM cannot and is collected by impaction on the caps or baffles. Bubble caps and the like also prevent liquid from flowing down the perforations if the gas flow is reduced.

In all types of impingement plate scrubbers, the scrubbing liquid flows across each plate and down the inside of the tower onto the plate below. After the bottom plate, the liquid and collected PM flow out of the bottom of the tower. A typical impingement plate scrubber is shown in Figure 5.4-6.[2,5] Impingement plate scrubbers are usually designed to provide operator access to each tray, making them relatively easy to clean and maintain.[2] Consequently, impingement plate scrubbers are more suitable for PM collection than packed-bed scrubbers. Particles greater than 1 :m in diameter can be collected effectively by impingement plate scrubbers, but many particles <1 μm will penetrate these devices.[5]

5.4.2.4 Mechanically-aided Scrubbers

Mechanically-aided scrubbers (MAS) employ a motor driven fan or impeller to enhance gas-liquid contact. Generally in MAS, the scrubbing liquid is sprayed onto the fan or impeller blades. Fans and impellers are capable of producing very fine liquid droplets with high velocities. These droplets are effective in contacting fine PM. Once PM has impacted on the droplets, it is normally removed by cyclonic motion. Mechanically aided scrubbers are capable of high collection efficiencies, but only with a commensurate high energy consumption. An example of a mechanically aided scrubber is provided in Figure 5.4-7.[1,2,5]

Because many moving parts are exposed to the gas and scrubbing liquid in a MAS, these scrubbers have high maintenance requirements. Mechanical parts are susceptible to corrosion, PM buildup, and wear. Consequently, mechanical scrubbers have limited applications for PM control.[2,5]

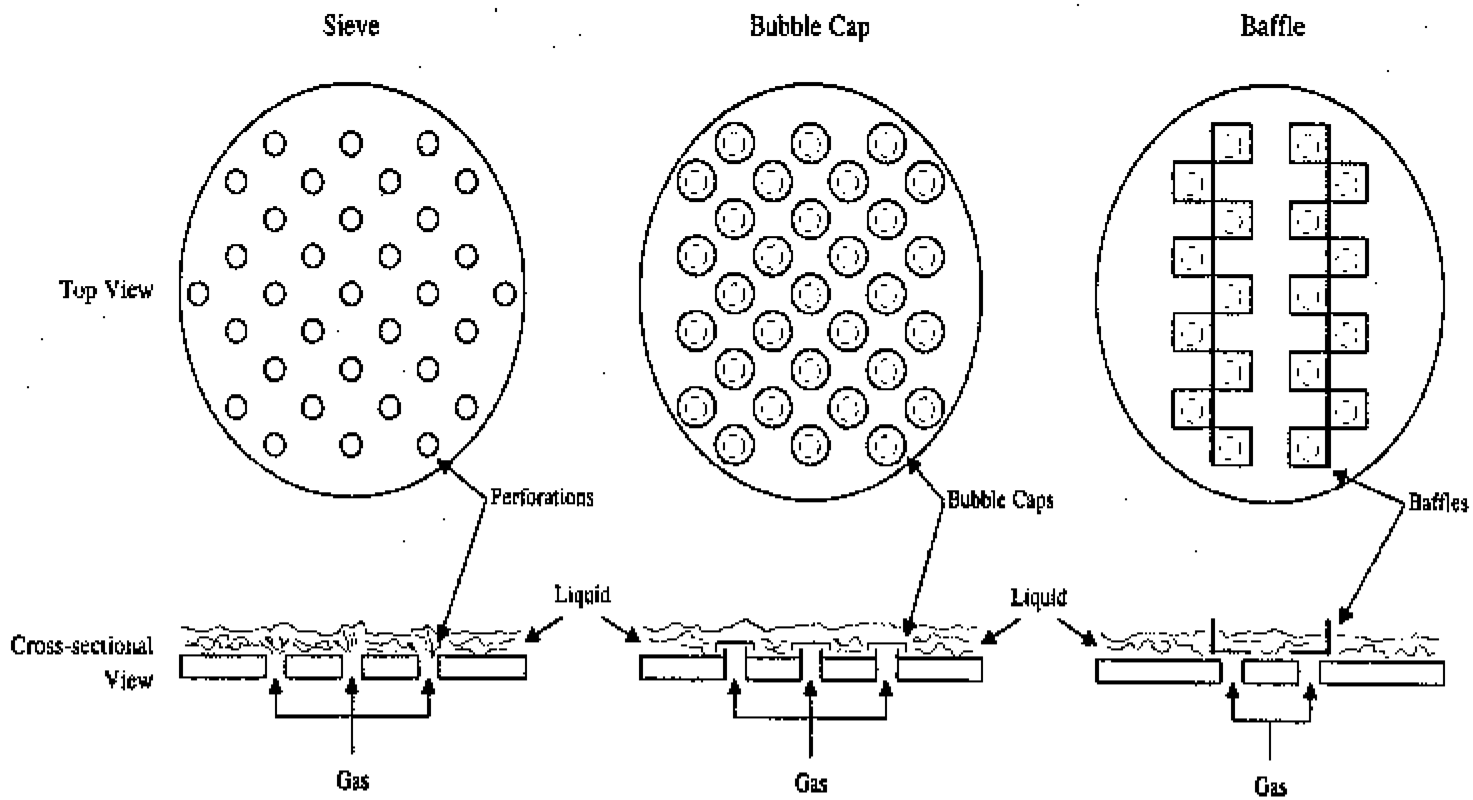


Figure 5.4-5. Common Plate Designs for Impingement Plate Scrubbers (adapted from Reference 2).

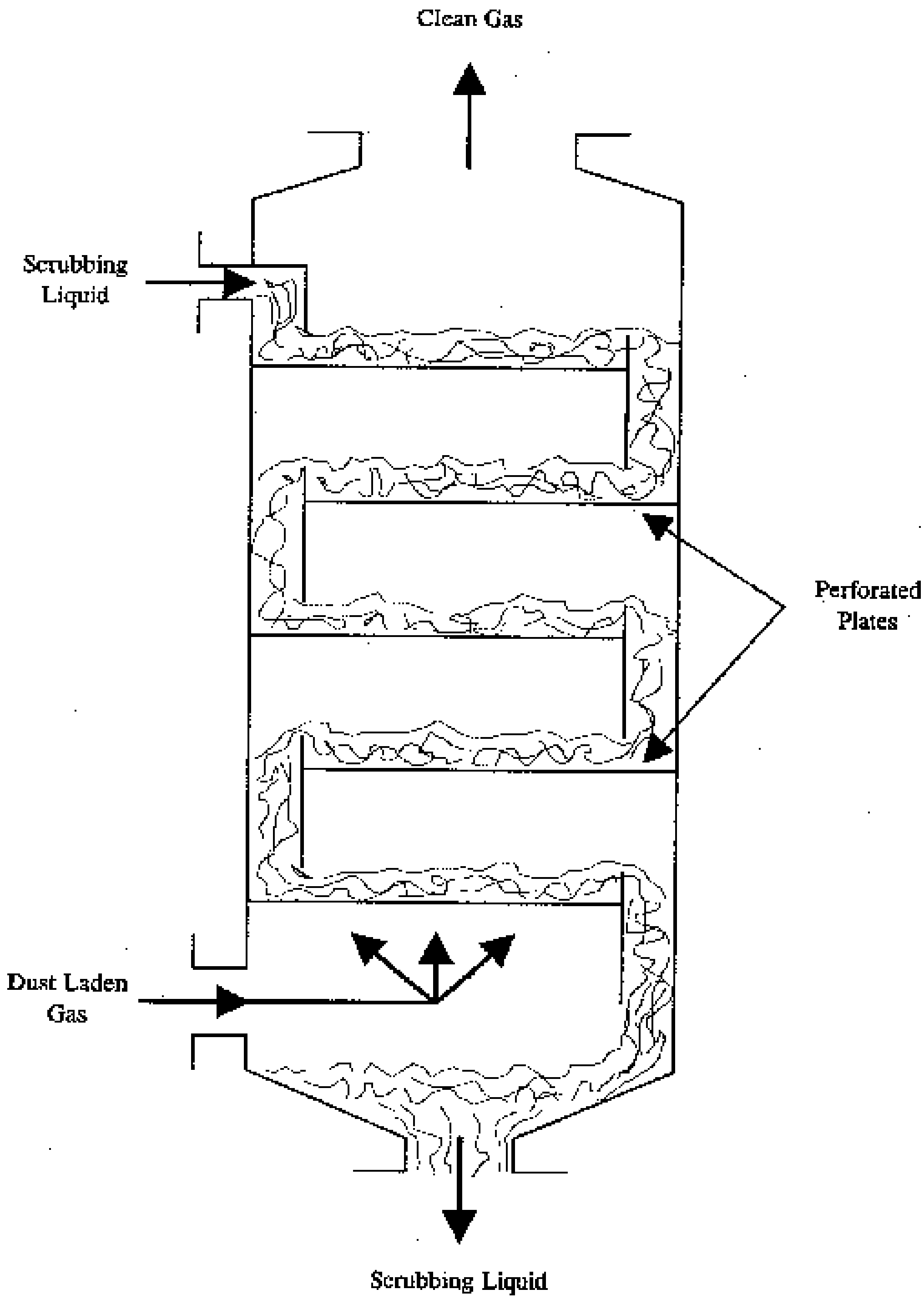


Figure 5.4-6. Schematic Diagram of a Plate Tower Scrubber (adapted from Reference 2).

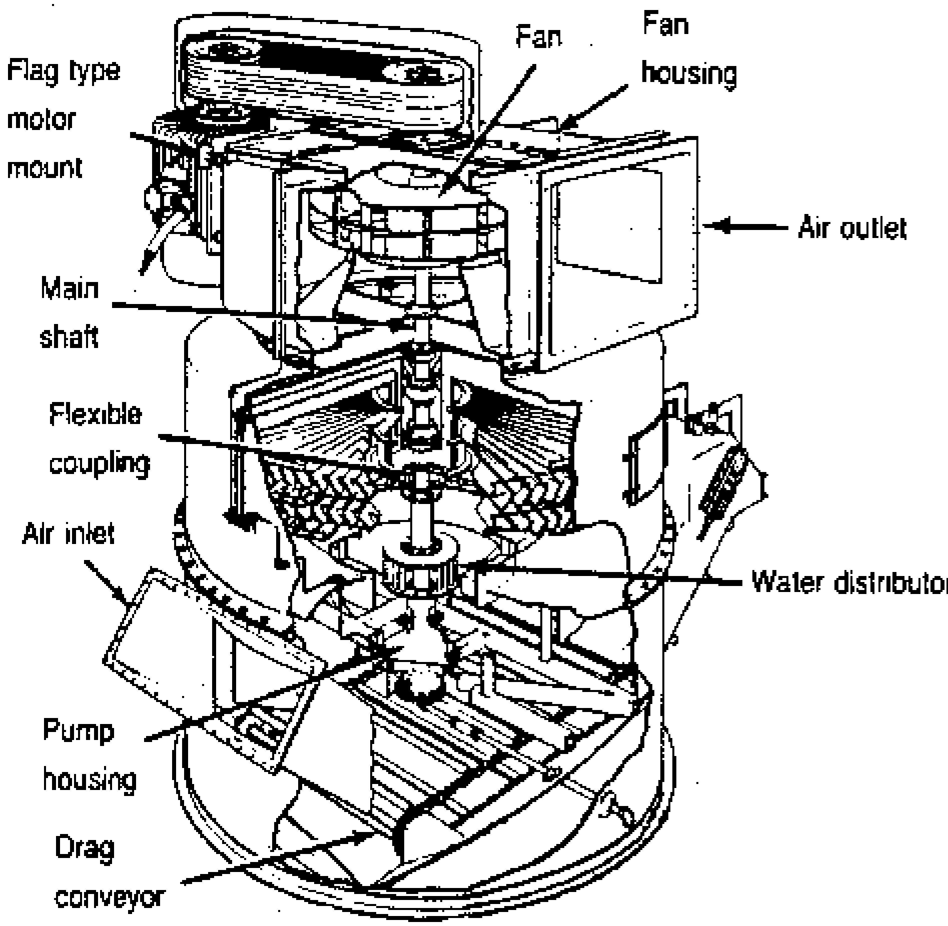


Figure 5.4-7. Diagram of a Mechanically-aided Scrubber (Reference 1).

5.4.2.5 Venturi Scrubbers

A venturi, or gas-atomized spray, scrubber accelerates the gas stream to atomize the scrubbing liquid and to improve gas-liquid contact. In a venturi scrubber, a "throat" section is built into the duct that forces the gas stream to accelerate as the duct narrows and then expands. As the gas enters the venturi throat, both gas velocity and turbulence increase. The scrubbing liquid is sprayed into the gas stream before the gas encounters the venturi throat. The scrubbing liquid is then atomized into small droplets by the turbulence in the throat and droplet-particle interaction is increased. After the throat section in a venturi scrubber, the wetted PM and excess liquid droplets are separated from the gas stream by cyclonic motion and/or a mist eliminator. Venturi scrubbers have the advantage of being simple in design, easy to install, and with low-maintenance requirements.[1] An example of a venturi scrubber is provided in Figure 5.4-8.

The performance of a venturi scrubber is dependent to some extent on the velocity of the gas through the throat. Several venturi scrubbers have been designed to allow velocity control by varying the width of the venturi throat.[2,5] Because of the high interaction between the PM and droplets, venturi scrubbers are capable of high collection efficiencies for small PM. Unfortunately, increasing the venturi scrubber efficiency requires increasing the pressure drop which, in turn, increases the energy consumption.[1]

5.4.2.6 Orifice Scrubbers

Orifice scrubbers, also known as entrainment or self-induced spray scrubbers, force the particle-laden gas stream to pass over the surface of a pool of scrubbing liquid as it enters an orifice. With the high gas velocities typical of this type of scrubber, the liquid from the pool becomes entrained in the gas stream as droplets. As the gas velocity and turbulence increases with the passing of the gas through the narrow orifice, the interaction between the PM and liquid droplets also increases. Particulate matter and droplets are then removed from the gas stream by impingement on a series of baffles that the gas encounters after the orifice. The collected liquid and PM drain from the baffles back into the liquid pool below the orifice.[2,5] Orifice scrubbers can effectively collect particles larger than 2 :m in diameter.[1,5] Some orifice scrubbers are designed with adjustable orifices to control the velocity of the gas stream. A typical orifice scrubber is shown in Figure 5.4-9.

Orifice scrubbers usually have low liquid demands, since they use the same scrubbing liquid for extended periods of time.[1] Because orifice scrubbers are relatively simple in design and usually have few moving parts, the major maintenance concern is the removal of the sludge which collects at the bottom of the scrubber. Orifice scrubbers rarely drain continually from the bottom because a static pool of scrubbing liquid is needed at all times. Therefore, the sludge is usually removed with a sludge ejector that operates like a conveyor belt. As the sludge settles to the bottom of the scrubber, it lands on the ejector and is conveyed up and out of the scrubber. Figure 5.4-10 shows a typical sludge ejector.[2]

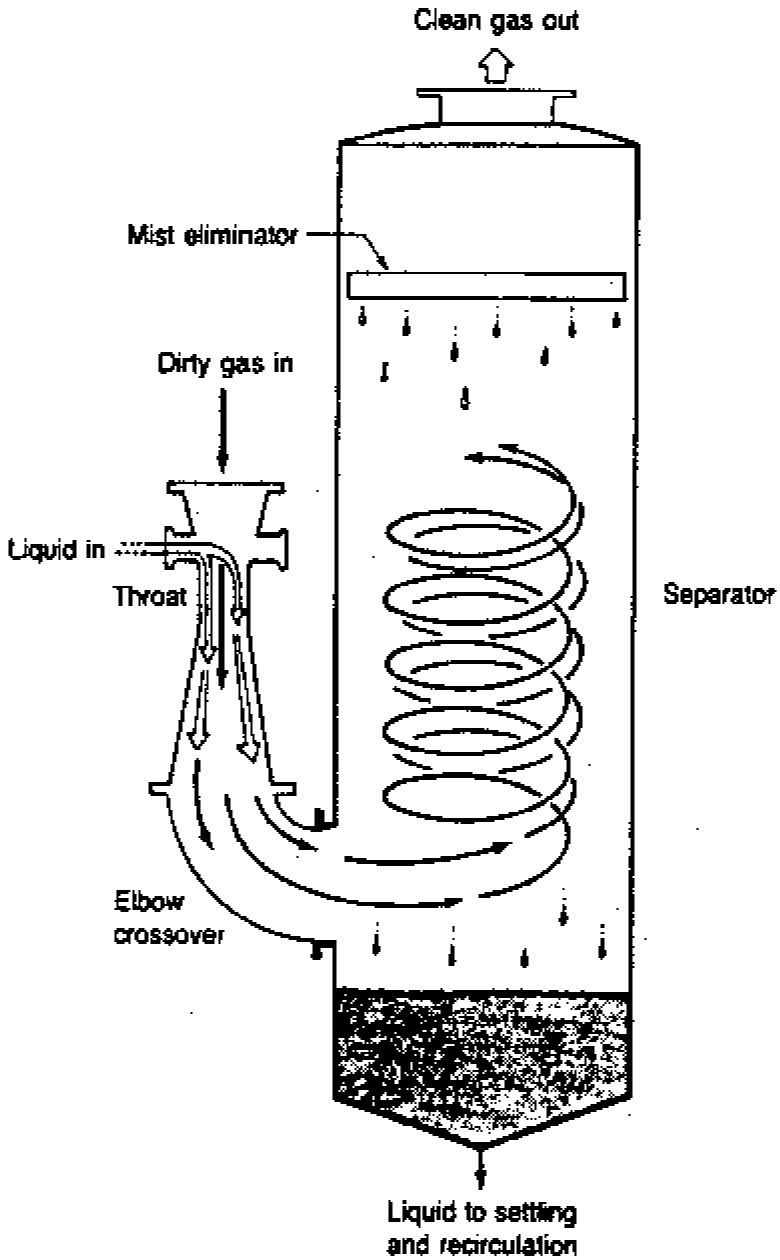


Figure 5.4-8. Schematic Diagram of a Venturi Scrubber with Cyclonic Separation (Reference 1).

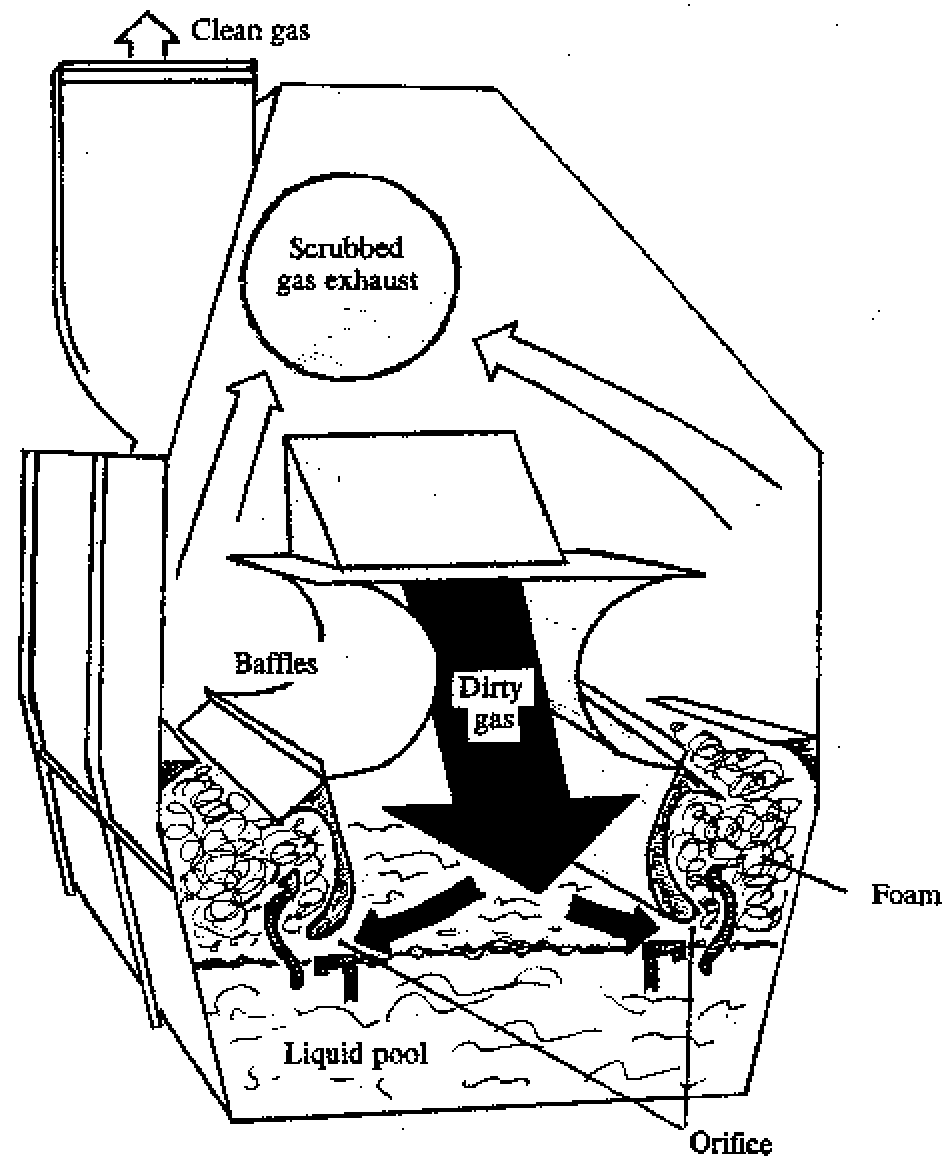


Figure 5.4-9. Diagram of an Orifice Scrubber (Reference 1).

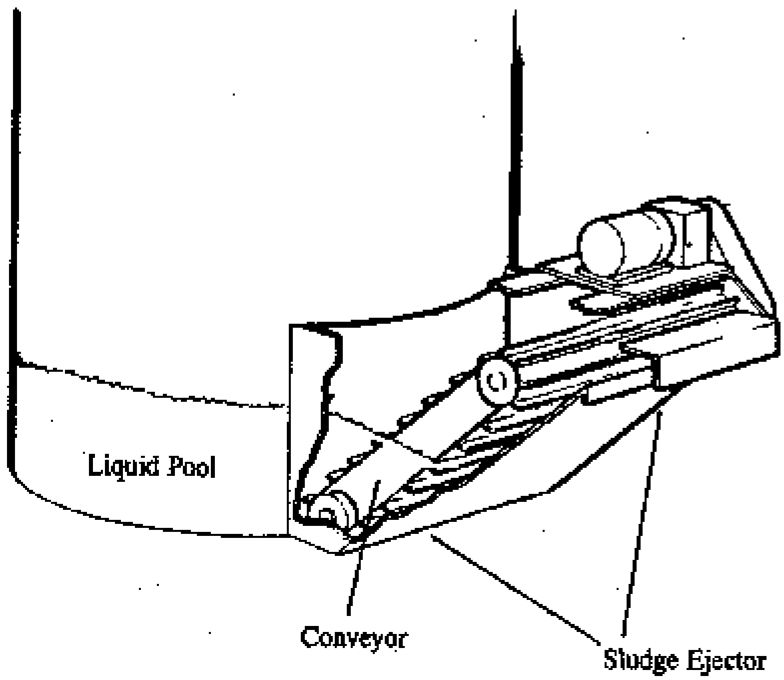


Figure 5.4-10. Diagram of a Sludge Ejector in an Orifice Scrubber (Reference 2).

5.4.2.7 Condensation Scrubbers

Condensation scrubbing is a relatively recent development in wet scrubber technology. Most conventional scrubbers rely on the mechanisms of impaction and diffusion to achieve contact between the PM and liquid droplets. In a condensation scrubber, the PM act as condensation nuclei for the formation of droplets. Generally, condensation scrubbing depends on first establishing saturation conditions in the gas stream. Once saturation is achieved, steam is injected into the gas stream. The steam creates a condition of supersaturation and leads to condensation of water on the fine PM in the gas stream. The large condensed droplets can be removed by several conventional devices. Typically, a high efficiency mist eliminator is also used.[2,4]

A high-efficiency condensation "growth" PM scrubber has been developed that is suitable for both new and retrofit installations, and is designed specifically to capture fine PM that escapes primary PM control devices. This type of scrubber utilizes a multistage process, including pretreatment and growth chambers, that provide an environment that encourages the fine PM to coagulate and form larger particles. A schematic diagram of this scrubber is provided in Figure 5.4-11.[4]

5.4.2.8 Charged Scrubbers

Charged, or electrically-augmented, wet scrubbers utilize electrostatic effects to improve collection efficiencies for fine PM with wet scrubbing. Since conventional wet scrubbers rely on the inertial impaction between PM and liquid droplets for PM collection, they are generally ineffective for particles with diameters less than 1 :m. Pre-charging of the PM in the gas stream can significantly increase scrubber collection efficiency for these submicrometer particles. When both the particles and droplets are charged, collection efficiencies for submicrometer particles are highest, approaching that of an ESP.[2]

There are several types of charged wet scrubbers. Particulate matter can be charged negatively or positively, with the droplets given the opposite charge. The droplets may also be bipolar (a mixture of positive and negative). In this case, the PM can be either bipolar or unipolar. Figure 5.4-12 is a schematic of a charged wet scrubber.[2]

5.4.2.9 Fiber-Bed Scrubbers

In a fiber-bed scrubbers, the moisture-laden gas stream passes through mats of packing fibers, such as spun glass, fiberglass, and steel. The fiber mats are often also spray wetted with the scrubbing liquid. Depending on the scrubber requirements, there may be several fiber mats and an impingement device for PM removal included in the design. The final fiber mat is typically dry for the removal of any droplets that are still entrained in the stream. Fiber-bed scrubbers are best suited for the collection of soluble PM, i.e. PM that dissolves in the scrubber liquid, since large amounts of insoluble PM will clog the fiber mats with time. For this reason, fiber-bed scrubbers are more often used as mist eliminators, i.e., for the collection of liquids, rather than for PM control.[2]

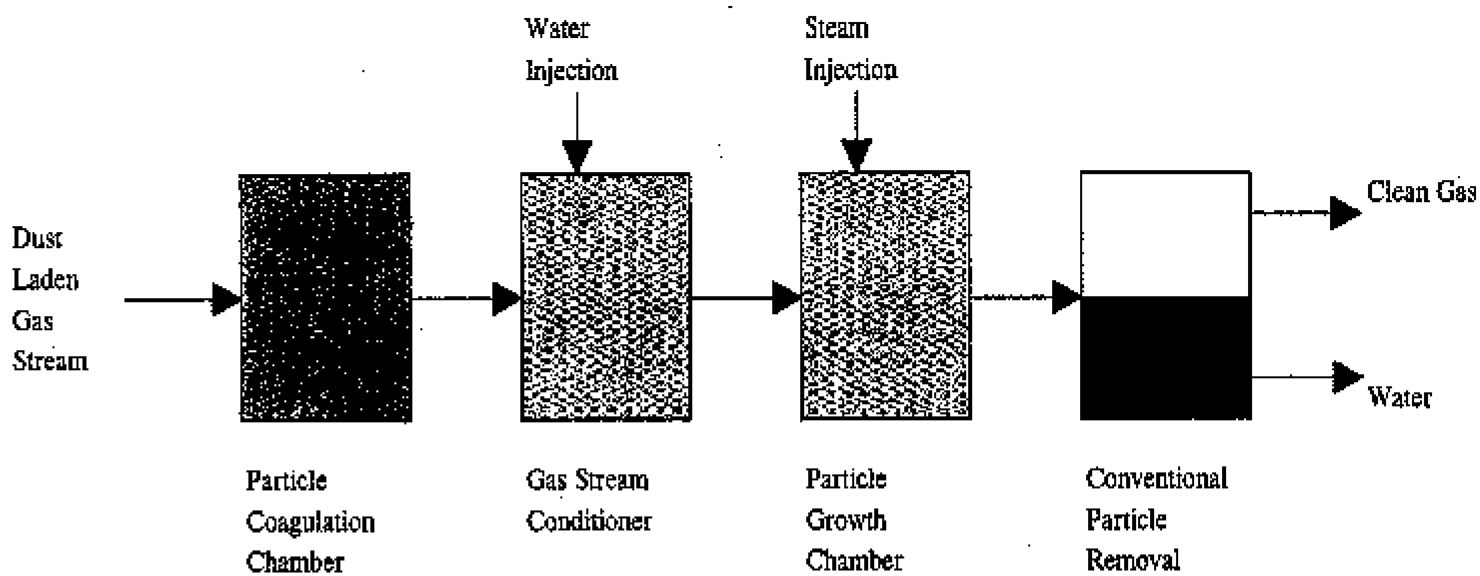


Figure 5.4-11. Schematic Diagram of a Condensation "Growth" Scrubber (adapted from Reference 4).

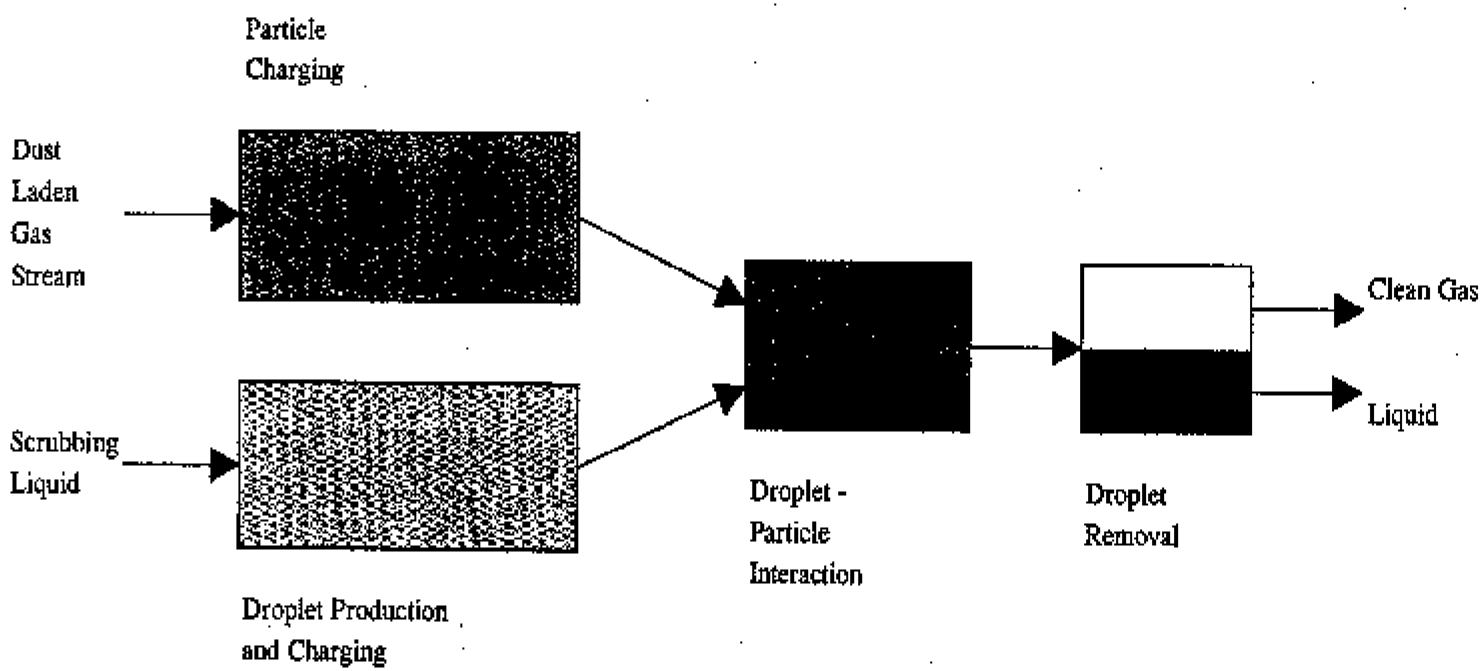


Figure 5.4-12. Schematic Diagram of Charged Wet Scrubber (adapted from Reference 2).

5.4.3 Collection Efficiency

Collection efficiencies for wet scrubbers are highly variable. Most conventional scrubbers can achieve high collection efficiencies for particles greater than 1.0 :m in diameter, however they are generally ineffective collection devices for submicrometer (<1 µm) particles. Some unconventional scrubbers, such as condensation and charged, are capable of high collection efficiencies, even for submicrometer particles. Collection efficiencies for conventional scrubbers depend on operating factors such as particle size distribution, inlet dust loading, and energy input. Figure 5.4-13 provides scrubber efficiency curves for coal and oil combustion, wood combustion, and coke production. Table 5.4-1 presents the PM-10 and PM-2.5 collection efficiencies.[6]

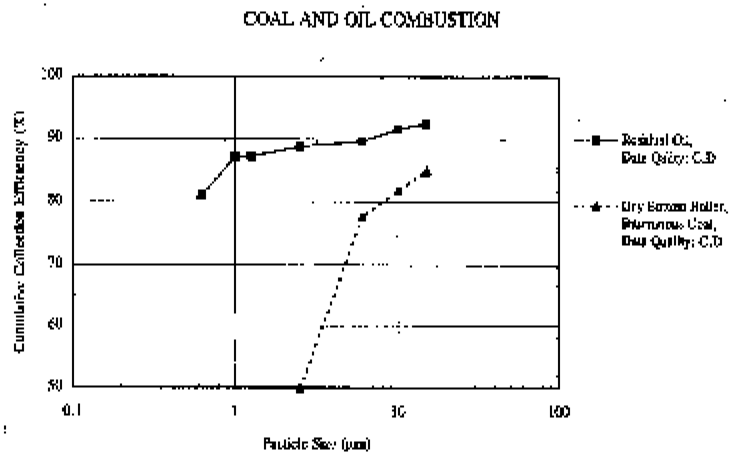
Conventional scrubbers rely almost exclusively on inertial impaction for PM collection. As discussed above, scrubber efficiency that relies on inertial impaction collection mechanisms will increase as particle size increases. Therefore, collection efficiency for small particles (<1 µm) are expected to be low for these scrubbers. The efficiency of scrubbers that rely on inertial impaction can be improved, however, by increasing the relative velocity between the PM and the liquid droplets. Increasing velocity will result in more momentum for all PM, enabling smaller particles to be collected by impaction. This can be accomplished in most scrubbers by increasing the gas stream velocity. Unfortunately, increasing the gas velocity will also increase the pressure drop, energy demand, and operating costs for the scrubber.[1,2,5]

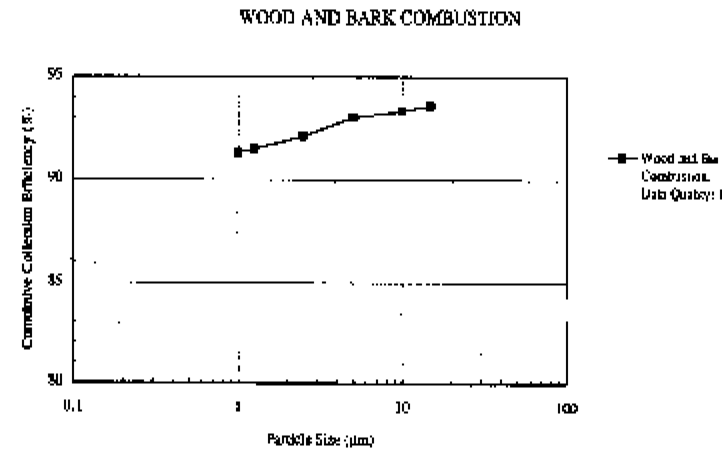
Another factor which contributes to low scrubber efficiency for small particles is short residence times. Typically, a particle is in the contact zone of a scrubber for only a few seconds. This is sufficient time to collect large particles that are affected by impaction mechanisms. However, since submicrometer particles are most effectively collected by diffusion mechanisms that depend on the random motion of the particles, sufficient time in the contact zone is needed for this mechanism to be effective. Consequently, increasing the gas residence time should also increase the particle/liquid contact time and the collection efficiency for small particles.[2]

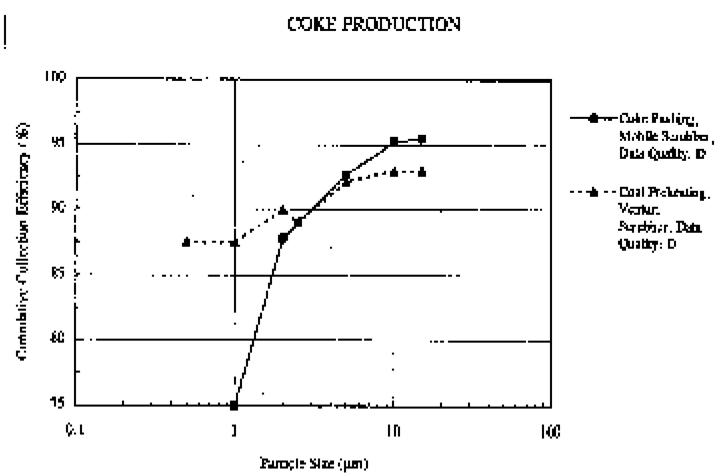
An important relationship between inlet dust concentration (loading) and collection efficiency for fine PM in scrubbers has been recently found.[7] Collection efficiency for scrubbers has been found to be directly proportional to the inlet dust concentration. That is, efficiency will increase with increasing dust loading. This suggests that scrubber removal efficiency is not constant for a given scrubber design unless it is referenced to a specific inlet dust loading. In contrast, it has been shown that scrubber outlet dust concentration is a constant, independent of inlet concentration.[7]

5.4.4 Applicability

Wet scrubbers have numerous industrial applications and few limitations. They are capable of collecting basically any type of dust, including flammable, explosive, moist, or sticky dusts. In addition, they can collect suspended liquids (i.e. mists) or gases alone or with PM simultaneously.[1] However, while scrubbers have many potential applications, there are some







Note: Data quality refers to the data quality ratings assigned to the emission factors from which the efficiencies were calculated (Reference 6), as follows:

A = excellent
B = above average
C = average
D = below average
E = poor.

Figure 5.4-13. Cumulative Collection Efficiency Data for PM Wet Scrubbers at Coal, Oil, Wood, and Bark Combustion Sources, and Coke Production Operations (Reference 6)

Table 5.4-1. PM-10 and PM-2.5 Cumulative Collection Efficiencies for Wet Scrubbers at Coal, Oil, Wood, and Bark Combustors; and Coke Production Units (Reference 6).

	Collection Efficiency (percent)	
Application	PM-10	PM-2.5
Combustion Sources		
Bituminous coal (dry bottom)	81.7	50.0
Residual oil	91.5	88.8
Wood and bark	93.3	92.1
Bark only	85.1	83.8
Coke Production		
Coal preheating (venturi scrubber)	92.9	89.0
Coke pushing (mobile-bed scrubber)	95.2	89.0

characteristics that limit their use. The most significant consideration is the relatively low collection efficiency for fine PM, especially those less than 1.0 μm in diameter. Therefore, conventional scrubbers may not be suitable for processes which emit many submicrometer particles. As discussed above venturi, condensation, and charged scrubbers are capable of collecting submicrometer particles at higher efficiencies than other scrubbers and, therefore, can be used effectively in applications where there are a large percentage of fine PM in the gas stream.[2]

Gas stream composition may also be a limiting factor in scrubber application for a specific industry, since wet scrubbers are very susceptible to corrosion.[1] The use of wet scrubbers also may not be desirable when collecting valuable dust which can be recycled or sold. Since scrubbers discharge collected dust in the form of a wet slurry, reclaiming clean dry dust from this slurry is often inconvenient and expensive.[1] Because of design constraints, particulate scrubbers are generally not used in very large installations, such as utilities where gas flowrates exceed 250,000 ACFM, since multiple scrubbers are needed once flowrates exceed 60,000-75,000 ACFM.

Table 5.4-2 lists current applications of wet scrubbers.[1,2,8] It should be noted that the level of PM control supplied by each of the scrubber types listed in Table 5.4-2 will vary according to the level of control currently required by each industry and/or facility. The driving

Table 5.4-2. Current Industrial Applications of Wet Scrubbers (References 1, 2, and 8)

Application	Source Category Code	Typical Scrubber Type
Utility Boilers (Coal, Oil)	1-01-002...004	Venturi
Industrial Boilers (Coal, Oil, Wood, Liquid Waste)	1-02-001...005, -009, -011, -013	Venturi, impingement plate (baffle)
Commercial/Institutional Boilers (Coal, Oil, Wood)	1-03-001...005 1-03-009	Venturi
Chemical Manufacture	3-01-001...999	Packed-bed, venturi, fiber-bed
Non-Ferrous Metals Processing (Primary and Secondary)		
Copper	3-03-005 3-04-002	Spray chamber
Lead	3-03-010 3-04-004	Venturi, (cyclonic) spray chamber, fiber-bed, charged
Aluminum	3-03-000...002 3-04-001	Spray chamber, packed-bed, venturi, charged
Other	3-03-011...014 3-04-005...006 3-04-010...022	(Cyclonic) spray chamber
Ferrous Metals Processing		
Coke Production	3-03-003...004	Charged, venturi, packed-bed (mobile)
Ferroalloy Production	3-03-006...007	Packed-bed, fiber-bed
Iron and Steel Production	3-03-008...009	Venturi
Gray Iron Foundries	3-04-003	Venturi, impingement plate (baffle)
Steel Foundries	3-04-007, -009	Venturi
Asphalt Manufacture	3-05-001...002	Venturi
Mineral Products		
Coal Cleaning	3-05-010	Venturi, fiber-bed
Other	3-05-003...999	Venturi
Wood, Pulp, and Paper	3-07-001	Venturi, (cyclonic) spray chamber

Application	Source Category Code	Typical Scrubber Type
Food and Agriculture	3-02-001...999	Impingement, fiber-bed, packed-bed
Incineration	5-01-001, 5-02-001, -005 5-03-001, -005	Venturi, packed-bed, condensation

force for PM control in many industries and/or facilities is the Federal, State, and local air pollution regulations. As more stringent PM regulations are put into place, a shift toward the use of higher efficiency scrubbers is likely to occur. Table 5.4-3 rates the various scrubber types according to their potential for controlling fine particles.

Table 5.4-3. $PM_{10}/PM_{2.5}$ Control Potential for Various Scrubber Designs

Scrubber Type	$PM_{10}/PM_{2.5}$ Control Potential	Comments
Spray Chamber	Fair	Cyclonic are better than conventional spray
Packed-Bed	Poor	Useful for low dust loadings only
Impingement Plate	Good	Not as good for PM <1 µm
Mechanically-aided	Good	High energy consumption to achieve $PM_{10}/PM_{2.5}$ control
Venturi	Good	High energy consumption to achieve $PM_{10}/PM_{2.5}$ control
Orifice	Good	Not as good for PM <2 µm
Condensation	Good	Excellent control possible with condensation "growth" scrubbers
Charged	Excellent	Electric power costs add to overall scrubber costs
Fiber-Bed	Fair	Useful for soluble PM only

5.4.5 Costs of PM Wet Scrubbers

The costs of installing and operating a scrubber include both capital and annual costs. Capital costs are all of the initial costs related to scrubber equipment and installation. Annual costs are the direct yearly costs of operating the scrubber, plus indirect costs such as overhead, capital recovery, taxes, insurance, and administrative charges. The following sections discuss capital and annual costs for scrubbers, referenced to the third quarter of 1995 unless otherwise noted.

5.4.5.1 Capital Costs

The total capital investment (TCI) for scrubbers includes all of the initial capital costs, both direct and indirect. Direct capital costs are the purchased equipment costs (PEC), and the costs of installation (foundations, electrical, piping, etc.). Indirect costs are related to the installation and include engineering, construction, contractors, start-up, testing, and contingencies. The PEC is calculated based on the scrubber specifications. The direct and indirect installation costs are calculated as factors of the PEC. Table 5.4-4 provides the TCI factors for a typical scrubber.[9,10]

Wet scrubber costs are dependent upon the type of scrubber selected, the required size of the scrubber, and the materials of construction. Scrubber sizing incorporates several design parameters, including gas velocity, liquid-to-gas ratio, and pressure drop. Gas velocity is the primary sizing factor. Increasing the gas velocity will decrease the required size and cost of a scrubber. However, pressure drop will increase with increasing gas velocity. This will also result in increased electricity consumption and, therefore, higher operating costs. Determining the optimum gas velocity involves balancing the capital and annual costs. In most cases, scrubbers are designed to operate within recommended ranges of gas velocity, liquid-to-gas ratio, and pressure drop. These ranges are provided in Table 5.4-5.[11]

Another important scrubber parameter that affects costs is the temperature of the gas stream at saturation once it has been cooled by the scrubber liquid. This temperature affects the volumetric flowrate of the outlet gas and, consequently, the size of the scrubber. In addition, the saturation temperature impacts the scrubbing liquid makeup and the wastewater flowrate. The saturation temperature is a complex function of essentially three variables: the temperature of the inlet gas stream, the absolute humidity of the inlet gas stream, and the absolute humidity at saturation. Typically, the saturation temperature is determined graphically from a psychometric chart once these three variables are known. For this document, the sizing and costing of wet scrubbers were aided by the use of the CO$T-AIR Control Cost Spreadsheets,[12] that employ an iterative procedure for estimating the saturation temperature.

Table 5.4-4. Capital Cost Factors for a Typical Scrubber (Reference 10).

Cost Item	Factor
Direct Costs	
Purchased equipment costs	
Scrubber + auxiliary equipment	As estimated (A)
Instrumentation	0.10 A
Sales taxes	0.03 A
Freight	0.05 A
Total Purchased Equipment Cost (PEC)	B = 1.18 A
Direct installation costs	
Foundations and supports	0.06 B
Handling and erection	0.40 B
Electrical	0.01 B
Piping	0.05 B
Insulation for ductwork	0.03 B
Painting	0.01 B
Total direct installation cost	0.56 B
Site Preparation and Buildings (Site)	As required
Total Direct Cost (DC)	1.56 B + Site
Indirect Costs (installation)	
Engineering	0.10 B
Construction and field expense	0.10 B
Contractor fees	0.10 B
Start-up	0.01 B
Performance test	0.01 B
Model study	Model
Contingencies	0.03 B
Total Indirect Cost (IC)	0.35 B
Total Capital Investment = DC + IC	1.91 B + Site + Model

Table 5.4-5. Recommended Gas Velocities, Liquid/Gas Ratios, and Pressure Drops for Particulate Wet Scrubbers (Reference 9).

Scrubber Type	Velocity (ft/sec)	Liquid/Gas Ratio (gal/1000 ACFM)	Pressure Drop (inches H_2O)
Venturi	90-400[a]	4-100	<100
Impingement plate	<14	2-10	2-3[c]
Spray chamber	10	---	2-4
Cyclonic spray chamber	105-140[b]	7	4-6
Packed tower			
Vertical	2-6	---	---
Horizontal	4-8	---	---

[a] Venturi throat velocity varies with pressure drop, volumetric flowrate, gas density, and liquid/gas ratio as follows: v_t = throat velocity (ft/sec) = $C(\Delta P/\rho_g)^{0.5}$, ΔP = pressure drop (inches H_2O), ρ_g = gas density (lb/ft^3), L/G = liquid/gas ratio (gal/1000 ACFM), C = 1,060 exp(-0.0279 L/G).

[b] Varies with pressure drop and gas density.

[c] Pressure drop per plate.

Once a scrubber has been properly designed and sized, the costs can generally be expressed as a function of the inlet or total gas flowrate.[9] Cost curves are shown below for the following types of scrubbers: venturi, impingement plate, and packed tower.

All the estimates for scrubber capital costs have been escalated to third quarter 1995 dollars. However, the capital costs presented in this section can be escalated further to reflect more current values through the use of the Vatavuk Air Pollution Cost Control Indexes (VAPCCI), which are updated quarterly, available on the OAQPS Technology Transfer Network (TTN), and published monthly in *Chemical Engineering* magazine. The VAPCCI updates the PEC and, since capital costs are based only on the PEC, capital costs can be easily adjusted using the VAPCCI. To escalate capital costs from one year ($Cost_{old}$) to another more recent year ($Cost_{new}$), a simple proportion can be used, as follows:[13]

$$Cost_{new} = Cost_{old}(VAPCCI_{new}/VAPCCI_{old})$$

The VAPCCI for wet scrubbers for third quarter 1995 was 114.7.

Venturi Scrubbers: Venturi scrubber costs are based on data for two ranges of gas flowrates. Cost curves for scrubbers treating less than 19,000 ACFM are provided in Figure 5.4-14. Cost curves for venturi scrubbers capable of handling greater than 19,000 ACFM but less than 59,000 ACFM are shown in Figure 5.4-15. For total flowrates greater than 59,000 ACFM, the gas stream should be divided evenly and treated by two or more identical scrubbers (with inlet flowrates of <59,000 ACFM) operating in parallel.

The most common construction material for venturi scrubbers is carbon steel. Special applications may require other materials, such as rubber-lined steel, epoxy-coated steel, fiber-reinforced plastic (FRP), that will increase the cost of the unit.[9] Separate cost curves for carbon steel and other specialized materials are included in Figures 5.4-14 and 5.4-15.[12]

Impingement Plate Scrubbers: Impingement plate scrubber costs are dependent on the number of plates and the total gas flowrate. The costs for impingement scrubbers are based on data that corresponds to a total gas flowrate between 900 and 77,000 ACFM or above. For total gas flowrates above 77,000 ACFM, multiple scrubbers are required. Figure 5.4-16 presents cost curves for impingement plate scrubbers with total gas flowrates between 900 and 77,000 ACFM. Cost curves for scrubbers with total flowrates above 77,000 ACFM are shown in Figure 5.4-17[12] and require the use of 2, 3, or 4 identical scrubber units. All the cost correlations shown here are for sieve plate scrubbers with three plates. Impingement plate scrubbers are usually constructed with carbon steel. Some applications may require more expensive materials, such as coated carbon steel, FRP, or polyvinyl chloride (PVC).[9]

Packed-bed Scrubbers: The costs for packed-bed scrubbers depend on the inlet gas velocity/column diameter, orientation of the column (vertical vs. horizontal), height of packing material, and the presence of any auxiliary equipment. Figures 5.4-18 and 5.4-19 present costs curves for two types of packed-bed scrubbers. Figure 5.4-18 presents a cost curve for a small vertical column packed-bed scrubber. The costs for this unit vary with the column diameter, which can range from 1 to 2.5 feet. Gas flowrates range from 200 to 1200 ACFM.[9] For Figure 5.4-18, the scrubber is assumed to be constructed of FRP with 6 feet of polypropylene packing. Costs also include the costs for a spray nozzle, liquid distributor, and mist eliminator. Figure 5.4-19 provides a cost curve for a large packed-bed scrubber with horizontal gas flow from 800 to 80,000 ACFM. Costs for this unit are based on the use of PVC or FRP construction materials and a design that includes a spray section, a 1-foot packed bed, and a mist eliminator.[9] Capital and annual costs are also available from Chapter 9 of the *OAQPS Control Cost Manual* (Reference 14).

5.4.5.2 Annual Costs

The total annual cost of a wet scrubber consists of both direct and indirect costs. Direct annual costs are those associated with the operation and maintenance of the scrubber. These include labor (operating, supervisory, coordinating, and maintenance), maintenance materials, operating materials, electricity, sludge disposal, wastewater treatment, and conditioning agents.[12] Heating and cooling may be required in some climates to prevent freezing or excessive vaporation loss of the scrubbing liquid.[2]

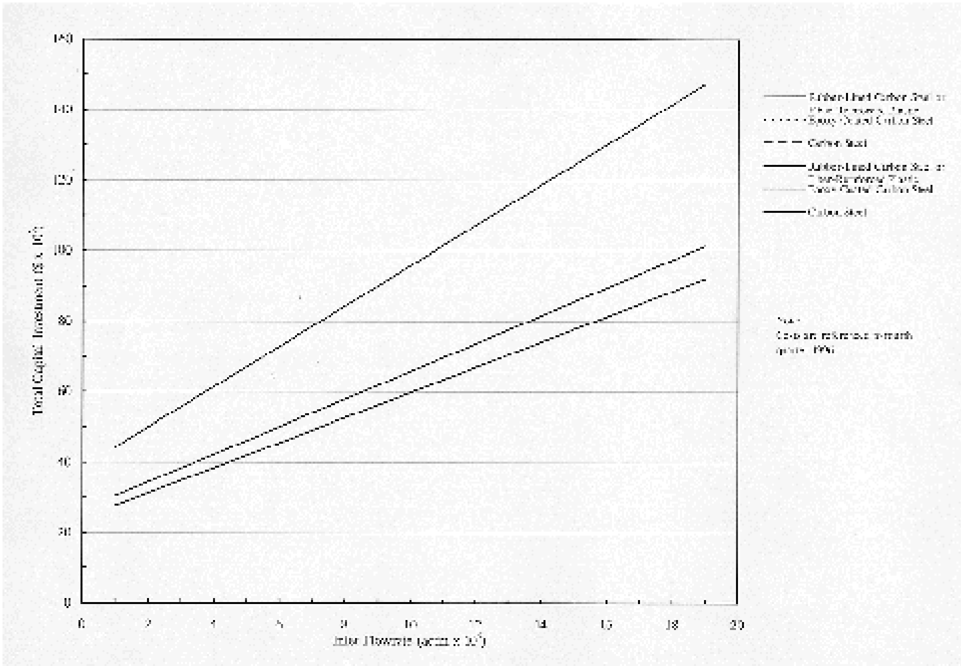


Figure 5.4-14. Venturi Scrubber Capital Costs, Inlet Flowrate < 19,000 ACFM (Reference 11)

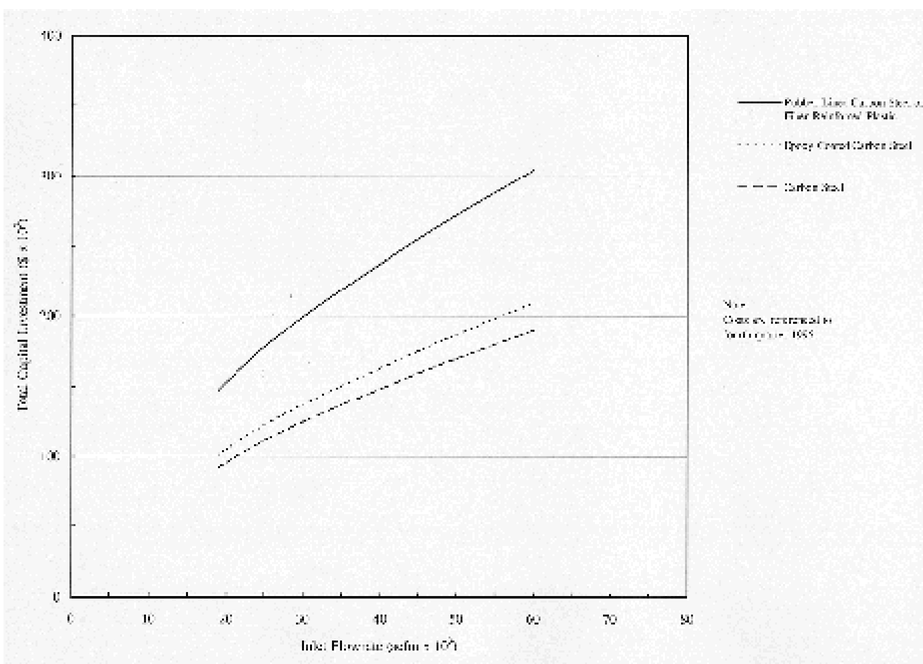


Figure 5.4-15. Venturi Scrubber Capital Costs, Inlet Flowrate >19,000 ACFM, <59,000 ACFM (Reference 11).

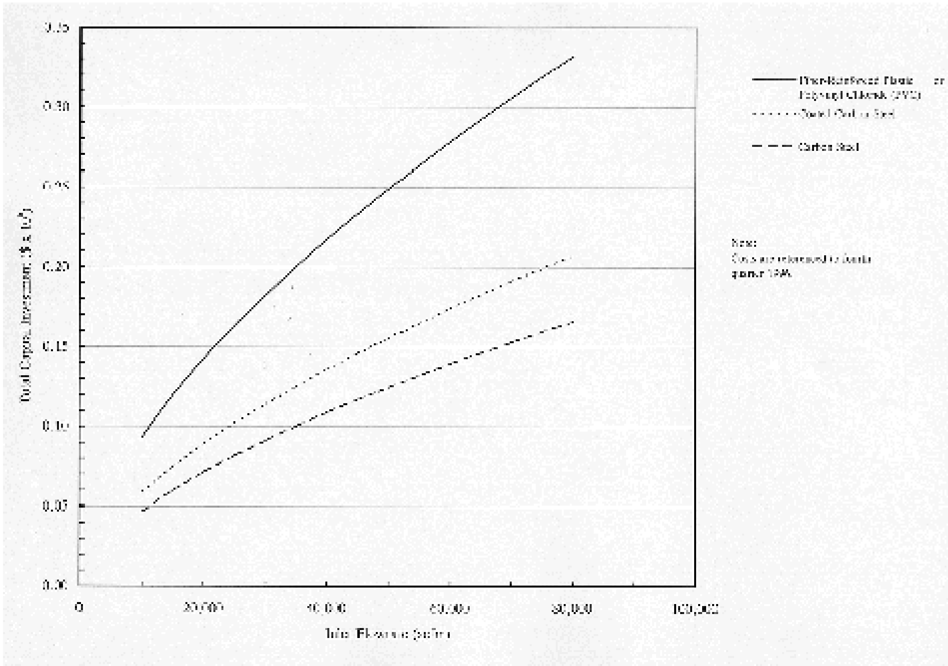


Figure 5.4-16. Impingement Scrubber Capital Costs, Inlet Flowrate <77,000 ACFM (Reference 11).

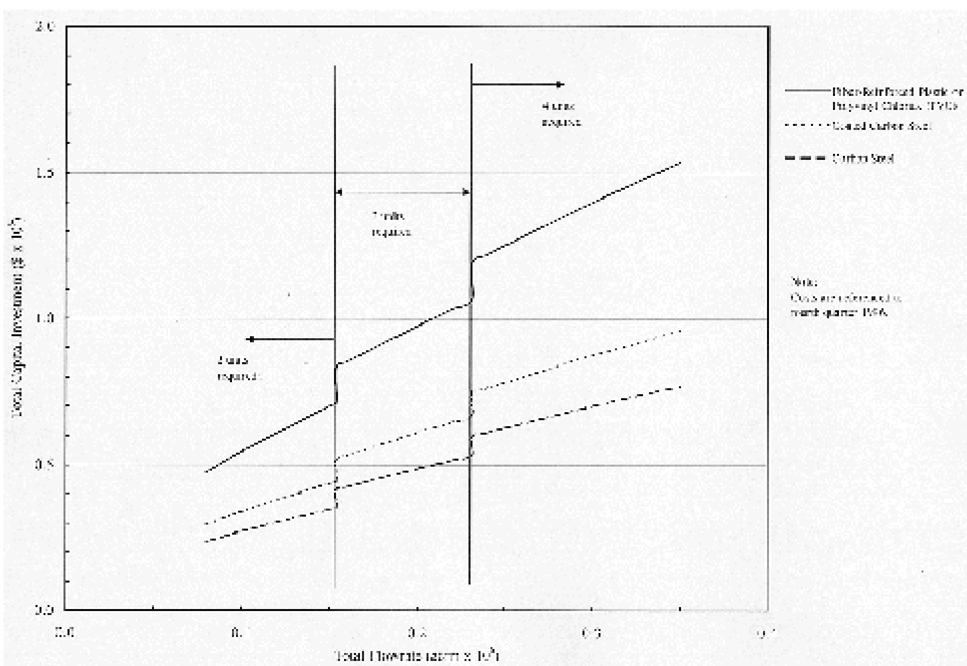


Figure 5.4-17. Impingement Scrubber Capital Costs, Inlet Flowrate >77,000 ACFM (Reference 11).

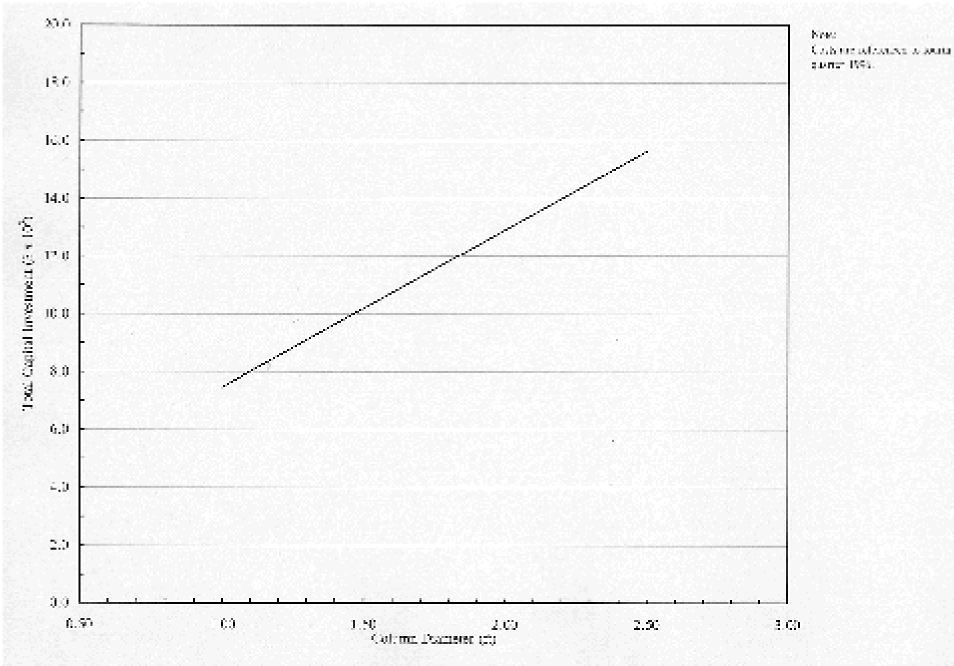


Figure 5.4-18. Vertical Packed-bed Scrubber Capital Costs (Reference 9).

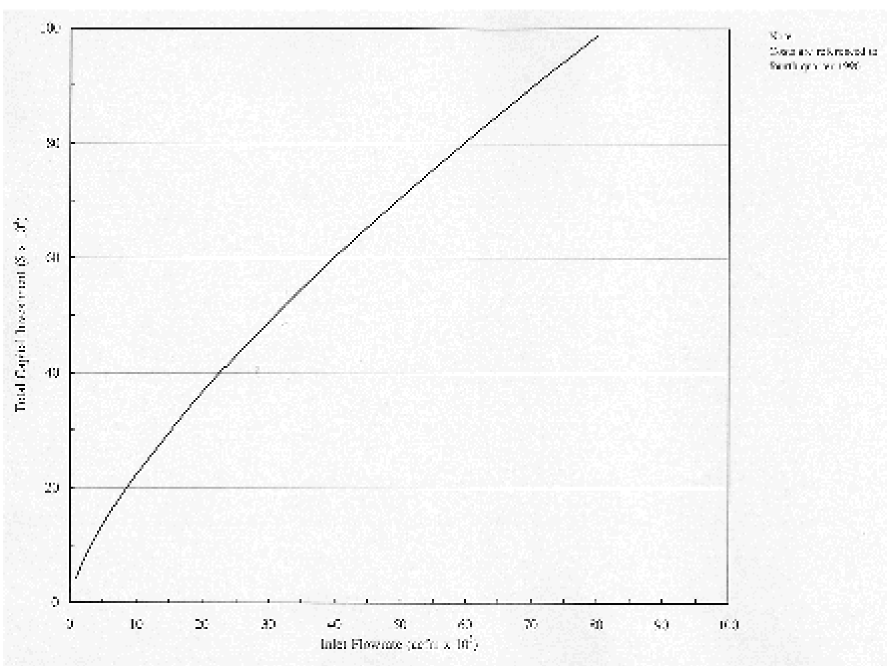


Figure 5.4-19. Horizontal Packed-bed Scrubber Capital Costs (Reference 9).

Indirect annual costs include taxes, insurance, administrative costs, overhead, and capital recovery. All of these costs except overhead are dependent on the TCI. Table 5.4-6 lists the parameters that impact wet scrubber annual costs with typical values provided for each parameter. Table 5.4.7 provides the annual cost factors for scrubbers. Annual costs for scrubbers are difficult to generalize because these costs are very site-specific.

5.4.6 Energy and Other Secondary Environmental Impacts

The secondary environmental impacts of wet scrubber operation are related to energy consumption, solid waste generation, and water pollution. The energy demands for wet scrubbers generally consist of the electricity requirements for fan operation, pump operation, and wastewater treatment. Charged scrubbers have additional energy demands for charging the water droplets and/or PM. Energy demands for wastewater treatment and charged scrubbers are very site specific and, therefore, are not estimated here.[2]

The fan power needed for a scrubber can be estimated by the following equation:[14]

$$\text{Fan Power (kW-hr/yr)} = 1.81 \times 10^{-4}(V)(\Delta P)(t) \qquad \text{(Eq. 5.4-1)}$$

where V is the gas flowrate (ACFM), ΔP is the pressure drop (in. H_2O), t is the operating hours per year, and 1.81×10^{-4} is a unit conversion factor. Electricity costs for fan operation can be determined by multiplying the cost of electricity (in $/kW-hr) by the fan power. Pump power requirements for wet scrubbers can be determined as follows:[14]

$$\text{Pump Power (kW-hr/yr)} = (0.746(Q_l)(Z)(S_g)(t)) / (3{,}960\ \eta) \qquad \text{(Eq. 5.4-2)}$$

where Q_l is the liquid flowrate (gal/min), Z is the fluid head (ft), S_g is the specific gravity of the liquid, t is the annual operating time (hr/yr), η is the pump-motor efficiency, and 0.746 and 3,960 are unit conversion factors.

Wet scrubbers generate waste in the form of a slurry. This creates a need for both wastewater treatment and solid waste disposal operations. Initially, the slurry should be treated to remove and clean the water. This water can then be reused or discharged. Once the water is removed, the remaining waste will be in the form of a solid or sludge. If the solid waste is inert and nontoxic, it can generally be landfilled. Hazardous wastes will have more stringent procedures for disposal. In some cases, the solid waste may have value and can be sold or recycled.[2]

Table 5.4-6. Annual Cost Parameters for Particulate Scrubbers (Reference 12).

Parameter	Description	Typical Values
Direct Cost Parameters		
Operating factor (OF)	Hours of scrubber operation per year	8,640 hr/yr
Operator labor rate (OR)	Operator labor pay rate	$12.50/hr[a]
Operator shift factor (OS)	Fraction of operator shift on scrubber	0.25[b]
Supervisor labor factor (SF)	Fraction of operator labor cost	0.15[b]
Maintenance labor rate (MR)	Maintenance labor pay rate	1.1 x OR[b]
Maintenance shift (MS) factor	Fraction of maintenance shift on scrubber	0.25[b]
Maintenance materials factor (MF)	Fraction of maintenance labor cost	1.0[b]
Electricity rate (ER)	Cost of electricity	$0.07/kW-hr[a]
Chemical cost (CC)	Cost of chemical conditioning agents	$/lb (Site specific)
Chemical rate (CR)	Rate of chemical use	lb/hr (Site specific)
Wastewater treatment (WT)	Cost of treating scrubber effluent	$/gal (Site specific)
Throughput (T)	Rate of liquid throughput	gal/hr (Site specific)
Waste fraction (WF)	Fraction of throughput that is wast	Site specific
Indirect Cost Parameters		
Overhead factor (OV)	Fraction of total labor and (MM) costs	0.60[b]
Annual interest rate (I)	Opportunity cost of the capital	7 percent[b]
Operating life (n)	Expected operating life of scrubber	10 years[b]
Capital recovery factor (CRF)	Function of (n) and (I)	0.1424[c]
Taxes (TAX)	Fraction of the TCI[d]	0.01[b]
Insurance (INS)	Fraction of the TCI[d]	0.01[b]
Administrative costs (AC)	Fraction of the TCI[d]	0.02[b]

[a] Estimated for 1996 from currently available information.

[b] Estimates from "CO$T-AIR" Control Cost Spreadsheets (Reference 12).

[c] Capital Recovery Factor is calculated from the following formula: $CRF = \{I(1+I)^n\} \div \{(1+I)^n - 1\}$, where I = interest rate (fraction) and n = operating life (years).

[d] The total capital investment (TCI) can be escalated to current values by using the Vatavuk Air Pollution Control Cost Indexes (VAPCCI), described in Section 5.4.5.

Table 5.4-7. Annual Cost Factors for Particulate Scrubbers (Reference 11).

Cost Item	Formula[a]	Factor
Direct Costs		
Labor		
Operator (OL)	(OF)×(OR)×(OS)	A
Supervisor (SL)	(SF)×(OL)	0.15 A
Maintenance (ML)	(OF)×(MR)×(MS)	1.1 A
Maintenance materials (MM)	(MF)×(ML)	1.1 A
Electricity (E)	Power[b] × (ER)	E
Chemicals (C)	(OF)×(CR)×(CC)	C
Wastewater treatment (W)	(OF)×(T)×(WF)×(WT)	W
Total Direct Cost (DC)		3.35 A + E + C + W + D
Indirect Costs		
Overhead	(OV)×(OL+SL+ML+MM)	2.01 A
Capital Recovery	(CRF)×(TCI)	0.1424 TCI
Taxes	(TAX)×(TCI)	0.01 TCI
Insurance	(INS)×(TCI)	0.01 TCI
Administrative Costs	(AC)×(TCI)	0.02 TCI
Total Indirect Cost (IC)		2.01 A + 0.1824 TCI
Total Annual Cost (DC + IC)		5.36 A + 0.1824 TCI + E + C + W + D

[a] Includes values also described in Table 5.4-6.

[b] Equal to total power requirements, e.g. fan, pump, etc.

5.4.7 References for Section 5.4

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