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Revision Memo

06/04	Minor editorial changes and clarifications. Inclusion of scrubbing process for NO _x removal. Minor editorial changes and clarifications. Inclusion of Jet Ejector Venturis in examples.
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1 SCOPE

This section discusses the use of wet gas scrubbers for air pollution control applications. FCCU scrubbing systems are emphasized because they have been ExxonMobil's major use of scrubber technology for environmental control. Wet gas scrubbing systems are capable of simultaneously removing both particulate matter and gases from gas streams. The information presented here provides the designer with background on the principles of wet gas scrubbing; it is not sufficient to create a detailed process design.

Brief descriptions of a number of scrubber types and configurations are presented, as well as mathematical models that describe the particulate collection performance of the high-energy venturi scrubbers commonly used by ExxonMobil. Components and characteristics common to all scrubber types are discussed briefly, but the most detailed information is provided only for the type of scrubber ExxonMobil calls HEV's or high-energy venturi scrubbers.

The following section focuses mainly upon wet gas scrubbing for particulate removal. Although basic principles of gaseous collection are presented here, more in-depth information, if necessary, should be obtained from the Distillation and Gas Processes Section of ExxonMobil Research and Engineering.

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3 BACKGROUND

Scrubbers have found widespread use in air pollution control applications due to their ability to simultaneously remove gaseous pollutants and particulate. In addition, they have high collection efficiency in applications where baghouses, electrostatic precipitators and cyclones cannot be effectively utilized (such as the collection of "sticky," flammable, or corrosive particles). Scrubbing removes particulate by washing it from the flue gas stream with a liquid. Simultaneously, pollutant gases are removed by absorption into the liquid, and in certain applications, by subsequent reaction with a buffered solution contained in the liquid. There are a wide variety of configurations and methodologies available for scrubbing operations. Regardless of the specific design, however, the separation of the pollutants from the gas by scrubbing requires three fundamental steps:

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- Separation of gas-borne contaminants from the gas stream by deposition or absorption onto a collecting surface.
- Retention of the deposit on or in the collector.
- Separation of the contaminant from the collecting substance, and subsequent recovery of the liquid and disposal of the contaminants.

The separation of gas-borne contaminants from the gas stream is accomplished by bringing the gas into contact with a collecting liquid. The contaminants may be captured by the liquid itself or, less typically, may first be caught on a scrubber structure (such as an impingement plate) and then washed off by the liquid. Regardless of the surface utilized, the final result is capture of particulate and acid gases in the liquid. The main mechanism of particle collection in a scrubbing system is driven by the relative velocity differences between particulate matter and the collection surface. Thus, more vigorous gas-liquid contact will result in higher collection efficiencies. Both the scrubbing liquid and the "cleaned" gas stream enter a separation vessel, where the contaminated liquid is separated from the gas stream. This is usually accomplished in a separate vessel called a separator or disengaging drum, where the drops are collected naturally (via gravity) or via centrifugal forces. Having been separated from the pollutant-bearing liquid, the cleaned gas can be vented to the atmosphere.

Solids must be removed from the scrubbing liquid and disposed of in an environmentally sound manner. Similarly, adverse chemical species, such as absorbed acid gases, must be reduced or neutralized. To prevent solids build-up in the scrubbing system, a purge stream is drawn and sent to a treatment facility. The purge stream may be treated in the plant's wastewater treatment facility, or may be sent to a separate purge treatment unit, depending upon the nature of the process and the quantity of pollutants. Regardless of where the purge stream is treated, the facility will include measures to separate captured, suspended, and dissolved solids from the liquid and to reduce the acidic nature of the liquid before it is released into the environment.

In order to select a specific pollutant control alternative, one must have information pertaining to the particular application and site. Reviewing the advantages and disadvantages of each type of air pollution control equipment, however, may provide a preliminary screening. The following list provides some of the advantages and disadvantages generally associated with scrubbing systems:

Advantages of Scrubbing Systems:

- Relatively high collection efficiency (90 to 99+%), depending on the particle size distribution.
- Relatively small space requirements.
- Ability to simultaneously collect gases as well as particulate.
- Ability to handle high-temperature, high humidity gas streams.
- Capable of removing "sticky", flammable and/or corrosive particles.
- Ability to achieve high collection efficiencies of fine particulate (however, at the expense of pressure drop).
- Generally lower capital costs than fabric filters or electrostatic precipitators.

Disadvantages of Scrubbing Systems:

- May create water disposal problem.
- Product is collected wet.
- Corrosion problems can be more severe than with dry systems.
- Steam plume opacity and droplet entrainment may be objectionable.
- Pressure drop and horsepower requirements may be high if pressure is unavailable.
- Solids build-up at the wet-dry interface may be a problem.

As early as 1974, New Source Performance Standards (NSPS) were promulgated to regulate the amount of particulate and carbon monoxide, which could be emitted from a Fluid Catalytic Cracking Unit (FCCU). On August 17, 1989 the US EPA promulgated an additional NSPS for sulfur dioxide emissions from FCCU's. In an NSPS, the EPA is required to set emissions standards based upon Best Demonstrated Technology (BDT). Under the current regulations, the EPA has chosen scrubbers as the BDT for reducing SO₂ emissions from FCCU units.

- ♦ As early as 1971, ExxonMobil began development work on a scrubbing system to control atmospheric emissions from FCC's, and March 1974 marked the first start-up of a venturi WGS system (a jet ejector venturi system) in refinery service. Since that time,

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over 15 ExxonMobil designed units have been put in place on FCC's. These include units at Baytown, Baton Rouge, Beaumont, Chalmette and the former Bayway refinery, as well as numerous licensed units. Additionally, fixed and variable throat venturi scrubber systems have been installed to remove particulates from FLEXICOKING units at the Baytown and Rotterdam refineries, and fixed throat venturis have been used as either the back-up unit or primary unit to capture particulates from the Benicia and Syncrude Coke Silos.

4 WET SCRUBBER CAPTURE MECHANISMS

There are a number of mechanisms by which a pollutant can be separated from a gas stream. The particular mechanism(s) utilized by a given air pollution control device will depend upon the device configuration, and the characteristics of the pollutant(s) which it is attempting to capture. The following sections briefly describe the possible mechanisms by which particulate and gases can be captured in wet gas scrubber systems.

4.1 SEPARATION OF PARTICULATE FROM THE GAS STREAM

Separation of the particulate from the gas stream requires both a force to provide relative motion between the particles and the collecting surface, and a gas residence time sufficient for the particles to come into contact with the surface. The three collection mechanisms of greatest importance for most scrubber systems are (in order of importance): Inertial Impaction, Direct Interception, and Diffusional Deposition. [Figures 1](#) through [3](#) illustrate these three mechanisms of particle deposition.

4.1.1 Inertial Impaction

The main mechanism by which particulate is collected in a typical scrubbing system is inertial impaction. Impaction is driven by the velocity differences between the dust particles and the collection surface. In the case of a venturi scrubber, water droplets provide the collection surface. Due to their inertia, particles which have a mass much greater than that of the surrounding air molecules will tend to travel in a straight-line path, and may depart from the gas streamlines that flow around the collection surface (see [Figure 1](#)). If the particle deviates far enough from the gas streamlines to contact the collecting surface, it will be captured. In general, the larger the velocity difference between the particle and the collection surface, the greater the collection efficiency, as the streamlines will diverge much closer to the collection surface, and the particles themselves will have increased inertia.

4.1.2 Direct Interception

The direct interception collection mechanism is based upon particle size. A given particle is assumed to follow the gas streamlines around the collection surface. If the center of a particle is traveling along a streamline which is within one particle radius of the collection surface, the particle will contact the collection surface and be captured, without the influence of inertia or particle meander (see [Figure 2](#)). As with inertial impaction, collection efficiency will increase when the velocity difference between the particle and the surface is large, due to the divergence of the gas streamlines closer to the collection surface.

4.1.3 Diffusion Interception

Diffusion interception is the main mechanism for the capture of small (sub-micron) particles, particularly those below about 0.3 microns in diameter. These particles do not have sufficient mass or volume to be captured effectively by inertial impaction or direct interception. Gas molecules constantly collide with the particles in the gas stream. For small particles with relatively low mass, these collisions result in a zigzag motion known as Brownian motion. Diffusion interception is the result of the Brownian movement of small particles; their zigzag motion results in deviation from the gas streamlines to the collection surface (see [Figure 3](#)).

4.1.4 Other Mechanisms

Other mechanisms exist by which solid particles can be removed from a gas stream, but the three mechanisms listed above are the most important for wet-gas scrubbing of particles. Among the other mechanisms are gravitational settling, thermal precipitation, electrostatic precipitation, and Stefan flow. The former three collection mechanisms are important for other separation devices, such as electrostatic precipitators, but typically have a relatively small effect on scrubbing systems. Stefan flow, which refers to the flow of gas (and entrained particles) towards a collection surface as a result of the condensation of water upon that surface, can substantially improve the performance of a scrubber. In the event that evaporation occurs, however,

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corresponding flow away from the particle can occur, resulting in decreased particle collection. Condensation of water vapor upon the aerosol particles can also increase efficiency by increasing the effective particle size, thus making the particles more susceptible to capture. However, there are limits to the amount of growth that condensation can have on particles. For example, when the temperature of a high dew point gas, typically 165 to 200°F (73 to 93°C), is cooled considerably, typically to 120 to 140°F (49 to 60°C) all of the particles in the range of 0.1 to 0.9 microns will grow to 0.9 microns. This will have a significant impact on the efficiency of any downstream scrubber. It must also be noted that the degree of cooling to achieve this growth is significant due to the high moisture content of the gas stream.

4.2 PARTICULATE COLLECTION EFFICIENCY

The overall particulate collection efficiency refers to the fraction of total particulate loading that is collected in the scrubbing process. The higher the efficiency, the more particulate is collected. In a given application, however, certain particle size ranges may be captured more readily than others. The collection efficiency of a given size range of particulate is referred to as the grade efficiency. The efficiency correlation presented in this section is dependent upon particle size, and is thus a correlation for grade efficiency. Although the overall efficiency cannot be approximated without a particle size distribution, the correlation can provide a qualitative description of the impact which parameters such as droplet diameter have upon the overall efficiency.

When modeling the collection of particles in a wet-gas scrubbing system, a number of simplifying assumptions are typically made. The most important assumption is that inertial impaction is the only particulate collection mechanism. This assumption may not hold true under all conditions, since the collection of sub-micron particles, for example, is likely to be dominated by diffusion interception. Additionally, the stream exiting the scrubber is typically assumed to be fully saturated. This may not be the case, particularly for very hot or "dry" flue gas streams, where the scrubber is operating at low liquid to gas ratios where extensive evaporation must occur to saturate the stream. For these streams, the residence time in the scrubber nor the amount of available water may not be sufficient for the necessary quantity of water to evaporate.

Generally, when dealing with scrubber systems, all mechanisms save for the inertial impaction are ignored. The particles impact upon the target. The specifics of the target depend upon the scrubber type. In venturi-type scrubbers and spray chambers, the targets are droplets of the scrubbing liquid; in packed, tray, and baffled towers, the targets are either tower internals or liquid streams associated with those internals.

The impaction efficiency is often correlated with the dimensionless parameter called the Stokes, or inertial, number (Stk). It is defined as:

$$\text{Stk} = \frac{u_r \rho_p D_p^2}{18 \mu_g D_t} C_u$$

where: with any dimensionally consistent units (meters, kilograms and seconds, for example):

- u_r = Relative velocity between the target and the particle
- ρ_p = Particle density
- D_p = Particle diameter
- D_t = Target dimension, the choice of which depends upon the scrubber type. For HEV scrubbers, the target dimension is the droplet diameter. In packed towers, the packing diameter is the dimension of interest, and in baffle towers, the width of the baffle is the characteristic dimension.
- μ_g = Gas viscosity
- C_u = Cunningham, or "slip" correction factor, which is most significant for small (diameter < 1 μm) particles. As a particle's diameter decreases and approaches the mean free path of the gas molecules, collision between the gas molecules and the particles becomes less likely. Small particles can more easily "slip" between the gas molecules. Their tendency to "slip" between gas molecules allows small particles to cross the streamlines of the bulk gas flow more readily than large particles, and results in an increased probability of collision with the obstacle around which the gas is flowing.

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$$C_u = 1 + \frac{2\lambda}{D_p} \left[1.26 + 0.4 \exp \left(-0.55 \frac{D_p}{\lambda} \right) \right]$$

where: λ = Mean free path of gas molecules. If λ is in μm , then:

$$\lambda = 12.38 \left(\frac{\mu_g}{P_g} \right) \sqrt{\frac{T_g}{M}} \quad (\text{Customary Units})$$

$$\lambda = 47.42 \left(\frac{\mu_g}{P_g} \right) \sqrt{\frac{T_g}{M}} \quad (\text{Metric Units})$$

where: μ_g = Gas viscosity in cP (cP)
 P_g = Gas pressure in psia (kPa)
 T_g = Gas temperature in °R (K)
 M = Gas molecular weight

Treating the particles according to Stokes' Law, their equations of motion can be found by equating the particle inertia force to the drag on the particle due to the air. Solutions to these equations will depend upon the velocity field, and thus will vary with the collector shape and the boundary conditions assumed. The maximum, or "ideal" flow and values of Stk greater than 0.1, the experimental values of inertial impaction collection efficiency, η_p , for spheres can be approximated by the correlation:

$$\eta_p = \left(\frac{2 \text{Stk}}{2 \text{Stk} + 0.7} \right)^2$$

where: η_p = The grade collection efficiency for particles of a particular diameter

The overall collection efficiency of a scrubber increases with increasing grade efficiency, which in turn, increases with an increasing Stokes number (Stk). For a particular scrubber type, the collection efficiency also depends upon other variables (i.e., the liquid-to-gas ratio and geometric factors) that do not appear in the Stoke's number. The [HIGH-ENERGY VENTURI SCRUBBER PERFORMANCE](#) section in this document provides an example of the effect, which these parameters have upon scrubber efficiency (for at least one scrubber type).

4.3 COLLECTION OF GASEOUS COMPONENTS

This section presents only the basic principles of gaseous collection. More detailed information can be obtained from the Distillation and Gas Processes Section of ExxonMobil Research and Engineering.

One of the main advantages of scrubber systems is their ability to remove both particulate and gaseous pollutants simultaneously. The process by which a gas or gaseous component is "captured" by a liquid is known as absorption. Absorption occurs when the solute gas and liquid absorbent are vigorously contacted and a concentration gradient is established between the two phases. Mass transfer between the two phases results in net movement of the solute gas molecules from relatively high concentrations in the gas phase to lower concentrations in the liquid phase. The rate of interphase mass transfer is controlled largely by the diffusivities between the phases, the effective surface area between the phases, and the concentration gradients. In cases where the gaseous components react with the liquid to form a new compound (chemical absorption), the concentration gradients are altered, resulting in more rapid diffusion and a greater pollutant handling capacity for the liquid.

When applicable, chemical absorption processes typically dominate. The rate of chemical absorption is typically much greater than the rate at which the gaseous components can diffuse into the droplet. The physical processes of diffusion and convection are still important, however, as they control the rate at which the reactants are brought together. In a gas film controlled where a fast

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chemical reaction occurs between the absorbed gas and scrubbing liquid, the rate limiting step in the absorption process is often considered to be gas diffusion through a thin boundary layer at the gas-liquid interface.

Physical and chemical equilibrium conditions play an important role in the selection of a scrubbing liquid as they impose an upper limit on the quantity of gas that can be absorbed. Departure from equilibrium provides the driving force for mass transfer, and once equilibrium is established, no further net absorption can occur. Thus, high gas solubilities are desirable in a scrubbing liquid. A particular scrubbing liquid is chosen for its absorption capacity for the gas (considering both solubility and chemical absorption), its selectivity, its (preferably low) vapor pressure, ease of regeneration, cost, flammability, toxicity, corrosiveness, viscosity and thermal stability.

4.3.1 Physical Equilibrium Conditions

In the absence of chemical reactions, the relationship between the pollutant concentration in the gas and liquid mixtures can be expressed in several ways. One of the most common expressions relates the vapor phase mole fraction of a component A, y_A , to a function of the activity coefficient of the species, γ_A , the mole fraction of the pollutant in the liquid, x_A , the saturation vapor pressure of the liquid, p_A^{sat} , and the total pressure in the system, P .

$$y_A P = \gamma_A x_A p_A^{\text{sat}}$$

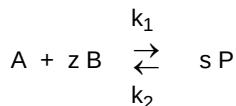
Under typical scrubber operating conditions, Henry's law can be applied:

$$y_A P = H_A x_A$$

where H_A , the Henry Coefficient, must be experimentally determined. Although values have been tabulated in most reference books for a number of systems the published values often differ widely. High values of H_A indicate low scrubbing capacity of the liquid for the pollutant, while low values indicate a high absorption capacity. To absorb a particular quantity of gas in the absence of chemical reactions, a much larger amount of liquid would be necessary for systems with a high value of H_A (on the order of more than 100 atmospheres) than in the case of a system with a small value of H_A .

4.3.2 Chemical Equilibrium Conditions

Gas absorption often uses a solvent that reacts with the gas. When a chemical reaction takes place in the liquid with the absorbed molecules as they are diffusing, the liquid concentration is reduced and the driving force for absorption increases. In the example of a chemical absorption process given below, diffusion or convective processes transfer the pollutant A to the liquid. Once in the liquid, it encounters a reactant B, and chemical conversion to a new product(s) P, which has no polluting properties, occurs:



where z and s are stoichiometric coefficients and k_1 and k_2 are rate constants for the forward and reverse reactions, respectively.

The chemical equilibrium constant, $K_{A,\text{ch}}$, is defined as follows:

$$K_{A,\text{ch}} = \frac{c_P^s}{c_A c_B^z}, \text{ where } c_A, c_B, c_P \text{ are the concentrations of compounds A, B and P, respectively.}$$

For the chemical absorption process, it is of great advantage when the chemical conversion is product oriented - when the rate of the forward reaction and the equilibrium constant are large. Under these circumstances, the chemical reaction occurs rapidly in the liquid phase close to the interface. Due to the high reaction rate, the absorbed gas is rapidly converted to another compound; thus maintaining a high concentration gradient, substantially accelerating the absorption process and increasing the absorption capacity.

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of the scrubbing liquid. The limiting step in the absorption process will be the rate of gas diffusion through the boundary layer between phases.

4.3.3 Mass Transfer

Diffusion between the gas and liquid phases results in the net movement of the solute gas molecules from the gas phase to the liquid phase. There are two main mechanisms of diffusion; molecular diffusion and eddy diffusion. Molecular diffusion is the mass transfer process that results when a component's concentration varies from point to point in a mixture. Molecules will move from regions of high concentration to regions of lower concentration because of their thermal motion. In a stagnant system, molecular diffusion will be the only mass transfer mechanism. Under these circumstances, the molar flux, and hence the rate of diffusion, is directly proportional to the concentration gradient and the diffusivity of the diffusing component.

In a turbulent systems like a venturi throat, impingement tray or packed tower however, eddy diffusion will typically be the dominant mass transfer mechanism. Eddy diffusion is caused by masses of gas and liquid moving as a whole, and results in a much more rapid mass transfer process than straight molecular diffusion. Mass is transferred by the circulation of fluid eddies, which are the result of velocity fluctuations from point to point in the turbulent fluid. The eddy diffusivity increases with the velocity of the fluid and the degree of turbulence and is generally several orders of magnitude larger than the molecular diffusivity. At high Reynolds numbers in gas mixtures, the eddy diffusivity can be 100 times greater than the molecular diffusivity.

Gas absorption in a typical scrubbing application can be envisioned as occurring in three steps: (1) a component in the gas phase moves to the gas-liquid boundary, (2) the component crosses the boundary, and then (3) the component moves into the bulk of the liquid phase. The rate of transfer in the gas and liquid phases is proportional to the concentration difference between the bulk fluid and the boundary. Depending upon the process conditions in the scrubber, any one of the three steps could be the rate-limiting step in the absorption process. A rate-limiting step is one, which is significantly slower than the other steps in a process, such that the overall rate of the process is equal to that of the limiting step. The rate of absorption under high velocity, high turbulence conditions (such as those occurring in an HEV) when coupled with rapid conversion of the gaseous pollutant(s) by chemical reaction in the liquid, will be limited by the diffusion of gas through the thin interface layer (gas-liquid boundary) between the phases in this gas-film controlled system.

Typically, the smaller the droplet size, the higher the rate of absorption. The rate of mass transfer between phases is often proportional to the area of the thin boundary layer film between phases. The area of thin film between phases is proportional to $1/d$, where d is the diameter of a liquid or gas drop, or the thickness of a liquid film. Thus, from a purely theoretical standpoint, liquid droplets or collection films should be as small as possible for absorption. Practically, the size of the droplets is limited by the amount of power needed to generate the small droplets, the need to separate them from the gas phase later in the process, and by limitations on film thickness due to the surface solid wettability.

The rate and extent of gas absorption in a scrubbing system cannot be easily expressed in the format of a general equation, as any such representation is dependent upon the rate limiting steps in the process. The rate-limiting step in the absorption process for a given scrubber application will depend upon several factors, including the properties of the liquid itself, the vigor of the mixing, the thickness of the collecting liquid surface, and the rate of any chemical reactions in the scrubbing liquid. For more detailed data on absorption processes, the reader should contact the Distillation and Gas Processes Section of ExxonMobil Research and Engineering.

4.3.4 Acid Gas Neutralization in the Scrubber

SO₂ is the most common acid gas removed in scrubbing systems. Alkali injection into the scrubbing liquid is necessary for acid neutralization if a scrubbing system is used to absorb acid gases. The following is a brief description of the neutralization process that occurs in a scrubbing liquid, which has absorbed SO₂ from a gas stream. An example of such a system would be a scrubber in FCCU service. Although the exact equations will vary, neutralization of other absorbed acid gases occurs by a similar set of reactions.

Alkali injection (generally caustic) into the scrubbing liquid is required to neutralize the SO₂ scrubbed out of the flue gas. The caustic is injected via a control valve connected to two parallel pH analyzers on the slurry recirculating loop. The system is designed to maintain the liquid at a pH level of 6.7. Below 6.2 pH, high rates of corrosion will result, while above 8 pH, additional caustic will be consumed by CO₂ absorption.

The following equations show the removal, buffering and regeneration of the buffering system of the slurry:

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Removal: $\text{SO}_2 (\text{g}) + 2\text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{HSO}_3^-$

Buffer: $\text{H}_3\text{O}^+ + \text{HSO}_3^- + \text{Na}_2\text{SO}_3 \rightarrow 2\text{NaHSO}_3 + \text{H}_2\text{O}$

Regeneration: $\text{NaHSO}_3 + \text{NaOH} \rightarrow \text{Na}_2\text{SO}_3 + \text{H}_2\text{O}$

Total caustic usage in the wet gas scrubber system is roughly stoichiometric to the amount of sulfur oxides removed, and must be replenished accordingly.

Oxygen levels in the inlet gas and in solution must be kept low or oxidation of the sulfite buffer will occur (forming sulfate and sulfite salts), and the acids will not be neutralized. Once sulfites are depleted, SO_2 and SO_3 absorbed into the scrubbing liquid will form sulfurous and sulfuric acid. These acids will drop the pH throughout the entire scrubber system, and lead to reduced SO_2 removal and increased corrosion. For this reason, oxygen content levels in the flue gas should be kept below 3 percent (by volume) to maximize SO_2 absorption.

NOx may also be removed using wet gas scrubbing. The majority of NOx from a FCCU or combustion process is NO, which has very low water solubility. However, addition of an oxidizing agent will oxidize NO to higher oxides, which can be removed in the scrubbing process. Sodium chlorite is one such oxidizer. However, it also oxidizes SO_2 , increasing chemical consumption and cost, and thus must be added downstream of SOx removal in a second scrubbing stage.

5 SCRUBBER TYPES

Scrubbers are available in a wide range of designs, collection abilities, and capital and operating costs. They can be categorized according to the mechanisms by which they operate. One characteristic mechanism of a scrubber's operation is the method by which water droplets are created and introduced into the gas stream. Scrubbers can either utilize a mechanically atomized spray, or a gas-atomized spray, where the kinetic energy of the gas stream is used to fragment the liquid into droplets. Additionally, scrubbers can be characterized as high or low energy, depending mainly upon the pressure drop across the scrubber. If the pressure drop resulting from passage through a scrubbing unit is greater than 30 in. (76 cm) of water, then the scrubber is referred to as "high-energy," if less than 30 in. (76 cm) of water, "low energy."

5.1 MECHANICALLY ATOMIZED SPRAY SCRUBBERS

Mechanically atomized spray scrubbers utilize nozzles or some other mechanical device to create and distribute liquid droplets in the gas stream. These droplets provide the collection surface for particulate capture and the increased liquid surface for gas absorption. Mechanically atomized scrubbers are generally characterized as low energy, and have lower pollutant collection efficiencies than most high-energy scrubbers.

5.1.1 Spray Chamber

These low energy scrubbers are perhaps the simplest of all scrubber designs, although several different variations of the basic concept exist. The most common of these is the gravity spray tower (see [Figure 4](#)). Liquid drops are formed by atomization of the liquid in a spray nozzle, and fall through the rising flue gases. For higher gas velocities, a mist eliminator may be necessary to remove any droplets entrained with the gas flow.

This scrubber type is characterized by a relatively low-pressure drop, typically 1 to 2 in. (2.5 to 5 cm) H_2O , and its ability to handle large gas and particulate flows without plugging. Actual particulate collection efficiencies will vary depending upon factors such as residence time, relative flow rate, and pressure from the water sprays, but, in general, spray towers are not as effective as other methods in removing small particulate (< 5 to $10 \mu\text{m}$). Particles larger than $10 \mu\text{m}$ can typically be removed with efficiencies up to about 70%. Use of high-pressure, typically 100 to 400 psi (7.0 to 28.0 kg/cm^2) water sprays may increase the efficiency by as much as 20%. Spray chambers are relatively inexpensive to build and operate, however, and are often used to pre-cool and/or saturate hot streams, and to collect large ($> 25 \mu\text{m}$) particulate.

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5.1.2 Centrifugal Scrubbers

Also known as cyclonic scrubbers, these devices impart a spinning motion to the gas stream (see [Figure 5](#)). Sprays are typically directed through the rotating gas stream to catch particles (although the walls can be wetted also) by impaction. The sprays are either directed inward from the collector wall, or outwards from a central spray manifold.

Centrifugal scrubbers typically operate under a pressure drop between 3 to 8 in. (7.6 to 20.3 cm) of water, with particulate collection efficiency up to 99% for particles greater than about 2 microns in diameter. Due to their low contact energy, they are generally inefficient for collection of particles smaller than 1 to 2 μm in diameter. The gas absorption capabilities of the centrifugal scrubber are slightly better than those of a comparable simple spray tower operating at the same liquid to gas ratio.

5.1.3 Baffled Towers

Baffle towers (see [Figure 9](#)) are collection devices that utilize solid surfaces to cause changes in gas flow and direction. Particle deposition occurs on the baffles due to inertial impaction and direct interception. Atomized liquid is injected into the gas stream and the combined mixture then enters the baffles. Liquid, which collects on the targets, falls to the bottom of the scrubber and into a collection sump. A number of different baffle designs are possible, including shed or disc-and-donut baffles.

Depending upon the type of target plates used, baffle towers can be designed to efficiently (typically about 90 to 95%) scrub particles as small as one or two microns in diameter. Not enough contact energy is provided, however, to provide efficient scrubbing of the sub-micron level. Typical operation of baffle towers for particulate scrubbing entails relatively low pressures drop; about 1 to 3 in. (2.5 to 7.6 cm) of water. In general, baffled towers are less efficient than packed or tray towers, but they are less prone to plugging.

5.1.4 Packed-Bed Scrubbers

Packed-bed scrubbers are commonly applied in the removal of pollutant gases and vapors, but may also be used for the removal of particulate matter. They are generally more efficient than spray or baffled towers, but result in a larger pressure drop across the scrubber. They can be operated either under co-current (horizontal or vertical), crosscurrent or counter-current flow regimes, depending upon the required flow rates and collection efficiencies (see [Figure 6](#)). Generally, counter-current flow provides the most efficient collection of particulates, but for high velocities (which are necessary for high efficiency removal of small particulates), co-current flow may be necessary to avoid flooding. The coarseness of the bed packing will depend upon the size of the particles to be collected; coarse packing will be used to remove larger particles and will be capable of handling larger and/or faster gas flows, while finer packing may be used to remove smaller particulate. Fine packing results in a higher pressure drop and have a greater potential for plugging. The final choice of packing material will be restricted by such considerations.

5.1.5 Jet Ejector Venturi Scrubbers

The jet ejector venturi scrubber (JEV) relies upon a co-current water jet from a spray nozzle located at the top of the jet scrubber to induce or increase air pressure within the scrubber. The water spray must be of sufficient volume and pressure to provide both adequate air entrainment and enough contacting power for scrubbing of particulate. The spray is introduced at a point above the "throat", or constricted section of the scrubber. Gas and liquid then pass through the throat, under conditions of high turbulence, and continue through the diverging section of the scrubber (one of expanding cross-sectional area). The gas-liquid contact provided by the sprays and the turbulence in the throat provide the scrubbing mechanism.

The JEV is often used as a gas absorption tool. Their relatively good dust collection efficiency (approximately 99%) and lack of any moving parts also makes JEV's an option for handling abrasive or sticky particulate materials. Gas pressure drop is negligible because the liquid spray provides the contacting power. Early FCCU scrubbers were of the JEV design to avoid backpressure on the CO boiler and upstream ducting for existing FCCU's. In most cases, these scrubbers are used to boost gas pressure or to induce a draft on the inlet side. Pressure increases of up to 7 in. (17.8 cm) of water can be induced, but rises of 1 to 3 in. (2.5 to 7.6 cm) of water column are more typical.

5.2 GAS ATOMIZING SPRAY SCRUBBERS

Gas atomizing scrubbers utilize the kinetic energy of the gas to create and distribute droplets of scrubbing liquid in the gas stream. The manner by which this is accomplished will differ for different scrubber types. Generally, the high velocity gas contacts a film,

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