United States Environmental Protection Agency Air Pollution Training Institute MD 20 Environmental Research Center Research Triangle Park, NC 27711 EPA 450/2-82-020 March 1984

Air

# APTI Course SI:412C Wet Scrubber Plan Review

## Self-instructional Guidebook



TECHNICAL DOCUMENT COLLECTION

United States Environmental Protection Agency Air Pollution Training Institute MD 20 Environmental Research Center Research Triangle Park, NC 27711 EPA 450/2-82-020 March 1984

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## APTI Course SI:412C Wet Scrubber Plan Review

## Self-instructional Guidebook

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## **Course Introduction**

## Description

This course is designed for engineers and other technical persons responsible for reviewing plans for the installation of wet scrubbers. This course focuses on review procedures for wet scrubbers used to reduce particulate and gaseous emissions from industrial sources. Major topics related to wet scrubbers include the following:

- General description
- Particle collection and absorption theory
- Estimating collection efficiency
- Components
- Use in flue gas desulfurization (FGD)
- Operation and maintenance problems.

## **Course Goal and Objectives**

#### Course Goal

To familiarize you with wet scrubbers—how they operate, their common operation and maintenance problems, and the review steps for evaluating their installation plans.

#### Course Objectives

At the end of the course, you should be able to-

- 1. recognize various scrubbers and briefly describe their operation,
- 2. briefly describe the mechanisms for particle collection and gas absorption in a scrubber,
- 3. recognize which scrubbers are used mainly for particle collection and which are used mainly for gaseous pollutant removal,
- 4. briefly describe four FGD systems used for removing sulfur dioxide emissions from boilers,
- 5. list three key design parameters affecting particle and gaseous pollutant removal, and
- 6. recognize typical operation and maintenance problems associated with each wet scrubber.

## **Requirements for Successful Completion**

In order to receive 4.0 Continuing Education Units (CEUs) and a certificate of course completion, you must achieve a final examination grade of at least 70%.

### Materials

#### Reading

This text-supplementary reading materials are not required.

## Using the Guidebook

This book directs your progress through the course. Ten lessons describe wet scrubbers and how they are used to control particulate and gaseous emissions.

There is a review exercise at the end of each lesson. To complete an exercise, place a piece of paper across the page, covering the questions below the one you are answering. After answering the question, slide the paper down to uncover the next question. The answer for the first question will be given on the right side of the page, separated by a line from the second question, as shown here. All answers to review questions will appear below and to the right of their respective questions. The answer will be numbered to match the question. **Please do not write in this book.** Complete each review exercise in the lessons. If you are unsure about a question or answer, review the material preceding the question. Then proceed to the next section.

Review Exercise			
1. Question louto ull i clio yllonulic			
2. Questionali aul li uluouyic a	1. Answer ulio		
3. Question , in lor the ult cllo yllon	2. Answer		

#### Lesson Content

- Lesson goal and objectives
- Text of lesson
- Review exercise and review exercise answers

The material contained in Lessons 9 and 10 is a review of the design theory for particle scrubbers and gaseous pollutant absorbers. Much of this material was covered in APTI Courses 413, Control of Particulate Emissions, and 415, Control of Gaseous Emissions.

However, these lessons provide a good review of the design theory and equations used to estimate collection efficiency, liquid-injection rates, absorber diameter, and the number of plates used in a plate tower. Material in all 10 lessons is covered in the final examination.

## Instructions for Completing the Final Examination

Contact the Air Pollution Training Institute if you have any questions about the course or when you are ready to receive a copy of the final examination.

After completing the final exam, return it and the answer sheet to the Air Pollution Training Institute. The final exam grade and course grade will be mailed to you.

> Air Pollution Training Institute Environmental Research Center MD 20 Research Triangle Park, NC 27711

# Lesson 1 Introduction to Wet Scrubbers

## Lesson Goal and Objectives

#### Goal

To familiarize you with the variables that affect particle and gas collection in wet scrubbers.

#### **Objectives**

Upon completing this lesson, you should be able to-

- 1. list four advantages and disadvantages of using wet scrubbers to collect particles and gases rather than using other air pollution control devices,
- 2. describe the two most important mechanisms for collecting particles in wet scrubbers,
- 3. name three process variables that affect particle collection in a wet scrubber,
- 4. describe the process of absorption, and
- 5. list three conditions that will enhance the absorption process.

## Introduction

Wet scrubbers are air pollution control devices that use liquid to remove particles or gases from industrial exhaust streams. The dirty exhaust stream is brought into contact with the liquid by spraying it with the liquid, by forcing it through a pool of liquid, or by some other contact method. When wet scrubbers are used for removing **particles**, the particles are captured by and incorporated into liquid droplets. These droplets must then be separated from the clean exhaust stream. When wet scrubbers are used for removing **gases**, the gases are dissolved or absorbed by the liquid.

The advantages or disadvantages of using a wet scrubber instead of some other control device depend on the pollutant (gas or particle) to be controlled. Wet collectors, baghouses, or electrostatic precipitators can be used when collecting small particles at a high efficiency (>95%) is necessary. When only large particles are to be removed, either a low-energy scrubber or a cyclone can be used. Choosing the "best" collection system depends on many factors. Often no obvious choice is best. Table 1-1 contains some of the advantages and disadvantages of using a wet collector to remove particulate and gaseous emissions.

Advantages	Disadvantages
<ul> <li>Small space requirements Scrubbers reduce the temperature and volume of the unsaturated exhaust stream.  Therefore, vessel sizes, including fans and ducts downstream, are smaller than those of other control devices. Smaller sizes result in lower capital costs and more flexibility in site location of the scrubber. No secondary dust sources  Once particles are collected, they cannot escape from hoppers or during transport.  Handles high-temperature, high-humidity gas streams  No temperature limits or condensation problems can occur as in baghouses or ESPs.  Minimal fire and explosion hazards  Various dry dusts are flammable. Using water eliminates the possibility of explosions.  Ability to collect both gases and particles</li></ul>	<ul> <li>Corrosion problems <ul> <li>Water and dissolved pollutants can form</li> <li>highly corrosive acid solutions. Proper construction materials are very important.</li> <li>Also, wet-dry interface areas can result in corrosion.</li> </ul> </li> <li>High power requirements <ul> <li>High collection efficiencies for particles are attainable only at high pressure drops, resulting in high operating costs.</li> </ul> </li> <li>Water-disposal problems <ul> <li>Settling ponds or sludge clarifiers may be needed to meet waste-water regulations.</li> </ul> </li> <li>Difficult product recovery <ul> <li>Dewatering and drying of scrubber sludge make recovery of any dust for reuse very expensive and difficult.</li> </ul> </li> <li>Meteorological problems <ul> <li>The saturated exhaust gases can produce a wet, visible steam plume. Fog and precipitation from the plume may cause local meteorological problems.</li> </ul> </li> </ul>

#### Table 1-1. Relative advantages and disadvantages of wet scrubbers.

For gaseous pollutant removal, the choice of the control device depends mainly on the type of gaseous pollutant to be controlled. In choosing a system to control organic vapors, the choice of control is among wet scrubbers, adsorbers, thermal oxidizers (incinerators), or condensers; to control most inorganic gases (HCl,  $H_2S$ , HF, and  $SO_2$ ), a wet scrubber is usually the primary control device. If the exhaust stream contains both particles and gases, wet scrubbers are generally the only air pollution control device used to remove both pollutants. One exception is using a baghouse or an electrostatic precipitator (ESP) with a spray dryer in a dry  $SO_2$  scrubbing system.

Wet scrubbers can achieve high removal efficiencies for either particles or gases and, in some instances, can achieve a high removal efficiency for both pollutants in the same system. However, in many cases, the best operating conditions for particle collection are the poorest for gas removal. In general, obtaining high simultaneous gas and particle removal efficiencies requires that one of them be easily collected (i.e., that the gases are very soluble in the liquid or that the particles are large and readily captured). Wet scrubbers have been used in a variety of industries such as acid plants, fertilizer plants, steel mills, asphalt plants, and large power plants.

This lesson will examine operating variables that influence scrubber performance for both particle and gas collection.

	Review Exercise			
1.	True or False? Particles and gases are absorbed in the scrubbing liquid. $\square$			
2.	In choosing a control device for high collection efficiency of small particles, wet collectors are compared to $\underline{F} \underbrace{e}$ or $\underline{e} \underbrace{e}$ .	1. False Only gases are absorbed.		
3.	When choosing a device for organic-vapor collection, wet collection is compared to $\underline{-iacia}$ or $\underline{-iacia}$	2. baghouses (or) electrostatic precipitators		
4.	<ul> <li>In general, high removal rates for both particles and gases in the same scrubber are obtained by</li> <li>a. the use of large amounts of water.</li> <li>b. having gases that are highly soluble and/or particles that are relatively large.</li> <li>c. the use of extremely high pressure drops.</li> <li>d. a reagent added to the water.</li> </ul>	3. incineration (or) adsorption		
		<ol> <li>b. having gases that are highly soluble and/or particles that are relatively large.</li> </ol>		

## **Particle Collection**

Wet scrubbers capture relatively small dust particles with large liquid droplets. Droplets are produced by injecting liquid at high pressure through specially designed nozzles, by aspirating the particle-laden gas stream through a liquid pool, or by submerging a whirling rotor in a liquid pool. These droplets collect particles by using one or more of several collection mechanisms. These mechanisms—impaction, direct interception, diffusion, electrostatic attraction, condensation, centrifugal force, and gravity—are listed in Table 1-2. However, impaction and diffusion are the two primary ones.

Mechanism	Explanation
Impaction	Particles too large to follow gas streamlines around a droplet collide with it.
Diffusion	Very tiny particles move randomly, colliding with droplets because they are confined in a limited space.
Direct interception	An extension of the impaction mechanism. The center of a particle follows the streamlines around the droplet, but a collision occurs if the distance between the particle and droplet is less than the radius of the particle.
Electrostatic attraction	Particles and droplets become oppositely charged and attract each other.
Condensation	When hot gas cools rapidly, particles in the gas stream can act as con- densation nuclei and, as a result, become larger.
Centrifugal force	The shape or curvature of a collector causes the gas stream to rotate in a spiral motion, throwing larger particles toward the wall.
Gravity	Large particles moving slowly enough will fall from the gas stream and be collected.

#### Table 1-2. Particle collection mechanisms for wet scrubbing systems.

#### Impaction

In a wet scrubbing system, dust particles will tend to follow the streamlines of the exhaust stream. However, when liquid droplets are introduced into the exhaust stream, particles cannot always follow these streamlines as they diverge around the droplet (Figure 1-1). The particle's mass causes it to break away from the streamlines and impact on the droplet. Impaction is the predominant collection mechanism for scrubbers having gas stream velocities greater than 0.3 m/s (1 ft/sec) (Perry 1973). Most scrubbers do operate with gas stream velocities well above 0.3 m/s. Therefore, at these velocities, particles having diameters greater than 1.0  $\mu$ m are collected by this mechanism.



Figure 1-1. Impaction.

As the velocity of the particles in the exhaust stream increases relative to the liquid droplets' velocity, impaction increases. Impaction also increases as the size of the liquid droplet decreases. This is because there will be more droplets (for the same amount of liquid) within the vessel, consequently increasing the likelihood that the particles will impact on the droplets.

#### Diffusion

Very small particles (less than  $0.1 \ \mu m$  in diameter) experience random movement in an exhaust stream. These particles are so tiny that they are bumped by gas molecules as they move in the exhaust stream. This bumping, or bombardment, causes them to first move one way and then another in a random manner, or *diffuse*, through the gas. This irregular motion can cause the particles to collide with a droplet and be collected (Figure 1-2). Because of this, in certain scrubbers, the removal efficiency of particles smaller than 0.1  $\mu m$  can actually increase.



Figure 1-2. Diffusion.

The rate of diffusion depends on relative velocity, particle diameter, and liquid-droplet diameter. As for impaction, collection due to diffusion increases with an increase in relative velocity (liquid- or gas-pressure input) and a decrease in liquid-droplet size. However, collection by diffusion increases as particle size decreases. This mechanism enables certain scrubbers to effectively remove the very tiny particles. In the particle size range of approximately 0.1 to 1.0  $\mu$ m, neither of these two dominates. Particles in this size range are not collected as efficiently as are either larger particles collected by impaction or smaller particles collected by diffusion.

#### Other Collection Mechanisms

In recent years, some scrubber manufacturers have designed scrubbers to use other collection mechanisms such as electrostatic attraction and condensation to enhance particle collection without increasing power consumption. Other mechanisms such as gravity, centrifugal force, and direct interception slightly affect particle collection.

	Review Exercise				
1.	<ul> <li>What are two primary mechanisms used for collecting particles in a scrubber?</li> <li>a. impaction and diffusion</li> <li>b. direct interception and diffusion</li> <li>c. impaction and condensation</li> <li>d. direct interception and gravity</li> </ul>				
2.	<ul> <li> is/are the predominant collection mechanism(s) for particles larger than 1.0 μm traveling faster than 0.3 m/s (1 ft/sec).</li> <li>a. Impaction</li> <li>b. Diffusion</li> <li>c. Direct interception</li> <li>d. all of the above</li> </ul>	1. a. impaction and diffusion			
3.	For very small particles, below 0.1 µm in diameter, is/are the predominant collection mechanism(s) in wet collection. a. impaction b. diffusion c. gravity d. all of the above	2. a. Impaction			
4.	<ul> <li>Collection efficiency for particles captured by the impaction mechanism increases as the</li> <li>a. particles' velocity in the exhaust stream increases relative to the liquid droplets' velocity.</li> <li>b. particle size decreases below 0.1 μm in diameter.</li> <li>c. liquid-droplet size increases.</li> </ul>	3. b. diffusion			
5.	Collection efficiency for particles captured by diffusion <u>decreases/increases</u> as the size of the particle decreases. MMMM	4. a. particles' velocity in the exhaust stream increases relative to the liquid droplets' velocity.			
		5. increases			

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## **Gas Collection**

The process of dissolving gaseous pollutants in a liquid is referred to as *absorption*. Absorption is a *mass-transfer operation*. Mass transfer can be compared to heat transfer in that both occur because a system is trying to reach equilibrium conditions. For example, in heat transfer, if a hot slab of metal is placed on top of a cold slab, heat energy will be transferred from the hot slab to the cold slab until both are at the same temperature (equilibrium). In absorption, mass instead of heat is transferred as a result of a concentration difference, rather than a heat-energy difference. Absorption continues as long as a concentration differential exists between the liquid and the gas from which the contaminant is being removed. In absorption, equilibrium depends on the solubility of the pollutant in the liquid.

To remove a gaseous pollutant by absorption, the exhaust stream must be passed through (brought in contact with) a liquid. Figure 1-3 illustrates the three steps involved in absorption. In the first step, the gaseous pollutant diffuses from the bulk area of the gas phase to the gasliquid interface. In the second step, the gas moves (transfers) across the interface to the liquid phase. This step occurs extremely rapidly once the gas molecules (pollutant) arrive at the interface area. In the third step, the gas diffuses into the bulk area of the liquid, thus making room for additional gas molecules to be absorbed. The rate of absorption (mass transfer of the pollutant from the gas phase to the liquid phase) depends on the diffusion rates of the pollutant in the gas phase (first step) and in the liquid phase (third step).



Figure 1-3. Absorption.

To enhance gas diffusion and, therefore, absorption:

- 1. provide a large interfacial contact area between the gas and liquid phases,
- 2. provide good mixing of the gas and liquid phases (turbulence), and
- 3. allow sufficient residence, or contact, time between the phases for absorption to occur.

Two of these three gas-collection mechanisms, large contact area and good mixing, are also important for particle collection. The third factor, sufficient residence time, works in direct opposition to efficient particle collection. To increase residence time, the relative velocity of the gas and liquid streams must be reduced. Therefore, achieving a high removal efficiency for both gaseous and particulate pollutants is extremely difficult unless the gaseous pollutant is very soluble in the liquid.

As previously mentioned, a very important factor affecting the amount of a pollutant that can be absorbed is its solubility. Solubility governs the amount of liquid (liquid-to-gas ratio) required and the necessary contact time. More soluble gases require less liquid. Also, more soluble gases will be absorbed faster. Solubility is a function of both the temperature and, to a lesser extent, the pressure of the system. As temperature increases, the amount of gas that can be absorbed by a liquid decreases. From the ideal gas law: as temperature increases, the volume of a gas also increases; therefore, at a higher temperature, gas volume increases and less gas is absorbed. For this reason, some absorption systems use inlet quench sprays to cool the incoming exhaust stream, thereby increasing absorption efficiency. Pressure affects the solubility of a gas in the opposite manner. When the pressure of a system is increased, the amount of gas absorbed generally increases.

Review Exercise				
1. In absorption, gaseous pollutants are in a liquid.				
<ul> <li>2. Absorption occurs because of a difference between the gas phase and liquid phase.</li> <li>a. heat</li> <li>b. mass</li> <li>c. concentration</li> <li>d. weight</li> </ul>	1. dissolved			
<ul> <li>3. Which of the following would not enhance the absorption process?</li> <li>a. providing a large contact area between the gas and liquid phases</li> <li>b. providing a turbulent mixing of the phases</li> <li>c. increasing the gas velocity relative to the liquid velocity</li> <li>d. allowing long contact, or residence, time</li> </ul>	2. c. concentration			
4. True or False? The solubility of the gaseous pollutant in the liquid will affect the required liquid-to-gas ratio of the system.	3. c. increasing the gas velocity relative to the liquid velocity			
<ul> <li>5. Which of the following reduces the solubility of gas in a liquid?</li> <li>a. increased temperature</li> <li>b. increased pressure</li> </ul>	4. True			

5. a. increased temperature As the temperature increases, the amount of gas that can be absorbed decreases because the gas expands.

## **Categorizing Wet Scrubbers**

Since wet scrubbers vary greatly in complexity and method of operation, devising categories into which all of them would neatly fit is extremely difficult. Scrubbers for particle collection are usually categorized by the gas-side\* pressure drop of the system. They are:

- low-energy scrubbers having pressure drops of less than 12.7 cm (5 in.) of water,
- medium-energy scrubbers having pressure drops between 12.7 and 38.1 cm (5 and 15 in.) of water, and
- high-energy scrubbers having pressure drops greater than 38.1 cm (15 in.) of water.

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

Another way to categorize scrubbers is by the manner in which the gas and liquid phases are brought into contact. In this category, the scrubbers use power, or energy, from the gas stream or the liquid stream, or they use some other method to bring the pollutant gas stream into contact with the liquid. These categories are given in Table 1-4.

Wet collector	Energy source used for contact
Gas-phase contacting	Gas stream
Liquid-phase contacting	Liquid stream
Wet film	Liquid and gas streams
Combination <ul> <li>Liquid phase and gas phase</li> <li>Mechanically aided</li> </ul>	Liquid and gas streams Mechanically driven rotor

Table 1-4.	Categories of	wet collectors	by energy	source	used for	contact.
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Another way to classify wet scrubbers is by their use – to primarily collect either particles or gaseous pollutants, or both. Each of the wet collectors listed in Table 1-4 will be discussed in this course, including various designs within each category, their operation, collection efficiency, industrial applications, prominant maintenance problems, if any, and their primary use.

<sup>\*</sup>Gas-side pressure drop refers to the pressure difference, or pressure drop, that occurs as the exhaust gas is pushed or pulled through the scrubber, disregarding the pressure that would be used for pumping or spraying the liquid into the scrubber. In this manual, the terms pressure drop and gas-side pressure drop will be used interchangeably.

## References

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# Lesson 2

## **Design Features of Wet Scrubbers**

### Lesson Goal and Objectives

#### Goal

To introduce you to the design features unique to wet scrubbers that enhance the collection of air pollutants.

#### **Objectives**

Upon completing this lesson, you should be able to-

- 1. list at least six major components of a wet scrubber,
- 2. recognize three spray nozzle designs,
- 3. list at least four characteristics of spray nozzles,
- 4. list five remedies for plugged nozzles, and
- 5. describe the operation of three entrainment separators.

## **Designing Wet Scrubbers**

Wet scrubbers are uniquely designed to enhance the collection of air pollutants. As discussed in the last lesson, several process design variables affect particulate pollutant collection—most importantly, particle size, particle velocity, and liquid-droplet size. For gaseous pollutant collection, the pollutant must be soluble in the chosen scrubbing liquid. In addition, the system must be designed to provide good mixing between the gas and liquid phases, and enough time for the gaseous pollutants to dissolve. Another consideration for both particulate and gaseous pollutant collection is the liquid-to-gas (L/G) ratio—the amount of liquid injected into the scrubber per given volume of exhaust flow. Lastly, the system must be designed to remove entrained mists, or droplets, from the cleaned exhaust gas stream before it leaves the stack.

### Scrubber Components

Several components are used when designing scrubbers to provide gas-liquid contact and separation. Spray nozzles are used to form droplets that, in turn, are used to capture pollutants. Other components are used to enhance gas-liquid contact. These include venturi throats, plates, baffles, packing, orifices, tangential openings, and mechanically driven rotors. These basic components are used by themselves or in combination in commercially available scrubbers. These will be discussed in detail in the following lessons as they apply to a specific scrubber design. Plastic pads, wire-mesh pads, blades, and cyclones are used to separate any entrained droplets from the cleaned exhaust gas stream. Spray nozzles and entrainment separators are found in some form in many scrubber systems. They will be discussed here and mentioned later as they apply to each specific scrubber.

#### Spray Nozzles

Three different nozzle designs are used to produce a fine, cone-patterned spray. In the *impingement nozzle* (Figure 2-1), highly pressurized liquid passes through a hollow tube in the nozzle and strikes a pin or plate at the nozzle tip. A very fine fog of tiny, uniform-sized droplets approximately 25 to 400  $\mu$ m in diameter is produced. Because there are no internal parts in the nozzle, it will not plug as long as particles larger than the opening are filtered out by a strainer. These nozzles are usually made of stainless steel or brass. In the *solid cone nozzle* (Figure 2-2), liquid is forced over an insert to break it up into a cone of fine droplets. Cones can be full, hollow, or square with spray angles from 15° to 140°. These nozzles can be made of stainless steel, brass, alloys, Teflon<sup>®</sup>, and other plastic materials. The *helical spray nozzle* (Figure 2-3), has a descending spiral impingement surface that breaks up the sprayed liquid into a cone of tiny droplets. The cones can be full or hollow with spray angles from 50° to 180°. There are no internal parts, which helps reduce nozzle plugging. These nozzles can be made of stainless steel, brass, alloys, Teflon<sup>®</sup>, and other plastic materials.



Figure 2-1. Impingement nozzle.

Figure 2-2. Solid cone nozzle.

Figure 2-3. Helical spray nozzle.

Different spray nozzles are appropriate for different scrubbing systems. Characteristics of the nozzles and sprays include the following:

- 1. Droplet size In general, scrubbers using sprays to provide gas-liquid contact (such as in spray towers) require tiny, uniform-sized droplets to operate effectively. If the sprays are used merely as a method of introducing liquid into the vessel (such as in packed towers), then droplet size is not as critical.
- 2. Opening size—The actual opening in the nozzle will vary depending on the applications and the amount of liquid required. Openings range from 0.32 to 6.4 cm (0.125 to 2.5 in.).
- 3. Spray pattern Nozzles are available that produce sprays in a number of geometric shapes such as square, fan, hollow cone, and full cone. Full-cone sprays are used to provide complete coverage of the areas sprayed.
- 4. Operating mechanism Droplets can be produced by a number of methods such as impinging the liquid on a solid surface or atomizing the liquid using air.
- 5. **Power consumption**—In general, the finer the liquid droplet, the higher the power consumption.

Nozzle plugging is one of the most common malfunctions in wet scrubbers. Plugged nozzles reduce the gas-liquid contact and can also result in scale buildup on, or heat damage to, the scrubber parts formerly sprayed by the nozzle. Nozzle plugging can be most readily detected by observing the liquid spray pattern; however, if the nozzles are not easily accessible, a decrease in liquid flow is also a telltale sign (EPA 1982). Remedies include replacing the nozzle with one that is more open, cleaning the nozzle frequently, filtering the scrubbing liquid, or increasing the bleed rate and makeup water rates.

Another problem that can arise is reduced pressure in the spray header. This can cause a reduction in the spray angle (area covered) and an increase in the size of droplets produced.

#### Entrainment Separators

As mentioned in Lesson 1, the pollutant must first be contacted with the liquid, then the liquid droplets must be removed from the exhaust gas stream before it is exhausted to the atmosphere. Entrainment separators, also called mist eliminators, are used to remove the liquid droplets. Although the major function of an entrainment separator is to prevent liquid carryover, it also performs additional scrubbing and recovers the scrubbing liquor, thus saving on operating costs. Therefore, entrainment separators are usually an integral part of any wet scrubbing system.

Entrained liquid droplets vary in size depending on how the droplets were formed. Droplets that are torn from the body of a liquid are large (10 to 100  $\mu$ m in diameter), whereas droplets that are formed by a chemical reaction or by condensation are on the order of 5  $\mu$ m or less in diameter. Numerous types of entrainment separators are capable of removing these droplets. Those most commonly used for air pollution control purposes are cyclonic, mesh-pad, and blade separators.

The cyclonic (centrifugal) separator is a cylindrical tank with a tangential inlet or turning vanes. The tangential inlet or turning vanes impart a swirling motion to the droplet-laden gas stream. The droplets are thrown outward by centrifugal force to the walls of the cylinder. Here they coalesce and drop down the walls to a central location and are recycled to the absorber (Figure 2-4). These units are simple in construction, having no moving parts.



Figure 2-4. Cyclonic separator.

Therefore, they have few plugging problems as long as continuous flow is maintained. Good separation of droplets 10 to 25  $\mu$ m in diameter can be expected. The pressure drop across the separator is 10 to 15 cm (4 to 6 in.) of water for a 98% removal efficiency of droplets in the size range of 20 to 25  $\mu$ m. Cyclonic separators are commonly used with venturi scrubbers (see Lesson 3).

In another design, wire or plastic is used to form mesh pads (Figure 2-5). These mesh-pad separators are approximately 10 to 15 cm (4 to 6 in.) thick and fit across the entire diameter of the scrubber. The mesh allows droplets to impact on the material surface, agglomerate with other droplets, and drain off by gravity. The pad is usually slanted (no more than a few degrees) to permit the liquid to drain off. Better than 95% collection of droplets larger than 3  $\mu$ m is obtained with pressure drops of approximately 1.0 to 15 cm (0.5 to 6 in.) of water (the pressure drop depends on depth and compaction of fibers). The disadvantage with mesh pads is that their small passages are subject to plugging. Periodically spraying pads from both below and above can remove some trapped material. However, spraying only from beneath will drive entrapped material further into the mesh, necessitating removal of the pads for cleaning or replacement (Schifftner 1979).



Figure 2-5. Mesh-pad separator.

Blade separators can be of two types: chevron or impingement. In the chevron separator (Figure 2-6), gas passes between the blades and is forced to travel is a zigzag pattern. The liquid droplets cannot follow the gas streamlines, so they impinge on the blade surfaces, coalesce, and fall back into the scrubber chamber or drain. Special features such as hooks and pockets can be added to the sides of these blades to help improve droplet capture. Chevron grids can be stacked or angled on top of one another to provide a series of separation stages. Pressure drop is approximately 6.4 cm (2.5 in.) of water for capture of droplets as small as 5  $\mu$ m in diameter. Impingement separators (Figure 2-7) create a cyclonic motion because they are similar in shape to the common house fan. As the gas passes over the curved blades, they impart a spinning motion that causes the mist droplets to be directed to the vessel walls, where they are collected. Pressure drop ranges from 5 to 15 cm (2 to 6 in.) of water.



Figure 2-6. Chevron blade separator.

Figure 2-7. Impingement blade separator.

The most important diagnostic aid in monitoring separator performance is the pressure drop. By measuring the pressure drop across the separator, the following problems can be identified (Wechselblatt 1975):

- A sudden decrease in pressure drop at constant load indicates that the separators have shifted out of place or are broken.
- An increase in pressure drop, even as little as 0.5 cm (0.2 in.) of water, is an indication of material buildup in the separator.

Another diagnostic measurement is gas velocity. Gas velocity through the separator must be kept below the maximum rate to avoid liquid reentrainment. Maximum velocities depend on operating conditions and the physical properties of the exhaust gas and liquid streams. The gas velocity should be kept below 3 m/s (10 ft/sec) for chevron separators, below 5 m/s (15 ft/sec) for mesh pads, and below 8 m/s (27 ft/sec) for impingement blades to reduce liquid carryover (Schifftner 1979). Table 2-1 summarizes some operating characteristics of entrainment separators.

Trees	Droplet size	Maximum	a gas velocity	Pressure drop	
I ype	confected at 99% (μm)	m/s	ft/sec	cm H <sub>2</sub> O	in. H <sub>2</sub> O
Mesh pads	3.0	5	15	1.0-15	0.5-6
Cyclone	10-25	20	65	10-15	4-6
Blades Chevron Impingement van <del>e</del>	35 20	<b>3</b> 8	10 27	6.4 5-15	2.5 2-6

Table 2-1. Typical operational characteristics of entrainment separators.\*

\*Note: Values in this table are given as a general guide only. The collection efficiency for various droplet sizes depends on the gas velocity through the entrainment separators.

	Review Exercise				
1.	Identify the following spray nozzle used in a wet scrubbing system.				
	I A PINSIMA				
2.	List five important characteristics of spray nozzles used in wet scrubbing systems.	1. impingement			
3.	True or False? Nozzle plugging is one of the most common malfunctions in wet scrubbers.	<ul> <li>2. • opening size</li> <li>• droplet size</li> <li>• spray pattern</li> <li>• operating mechanism</li> <li>• power consumption</li> </ul>			
4.	List five remedies for plugged nozzles.	3. True			
5.	Entrainment separators are used to a. prevent liquid carryover. b. recover scrubbing liquor. c. perform additional scrubbing. d. all of the above	<ul> <li>4. • Replace nozzle with one having a more open design.</li> <li>• Clean nozzles frequently.</li> <li>• Filter the scrubbing liquor.</li> <li>• Increase bleed rate.</li> <li>• Increase makeup water rate.</li> </ul>			
6.	Cyclonic separators can remove liquid droplets as small as in diameter. a. $0.01 \ \mu m$ b. $0.1 \ \mu m$ c. $1.0 \ \mu m$ d. $10.0 \ \mu m$	5. d. all of the above			
		6. d. 10.0 μm			

7. True remo sepa: plug	e or False? Wire- or plastic-mesh pads are oving smaller droplets than are either cyc rators; however, they are also more susce ging.	e capable of lonic or blade ptible to	
8. In g prev a. ir b. sp c. sp d. sp e. a	eneral, wire-mesh pads should be ent plugging. Istalled at a slant brayed from the bottom brayed from the top brayed from the top and bottom ll of the above	to	7. True
		~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	8. d. sprayed from the top and bottom

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# Lesson 3

## **Gas-Phase Contacting Scrubbers**

## Lesson Goal and Objectives

#### Goal

To familiarize you with the operation, collection efficiency, and maintenance problems of gasphase contacting scrubbers.

### **Objectives**

Upon completing this lesson, you should be able to-

- 1. list three gas-phase contacting scrubbers and briefly describe how each operates,
- 2. recall operating characteristics such as pressure drop, liquid-to-gas ratio, and collection efficiency (for both particulate and gaseous pollutants) of each of the above scrubbers, and
- 3. describe typical operating and maintenance problems associated with each gas-phase contacting scrubber design.

## Introduction

Scrubbers using the exhaust (gas) stream to provide the energy for gas-liquid contact are called gas-phase contacting scrubbers. The exhaust stream moves across or through a liquid surface, shearing it to form tiny droplets. Breaking the liquid into fine droplets helps increase both particle and gas collection. The droplets provide targets on which the particles hit and are collected. They also provide a huge surface area for collecting (absorbing) gaseous pollutants.

A number of methods are used to provide this shearing action. The gas can be forced through cascades of liquid falling over flat plates. Holes can be punched in the plates, and the gas can aspirate the water flowing over the plate. Or the gas can be forced through constricted passages wetted with liquid, such as in orifice and venturi scrubbers. Three collectors work primarily by this action: *venturi scrubbers, plate towers, and orifice scrubbers.* 

### Venturi Scrubbers

A venturi scrubber is designed to effectively use the energy from the exhaust stream to atomize the scrubbing liquid. Venturi devices have been used for over 100 years to measure fluid flow (venturi tubes derived their name from G. B. Venturi, an Italian physicist). About 35 years ago, Johnstone (1949) and other researchers found that they could effectively use the venturi configuration to remove particles from an exhaust stream. Figure 3-1 illustrates the classic venturi configuration.



Figure 3-1. Venturi configuration.

A venturi scrubber consists of three sections — a converging section, a throat section, and a diverging section. The exhaust stream enters the converging section and, as the area decreases, gas velocity increases. Liquid is introduced either at the throat or at the entrance to the converging section. The exhaust gas, forced to move at extremely high velocities in the small throat section, shears the liquid from its walls, producing an enormous number of very tiny droplets. Particle and gas removal occur in the throat section as the exhaust stream mixes with the fog of tiny liquid droplets. The exhaust stream then exits through the diverging section, where it is forced to slow down. Venturis can be used to collect both particulate and gaseous pollutants, but they are more effective in removing particles than in removing gaseous pollutants.

Liquid can be injected at the converging section or at the throat. Figure 3-2 shows liquid injected at the converging section. Thus, the liquid coats the venturi throat. This venturi is very effective for handling hot, dry exhaust gas that contains dust. The dust would have a tendency to cake on or abrade a dry throat. These venturis are sometimes referred to as having a wetted approach.

Figure 3-3 shows liquid injected at the venturi throat. Since it is sprayed at or just before the throat, it does not actually coat the throat surface. These throats are susceptible to solids buildup when the throat is dry. They are also susceptible to abrasion by dust particles. These venturis are best used when the exhaust stream is cool and moist. In this venturi, the relative particle-to-liquid velocity is the highest of any of the venturis; therefore, the smallest particles can be collected efficiently. These venturis are referred to as having a non-wetted approach.



Figure 3-2. Venturi scrubber with a wetted throat.



Figure 3-3. Venturi with throat sprays.

Venturis with round throats (Figures 3-2 and 3-3) can handle exhaust flows as large as  $88,000 \text{ m}^3/\text{h}$  (40,000 cfm) (Brady and Legatshi 1977). At exhaust flow rates greater than this, achieving uniform liquid distribution is difficult, unless additional weirs or baffles are used. To handle large exhaust flows, scrubbers designed with long, narrow, rectangular throats (Figure 3-4) have been used.



Figure 3-4. Spray venturi with rectangular throat.

Manufacturers have developed other modifications to the basic venturi design to maintain scrubber efficiency by changing the pressure drop for varying exhaust gas rates. Certain types of orifices that create more turbulence than a true venturi were found to be equally efficient for a given unit of energy consumed (McIlvaine Company 1974). Results of these findings led to the development of the annular-orifice, or adjustable-throat, venturi scrubber (Figure 3-5). The throat area is varied by moving a plunger, or adjustable disk, up or down in the throat, decreasing or increasing the annular opening. Gas flows through the annular opening and atomizes liquid that is sprayed onto the plunger or swirled in from the top. Another adjustable-throat venturi is shown in Figure 3-6. In this scrubber, the throat area is varied by using a movable plate. A water-wash spray is used to continually wash collected material from the plate.



Figure 3-5. Adjustable-throat venturi with plunger.



Figure 3-6. Adjustable-throat venturi with movable plate.

Another modification can be seen in the venturi-rod scrubber. By placing a number of pipes parallel to each other, a series of longitudinal venturi openings can be created as shown in Figure 3-7. The area between adjacent rods is a small venturi throat. Water sprays help prevent solids buildup. The principal atomization of the liquid occurs at the rods, where the high-velocity gas moving through spacings creates the small droplets necessary for fine particle collection.

All venturi scrubbers require an entrainment separator because the high velocity of gas through the scrubber will have a tendency to exhaust the droplets. Cyclonic, mesh-pad, and blade separators are all used. Cyclonic separators, the most popular, are connected to the venturi vessel by a flooded elbow (Figure 3-8). The liquid reduces abrasion of the elbow as the exhaust gas passes at high velocities from the venturi to the separator.



Figure 3-7. Venturi-rod scrubber.



Figure 3-8. Flooded elbow leading into cyclonic separator.

#### Particle Collection

Venturis are the most commonly used scrubber for particle collection and are capable of achieving the highest particle collection efficiency of any wet scrubbing system. As the exhaust stream enters the throat, its velocity increases greatly, atomizing and turbulently mixing with any liquid present. The atomized liquid provides an enormous number of tiny droplets for the dust particles to impact on. These liquid droplets incorporating the particles must then be removed from the scrubber exhaust stream, generally by cyclonic separators.

Particle removal efficiency increases with increasing pressure drop (resulting in high gas velocity and turbulence). Venturis can be operated with pressure drops ranging from 12 to 250 cm (5 to 100 in.) of water. Most venturis normally operate with pressure drops in the range of 50 to 150 cm (20 to 60 in.) of water. At these pressure drops, the gas velocity in the throat section is usually between 30 and 120 m/s (100 and 400 ft/sec), or approximately 270 mph at the high end. These high pressure drops result in high operating costs.

The liquid-injection rate, or liquid-to-gas ratio (L/G), also affects particle collection. The liquid-injection rate depends on the temperature (evaporation losses) of the incoming exhaust stream and the particle concentration. Most venturi systems operate with an L/G ratio of 0.4 to 1.3 L/m<sup>3</sup> (3 to 10 gal/1000 ft<sup>3</sup>) (Brady and Legatshi 1977). L/G ratios less than 0.4 L/m<sup>3</sup> (3 gal/1000 ft<sup>3</sup>) are usually not sufficient to cover the throat, and adding more than 1.3 L/m<sup>3</sup> (10 gal/1000 ft<sup>3</sup>) does not usually significantly improve particle collection efficiency.

#### **Gas** Collection

Venturi scrubbers can be used for removing gaseous pollutants; however, they are not used when removal of gaseous pollutants is the only concern. The high exhaust gas velocities in a venturi result in a very short contact time between the liquid and gas phases. This short contact time limits gas absorption. However, venturi scrubbers are very useful for simultaneous gaseous and particulate pollutant removal, especially when:

- scaling could be a problem,
- a high concentration of dust is in the exhaust stream,
- the dust is sticky or has a tendency to plug openings, and/or
- the gaseous contaminant is very soluble or chemically reactive with the liquid.

To maximize absorption of gases, venturis operate at a set of conditions different from those used to collect particles. Lower gas velocities and higher liquid-to-gas ratios are necessary for efficient absorption. These values should be approximately 2.7 to 5.3 L/m<sup>3</sup> (20 to 40 gal/1000 ft<sup>3</sup>). At high liquid-to-gas ratios, the gas velocity in the venturi throat is reduced (for a given pressure drop). The reduction in gas velocity allows for a longer contact time between phases.

#### Maintenance Problems

The primary maintenance problem for venturi scrubbers is wear, or abrasion, of the scrubber shell because of high gas velocities. Gas velocities in the throat can reach speeds of 430 km/h (270 mph). Particles and liquid droplets traveling at these speeds can rapidly erode the scrubber shell. Abrasion can be reduced by lining the throat with silicon carbide brick or fitting it with a replaceable liner. Abrasion can also occur downstream of the throat section. To reduce abrasion here, the elbow at the bottom of the scrubber (leading into the separator) can be flooded. Particles and droplets impact on the pool of liquid, reducing wear on the scrubber shell. Another technique to help reduce abrasion is to use a precleaner (i.e., quench sprays or cyclone) to remove the larger particles.

The method of liquid injection at the venturi throat can also cause problems. Spray nozzles are used for liquid distribution because they are more efficient (have a more effective spray pattern) for liquid injection than are weirs. However, spray nozzles can easily plug when recirculating the liquid. Automatic or manual reamers can be used to correct this problem. However, when heavy liquid slurries (either viscous or particle-loaded) are recirculated, openweir injection is often necessary. Table 3-1 summarizes some of the operational problems associated with venturi scrubbers.

Problem	Probable cause	Corrective action
Low efficiency	Low scrubbing-liquid flow rate	Check for plugged pipe or nozzles, incorrectly opened valves, or over- throttled pump-discharge valve.
	Low pressure drop	Check for low scrubbing liquor, low gas flow; inoperative or uncalibrated variable-throat controller; damaged variable-throat blade or disk.
	Partially blocked entrainment separator	Check washdown sprays, spray liquor composition, and pH (for scaling).
	Excessive gas flow	Check for damper setting or venturi throat setting.
	Inlet dust loading or particle size distribution different from that for which scrubber is designed	
High exit-gas temperature	Low scrubbing-liquid rate	Check for plugged pipe or nozzles, incorrectly opened valves, or over- throttled pump-discharge valve.
	High water-inlet temperature	Check and adjust makeup or heat- exchanger liquid flow rates.
	High inlet-gas temperature	Check quench sprays, if applicable, or upstream equipment.
Exhaust gas liquor entrainment	Plugged entrainment separator	Check washdown sprays and spray pattern; use more flushing periods if necessary. Check liquor chemistry for scaling agents.
	Plugged moisture-eliminator drain	Clean drain; add flushing water to con- tinuously irrigate drain pipe.
	Excessive gas flow	Reduce gas flow.
Plugging or excessive wear of spray nozzles	Nozzle openings too small	Modify strainer/nozzle opening ratio so that nozzle holes are at least twice the diameter of strainer openings.
	Solids concentration too high in spray liquor	Check bleed line for malfunctions; check for excessive dust loading. Check strainers.
	Abrasives in spray liquor	Remove abrasives or install abrasion- resistant linings.
	Low pH in combination with abrasives is causing erosion or corrosion	Check separation equipment. Check for excessive dust loading in gas stream and for purge-line malfunctioning. Remove abrasives from liquor stream or install abrasion-resistant linings in wear zones. Add alkali for pH modification.

#### Table 3-1. Operational problems associated with venturi scrubbers.

Problem	Probable cause	Corrective action
Excessive throat wear	High solids recirculation	Check bleed line for malfunctions. Check for excessive dust loading. Check strainers.
	Excessive gas velocity	Check throat pressure drop.
	Corrosion/erosion	Check separation equipment. Check for excessive dust loading in gas stream and for purge-line malfunctioning. Add alkali for pH modification. Install abrasion-resistant liners in high-wear zones if liquor modifications are not practical.
Erratic automatic-	Throat-mover malfunction	Remove from service; repair or replace.
throat operation	Sensor signal incorrect	Check sensor taps for solids buildup. Check transmission tubing for liquid buildup or air leaks. Clean or repair sensor.
	Damaged damper-disk mechanism	First make external inspection of drive train. If damaged area is not observed, shut unit down and make internal inspection using a throat-actuator man- ual override. Check for packing damage and excessively tight packing gland.
Low pressure drop	Broken, leaking, or plugged static-tap line	Repair.
	Low gas-flow rate	Check gas flow against design. Check and, if necessary, adjust fan belt or speed. Check inlet duct for obstructions.
Fan overloads and shuts off	Excessive flow rate through fan	Check fan damper and variable- throat opening.
	Low scrubbing-liquor flow rate	Check for plugged pipe or nozzles, incorrectly opened valves, or over- throttled pump-discharge valve.
Wet-dry interface buildup	Particle buildup where gas goes from unsaturated to saturated condition	Install special inlets. Reduce dissolved solids in scrubbing liquor. Devote routine maintenance to removal of buildup.

Table 3-1. Operational problems associated with venturi scrubbers (continued).

Sources: Kelly 1978 and Anderson 2000 Co.

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#### Summary

Venturi scrubbers can have the highest particle collection efficiencies (especially for very small particles) of any wet scrubbing system. They are the most widely used scrubbers because their open construction enables them to remove most particles without plugging or scaling. Venturis can also be used to absorb pollutant gases; however, they are not as efficient for this as are packed or plate towers. The operating characteristics of venturi scrubbers are listed in Table 3-2.

Pollutant	Pressure drop (Ap)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p <sub>L</sub> )	Removal efficiency (%) and cut diameter for particles*
Gases	13-250 cm of water (5-100 in. of water)	2.7-5.3 L/m <sup>3</sup> (20-40 gal/1000 ft <sup>3</sup> )	<7-100 kPa	30-60% per venturi, depending on pollutant solubility
Particles	50-250 cm of water [50-150 cm of water]	$0.4-2.7 \text{ L/m}^3$ (3.0-20.0 gal/1000 ft <sup>3</sup> )	(<1-15 psig)	[90-99% is typical]
	is common (20-100 in. of water) 20-60 in. of water is common	····· ,		0.2- $\mu$ m cut diameter, depending on $\Delta$ p

Table 3-2. Operating characteristics of venturi scrubbers	Table	3-2.	Operating	characteristics	of	venturi	scrubbers
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\*Cut diameter is the size (diameter) of the particle that is collected with at least 50% efficiency.

Venturi scrubbers have been designed to collect particles at very high collection efficiencies, sometimes exceeding 99%. The ability of venturis to handle large exhaust volumes at high temperatures makes them very attractive to many industries; consequently, they have been used to reduce particulate emissions in a number of industrial applications. This ability is particularly desirable for cement kiln emission reduction and for control of emissions from basic oxygen furnaces in the steel industry, where the exhaust gas enters the scrubber at temperatures greater than 350 °C (660 °F). Venturis have also been used to control fly ash and sulfur dioxide emissions from industrial and utility boilers. A list of performance data for venturi scrubbers is given in Table 3-3.

Application	Dust	Typical particle-size range (µm)	$\Delta \mathbf{p}$ (in. H <sub>2</sub> O)	Average collection efficiency (%)
Iron and steel				
Electric furnace	Ferro-manganese and ferro silicon	0.1-1.0	30-50	92-99
BOF	Iron oxide	0.5-2.0	40-60	98.5
Gray iron cupola	Iron, coke, and silica	0.1-10.0	30-50	95
Mineral products				
Asphalt dryer	Limestone and rock	1.0-50.0	10-15	98
Lime kiln	Lime	1.0-50.0	15-25	99
Cement kiln	Cement	0.5-55.0	10-15	97
Crushing and screening areas	Rock	0.5-100.0	6-20	99.9
Fertilizer manufacturing				
Dryers	Ammonium chloride fumes	0.05-1.0	10-20	85
Petroleum refining				
Catalytic cracking unit	Catalyst dust	0.5-50.0	~~	95
Chemical				
Spray dryers	Fumes and odor	_	20-60	-
Phosphoric acid plant	Acid mist	_	40-80	98
Pulp and paper				
Lime kiln	Soda ash	0.1-2.0	20-40	99
Recovery boiler	Salt particles	—	30-40	90
Boilers				
Coal pulverizer	Fly ash	20 (mass median)	15-40	97-99
Stoker	Fly ash	75 (mass median)	10-15	97-99

Table 3-3. Performance data of typical venturi scrubbers.

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Review Exercise	· · · · · · · · · · · · · · · · · · ·
1. Label the following sections of the venturi.	
<ul> <li>2. In a venturi scrubber, the majority of pollutant removal occurs in the</li> <li>a. converging section.</li> <li>b. throat.</li> <li>c. diverging section.</li> </ul>	<ol> <li>a. converging</li> <li>b. throat</li> <li>c. diverging</li> </ol>
<ul> <li>3. A venturi scrubber in which liquid is introduced above the throat section <ul> <li>a. increases the likelihood of dust buildup on the throat.</li> <li>b. reduces dust buildup on throat surfaces.</li> <li>c. has the highest gas absorption capabilities of any wet collector.</li> <li>d. none of the above</li> </ul> </li> </ul>	2. b. throat
<ul> <li>4. Many venturi scrubbers have devices by which the throat area can be varied to maintain</li> <li>a. gas velocity through the throat.</li> <li>b. pressure drop.</li> <li>c. turbulence in the throat.</li> <li>d. all of the above</li> </ul>	3. b. reduces dust buildup on throat surfaces.
5. True or False? Venturis are the most commonly used $$ scrubber for particle collection.	4. d. all of the above
	5. True

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6. In a venturi scrubber, particle collection increases with an increase in	
<ul> <li>7. Venturi scrubbers are generally limited in their capability of removing gaseous pollutants because of</li> <li>a. the short gas-liquid contact time.</li> <li>b. low L/G ratios.</li> <li>c. small liquid droplets formed in the throat.</li> <li>d. all of the above</li> </ul>	6. pressure drop
<ul> <li>8. Venturi scrubbers are useful for simultaneous gas and particle removal, especially when <ul> <li>a. scale buildup could be a problem.</li> <li>b. a high concentration of dust is in the exhaust stream.</li> <li>c. the dust is sticky or has a tendency to plug openings.</li> <li>d. the gaseous pollutant is very soluble.</li> <li>e. all of the above</li> </ul></li></ul>	7. a. the short gas- liquid contact time.
9. To maximize gas collection in a venturi scrubber, the pressure drop is <u>increased/decreased</u> and the L/G Orratio is usually <u>increased/decreased</u> when compared to operating conditions for particle collection.	8. e. all of the above
<ul> <li>10. The primary maintenance problem for venturis is</li> <li>a. plugging due to the many internal parts.</li> <li>b. weeping due to low gas flows.</li> <li>c. abrasion of the throat due to the high gas velocities.</li> <li>d. all of the above</li> </ul>	9. decreased, increased
<ul> <li>11. What does flooding the elbow between the venturi and the separator reduce?</li> <li>a. abrasion of the elbow</li> <li>b. velocity of the gas stream</li> <li>c. plugging in the elbow</li> <li>d. pressure drop across the device</li> </ul>	10. c. abrasion of the throat due to the high gas velocities.
<ul> <li>12. To be effective in collecting particles, venturi scrubbers must operate at a pressure drop of</li> <li>a. 10 cm (5 in.) of water.</li> <li>b. 50 cm (20 in.) of water.</li> <li>c. 150 cm (60 in.) of water.</li> <li>d. any of the above</li> </ul>	11. a. abrasion of the elbow
<ul> <li>13. In general, venturis are more effective in removing</li> <li> than they are in removing</li> <li>a. gases, particles</li> <li>b. particles, gases</li> </ul>	12. d. any of the above (depending on the specific scrubber design and application)
	13. b. particles, gases

## **Plate Towers**

A plate tower is a vertical column with one or more plates (trays) mounted horizontally inside. As shown in Figure 3-9, the exhaust stream enters at the bottom and flows upward, passing through openings in the plates. Liquid enters at the top of the tower, traveling across each plate to a downcomer through which it reaches either the next plate below or the bottom of the tower. Pollutant collection occurs on each plate as the exhaust gas stream contacts and then atomizes the liquid flowing over each plate. Plate towers are very effective in removing gaseous pollutants and can be used simultaneously for particle removal. Plate towers may not be appropriate when particle removal is the only consideration.



Figure 3-9. Plate tower.

Plates, or trays, are designed in a variety of ways. The ones most commonly used for industrial sources are the sieve, impingement, bubble-cap, and valve. The sieve, impingement, and bubble-cap plates do not have moving parts, while the valve plates have liftable caps above the opening in the plate. Plate openings can range from 0.32 to 2.50 cm (0.125 to 1.0 in.) in diameter for the sieve plate. Openings for the other plate designs are generally larger.

Sieve plates contain approximately 6456 to 32,280 holes per square meter (600 to 3000 per square foot) of surface. Exhaust gas rises through these small holes and contacts the liquid at the holes. The gas atomizes the liquid, forming a froth with droplets ranging from 10 to 100  $\mu$ m in diameter. Particle collection efficiency increases as the size of the sieve opening decreases. This is because of an increasing gas velocity and because smaller droplets are formed. Sieve plates with large openings will not become plugged as easily as will other plate designs. Figure 3-10 depicts gas-liquid contact on a sieve plate.

Impingement plates are similar to sieve plates with the addition of an impaction target placed above each hole in the plate (Figure 3-11). The gas coming up through the hole forces the liquid on the plate up against the target (impingement surface). This design increases the mixing of the gas and liquid, provides an additional contact zone, and creates more liquid droplets.



Figure 3-10. Sieve plate.

Figure 3-11. Impingement plate.

In the *bubble-cap plate* design, the exhaust gas enters each cap through a riser around each hole in the plate and exits from several slots in each cap (Figure 3-12). This combination of caps and risers creates a bubbly froth that allows good gas-liquid mixing, regardless of the gas-to-liquid ratio. In addition, the caps provide a longer gas-liquid contact than either sieves or impingement plates, thus increasing absorption efficiency. Plugging and corrosion can be a problem for bubble-cap plates because of this more complex design.

In the *valve plate* design, the exhaust gas passes through small holes in the plate, pushing up against a metal valve that covers each hole. The metal valve moves up and down with the gas flow. The valve is limited in its vertical movement by legs attached to the plate (Figure 3-13). Therefore, the liftable valve acts as a variable orifice. Caps are available in different weights to provide flexibility for varying exhaust gas flow rates. Floating valves increase gaseous pollutant collection efficiency by providing adequate gas-liquid contact time, regardless of the exhaust gas flow rate. This design is also suited for very small particle collection; however, valves will plug if large particles are in the exhaust stream. Wear and corrosion are also a problem for the retaining legs. Valve plates are more expensive than sieve and impingement plates, but less expensive than bubble-cap plates.



Figure 3-12. Bubble-cap plate.

Figure 3-13. Valve plate.

#### Particle Collection

Particles are collected in plate towers as the exhaust gas atomizes the liquid flowing over the holes in the plates. The atomized droplets serve as impaction targets for the particles. Plate towers are considered to be medium-energy scrubbers having moderate particle collection efficiencies. Collection efficiency does not significantly increase by increasing the number of plates over two or three. Collection efficiency can be increased by decreasing the hole size and increasing the number of holes per plate. This produces more liquid droplets of a smaller size and increases the gas velocity through the plate. However, it also increases the pressure drop of the system.

#### Gas Collection

Plate towers are very effective for removing gaseous pollutants from an exhaust stream. They can easily achieve greater than 98% removal in many applications. Absorption occurs as the exhaust stream bubbles up through the liquid on the plates and contacts the atomized liquid droplets. This action provides intimate contact between the exhaust gas and liquid streams, allowing the liquid on each plate to absorb the pollutant gas. Each plate acts as a separate absorption stage; therefore, absorption efficiency can be increased by adding plates. Absorption efficiency can also be improved by adding more liquid or by increasing the pressure drop across each plate, which increases gas-liquid contact.

#### Maintenance Problems

Plate towers are susceptible to plugging and/or scale-buildup problems. If the exhaust stream contains a high concentration of dust or sticky materials, plate towers are generally not used. To clean the plates, access ports to each one are usually installed. In some systems, plates can actually be removed for cleaning. In addition, water sprays can be used to spray the underside of the lowest plate in the tower to eliminate the possibility of a wet-dry interface, which causes plugging.

Gas-liquid distribution may also be a problem with plate towers. If the plates are not level, gas-liquid contact will be reduced, thus reducing collection efficiency. Flooding (liquid buildup on a plate) can occur if either the liquid-injection or exhaust gas velocity is excessive. Flooding causes an increase in pressure drop and a decrease in gas-liquid mixing. Weeping (liquid dripping through the holes in the plates) can occur if the gas velocity is too low. Weeping also reduces gas-liquid contact. Table 3-4 summarizes some of the operational problems associated with plate towers.

Problem Probable cause		Corrective action
Weeping	Too large an open area (holes) on tray Gas rate lower than design	Try bleeding in excess air or blocking off excess area. Check and adjust fan belt or speed. Check inlet duct for obstructions
Flooding	Too much liquid injected onto a plate	Reduce the liquid-injection rate.
	Too much gas flowing through a plate, causing the liquid to "stand" on a plate	Lower the gas flow rate, if possible. If the gas flow rate is set because of process conditions (and it is excessive), an increase in tower design (size) may be necessary.
Plugging	High solids concentration in scrubbing liquor	Check percentage of solids in recycle liquid. Check solid-separation equip- ment on recycle liquor. Use spray wash header. Clean trays periodically.
	Little or no water flow to trays	Check pump output; look for plugged piping, nozzles, incorrectly opened valves, or overthrottled pump- discharge valves.
	Higher-than-expected particle content in inlet gas	Add prequench sprays.
	Scale buildup	Use a low-pH wash periodically to dis- solve scale.
Poor distribution	Trays not level	Check and level.
	Liquid flow rate too high or gas flow rate too low	Check pump output: look for plugged piping, nozzles, incorrectly opened valves, or overthrottled pump-discharge valves.
	Mechanical problems with trays	Check for warped trays, loose fittings, and loose or broken baffle strips or caps.

Table 3-4. Operational problems associated with plate towers.

Sources: Kelly 1978 and Buonicore 1982.

#### Summary

Plate towers are used most often when gaseous pollutant removal is the major concern. They can achieve greater than 98% collection efficiency, depending on the solubility of the gaseous pollutant. They can also be used to collect particles, but plugging and scale buildup problems may occur. They have been used successfully in flue gas desulfurization systems to remove sulfur dioxide emissions from utility boilers.

They have also been used to reduce pollutants emitted from petroleum refineries, chemical processes, acid manufacturing plants, and metal smelters. A summary of the operating characteristics of plate towers is given in Table 3-5.

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p <sub>2</sub> )	Removal efficiency (%) and cut diameter	Applications
Gases	2.5-20 cm of water per tray (1-8 in. of water)	0.7-2.0 L/m <sup>3</sup> (5-15 gal/1000 ft <sup>3</sup> )	<34.5 kPa	Very effective (>98%), depending on the solubility of the gaseous	Coal dryers Copper roasting Industrial boilers Chemical process
Particles	Normal pressure drops are 7.6 cm (3 in.) of water	0.3-0.7 L/m <sup>3</sup> (2-5 gal/1000 ft <sup>3</sup> )	(<5 psig)	pollutant >2.0-μm cut diameter	Petroleum refineries Incineration processes

Table 3-5.	Operating	characteristics	of	plate	towers.
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Review Exercise	
<ol> <li>Name each of the following designs for plates in plate towers.</li> </ol>	
a.	
b. C.	
2. True or False? For particle collection, efficiency does not significantly increase by increasing the number of plates in a plate tower.	<ul> <li>a. bubble-cap</li> <li>b. sieve</li> <li>c. valve</li> </ul>
3. In a plate tower, particle collection can usually be enhanced by increasing/decreasing the hole size and/or increasing/decreasing the number of holes per plate.	2. True
<ul> <li>4. For gaseous pollutant collection in a plate tower, absorption can usually be enhanced by</li> <li>a. adding plates.</li> <li>b. increasing the amount of liquid.</li> <li>c. both a and b</li> </ul>	3. decreasing, increasing
	4. c. both a and b

5.	If the plates in a tower are not, gas-liquid contact can be reduced, thus reducing collection efficiency. a. the same size b. level c. staggered d. omitted	
6.	Liquid dripping through the holes in the plates, due to a low gas velocity, is referred to as a. flooding. b. dropsy. c. weeping. d. drooling.	5. b. level
7.	List at least three common operational problems associated with plate towers.	6. c. weeping.
	Ð	<ul><li>7. • weeping</li><li>• plugging</li><li>• flooding</li></ul>

5.55%

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e

## **Orifice Scrubbers**

In orifice scrubbers, the exhaust stream from the process is forced through a pool of liquid, usually water. The exhaust stream moves through restricted passages, or orifices, to disperse and atomize the water into droplets. These scrubbers are also called *self-induced spray*, *inertial*, or *submerged orifice scrubbers*.

Several orifice scrubber designs are typically used. In each, the incoming exhaust stream is directed across or through a pool of water as shown in Figure 3-14. The high exhaust stream velocity, approximately 15.2 m/s (50 ft/sec), creates a large number of liquid droplets. Both particles and gaseous pollutants are collected as they are forced through the liquid pool and impact the droplets. However, these scrubbers are generally used for removing particles. Large particles are collected when they impact the liquid pool or its surface. Small particles are collected when they impact the droplets. Baffles, or air foils, are added to provide turbulent mixing of the exhaust stream and droplets.



Figure 3-14. Detail of orifice action.

In the self-induced spray scrubber, the exhaust stream enters through a duct as shown in Figure 3-15. The exhaust stream is forced by baffles through a pool of liquid. Particles and gases are collected in the pool and by the droplets. Additional baffles placed in the path of the "clean" exhaust stream as it exits the vessel serve as impingement surfaces to remove entrained droplets.

Particulate matter collected in the scrubber forms a sludge that must be disposed of. Sludge disposal involves removing and recycling large amounts of liquid, from 3.5 to 4.2 L/m<sup>3</sup> (25 to 30 gal/1000 acfm). Some designs use a sludge separation and removal system inside the scrubber. The water level inside the scrubber must be maintained during the sludge separation and removal cycle so that the unit can operate efficiently.



Figure 3-15. Self-induced spray orifice scrubber.

#### **Particle Collection**

Large particles in the incoming exhaust stream are collected as they impinge on the surface of the pool. Smaller particles are collected as they impact on the droplets produced by the high-velocity gas skimming over the liquid. Overall particle collection in an orifice scrubber depends on the level of the liquid. The level of the liquid determines the gas velocity (and, thus, the pressure drop) through the orifice. If the liquid level is low, gas velocities decrease because the orifice opening is larger. Lower velocities produce fewer droplets that are larger in size, decreasing particle collection. A *turn-down* of the system, or reduction in gas volume, will also result in less atomization and produce larger droplets. It is recommended that gas velocities should not fluctuate by more than 10 to 15% of design values to provide maximum effectiveness (Bethea 1978).

#### Gas Collection

Orifice scrubbers are rarely used for absorption (McIlvaine Company 1974). However, because orifice scrubbers provide both thorough mixing of the gas and liquid, and large liquid-surface contact areas (many tiny droplets), these devices can be effective for reactive scrubbing or for removing gaseous pollutants that are already very soluble in the liquid. In reactive scrubbing, the gaseous pollutants chemically react with the scrubbing liquid. These reactions occasionally produce scale or sludge that can plug scrubber internals. The relatively large orifice openings will not plug as easily as those in plate towers.

#### Maintenance Problems

The greatest problem for orifice scrubbers is maintaining the liquid at the proper level for a constant gas flow rate. Orifice scrubbers are designed to operate with a specific liquid level for a given gas velocity. If the gas flow decreases (or the liquid level decreases), less atomization occurs, thus reducing collection efficiency. If gas flow rate increases too much, it is possible to blow the liquid chamber dry (Bethea 1978). Systems are generally designed to operate at the upper end of the process exhaust rate and to introduce makeup air if the exhaust stream velocity becomes too low. Controlling the liquid level is much more difficult than maintaining a constant exhaust flow rate because of the turbulent condition of the water.

#### Summary

Orifice scrubbers are medium-energy devices with moderate collection efficiencies. The pressure drops across these devices are usually between 5 and 25 cm (2 and 10 in.) of water. The relatively large openings enable them to accommodate exhaust streams with high concentrations of particulate matter. Plugging by sticky or stringy material and scale buildup are not major problems. Because the gas stream is forced through a pool of liquid to create liquid droplets, spray nozzles are not necessary.

Orifice scrubbers are used mainly on metallurgical processes (crushing, screening, grinding, etc.), where the particles generated are mostly above 1  $\mu$ m in diameter. Removal efficiencies depend on exhaust stream velocities. Reduction in exhaust stream velocities or liquid levels in the device will cause a reduction in collection efficiency. Table 3-6 lists operating characteristics of orifice scrubbers.

Pollutant	Pressure drop (Ap)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p <sub>L</sub> )	Removal efficiency (%) and cut diameter	Applications
Gases	5-25 cm of water	0.07-0.7 L/m <sup>3</sup> (0.5-5 gal/1000 ft <sup>3</sup> )	Not applicable	Limited to very soluble gases or reactive scrubbing	Mining operations Rock products industries Foundries
Particles	(2-10 in. of water)	1.3-5.3 L/m <sup>3</sup> (10-40 gal/1000 ft <sup>3</sup> ) for sludge removal and recycle	used)	0.8-1-μm cut diameter	Pulp and paper industries Chemical process industries

#### Table 3-6. Operating characteristics of orifice scrubbers.

	Review Exercise	· · ·
1.	Although orifice scrubbers are produced in a variety of configurations, all are designed so that the exhaust gas stream a. is split into two streams. b. travels concurrently with the liquid stream. c. breaks through a pool of liquid. d. none of the above	
2.	True or False? In an orifice scrubber, all particles are collected as they impinge on the surface of the liquid. $\Box$	<ol> <li>c. breaks through a pool of liquid.</li> </ol>
3.	The exhaust gas velocity (thus, the pressure drop) in an orifice scrubber is dictated by the <ul> <li>a. adjustable throat.</li> <li>b. level of liquid.</li> <li>c. the plant foreman.</li> <li>d. precise calculations.</li> </ul>	<ol> <li>False.</li> <li>Only large particles.</li> <li>Small particles are collected by liquid droplets produced by the exhaust stream.</li> </ol>
4.	True or False? Orifice scrubbers are not primarily used for gas absorption.	3. b. level of liquid.
5.	<ul> <li>The greatest problem with orifice scrubbers is</li> <li>a. maintaining the proper liquid level.</li> <li>b. plugging.</li> <li>c. scale buildup.</li> <li>d. erosion.</li> </ul>	4. True
6.	True or False? An orifice scrubber is capable of operating over a wide range of gas flow rates. $F$	5. a. maintaining the proper liquid level.
7.	<ul> <li>In orifice scrubbers, a reduction in the design exhaust gas flow rate results in</li> <li>a. an increase in gas collection.</li> <li>b. an increase in particle collection.</li> <li>c. less atomization and production of larger liquid C droplets.</li> <li>d. both a and b</li> </ul>	6. False. Exhaust gas velocities should not fluctuate greatly.
8.	Orifice scrubbers are generally classified as energy devices capable of collection efficiencies. a. very low, very high b. medium-, moderate c. high-, very high d. none of the above	7. c. less atomization and production of larger liquid droplets.
	·	8. b. medium-, moderate

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9. True or False? Plugging and scale buildup are not major operating problems with orifice scrubbers.

9. True

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## Lesson 4

## Liquid-Phase Contacting Scrubbers

## Lesson Goal and Objectives

#### Goal

To familiarize you with the operation, collection efficiency, and major maintenance problems of liquid-phase contacting scrubbers.

#### **Objectives**

Upon completing this lesson, you should be able to-

- 1. list two liquid-phase contacting scrubbers and briefly describe the operation of each,
- 2. recall the operating characteristics such as pressure drop, liquid-to-gas ratio, and collection efficiency of each liquid-phase contacting scrubber, and
- 3. describe typical operating and maintenance problems associated with each design of liquid-phase contacting scrubbers.

## Introduction

The previous lesson described scrubbers that use the process gas stream as energy to atomize liquid into collection droplets. Energy can also be applied to a scrubbing system by injecting liquid at high pressure through specially designed nozzles. Nozzles produce droplets that fan out into a spray in the scrubber chamber. Droplets act as targets for collecting particles and/or absorbing gas in a pollutant exhaust stream. In liquid-phase contacting scrubbers, the liquid-inlet pressure provides the major portion of the energy required for contacting the gas (exhaust stream) and liquid phases.

Two liquid-phase contacting scrubbers are the spray tower and the ejector venturi. Many other scrubber designs also incorporate sprays produced by nozzles, but in those scrubbers, the sprays are used to clean trays or to wet scrubber surfaces and orifices, and **not** to provide the gas-liquid contact in the system. 

## Spray Towers

Spray towers, or chambers, are constructed very simply—consisting of empty cylindrical vessels made of steel or plastic and nozzles that are used to spray liquid in the vessels. The exhaust stream usually enters the bottom of the tower and moves upward, while liquid is sprayed

downward from one or more levels. This flow of exhaust gas and liquid in opposite directions is called *countercurrent flow*. Figure 4-1 shows a typical countercurrent-flow spray tower. Countercurrent flow exposes the exhaust gas with the lowest pollutant concentration to the freshest scrubbing liquid.



Figure 4-1. Countercurrent-flow spray tower.

Many nozzles are placed across the tower at different heights to spray all of the exhaust gas as it moves up through the tower. The major purpose of using many nozzles is to form a tremendous amount of fine droplets for impacting particles and to provide a large surface area for absorbing gas. Theoretically, the smaller the droplets formed, the higher the collection efficiency achieved for both gaseous and particulate pollutants. However, the liquid droplets must be large enough to **not** be carried out of the scrubber by the exhaust stream. Therefore, spray towers use nozzles to produce droplets that are usually 500 to 1000  $\mu$ m in diameter. The exhaust gas velocity is kept low, from 0.3 to 1.2 m/s (1 to 4 ft/sec) to prevent excess droplets from being carried out of the tower. Because of this low exhaust velocity, spray towers must be larger than other scrubbers that handle similar exhaust stream flow rates. Another problem occurring in spray towers is that after the droplets fall short distances, they tend to agglomerate or hit the walls of the tower. Consequently, the total liquid surface area for contact is reduced, thus reducing the collection efficiency of the scrubber.

In addition to a countercurrent-flow configuration, the flow in spray towers can be either a *cocurrent* or *crosscurrent* configuration. In cocurrent-flow spray towers, the exhaust gas and liquid flow in the same direction. Because the exhaust gas stream does not "push" against the

liquid sprays, these units operate at higher exhaust gas velocities (through the vessels) than do countercurrent-flow spray towers. Consequently, cocurrent-flow spray towers are smaller than are countercurrent-flow spray towers (treating the same amount of exhaust flow).

In crosscurrent-flow spray towers, called horizontal-spray scrubbers, the exhaust gas and liquid flow in directions perpendicular to each other (Figure 4-2). In this vessel, the exhaust gas flows horizontally through a number of spray sections. The amount and quality of liquid sprayed in each section can be varied, usually with the cleanest liquid (if recycled liquid is used) sprayed in the last set of sprays.



Figure 4-2. Crosscurrent-flow spray tower.

#### **Particle Collection**

Spray towers are low-energy scrubbers. Contacting power is much lower than in venturi scrubbers, and the pressure drops across such systems are generally less than 2.5 cm (1 in.) of water. The collection efficiency for small particles is correspondingly lower than in more energy-intensive devices. They are adequate for the collection of coarse particles larger than 10 to 25  $\mu$ m in diameter, although with increased liquid inlet nozzle pressures, particles with diameters of 2.0  $\mu$ m can be collected. Smaller droplets can be formed by higher liquid pressures at the nozzle. The highest collection efficiencies are achieved when small droplets are produced and the difference between the velocity of the droplet and the velocity of the upward-moving particles is high. Small droplets, however, have small settling velocities, so there is an optimum range of droplet sizes for scrubbers that work by this mechanism. Stairmand (1956) found this range of droplet sizes to be between 500 and 1000  $\mu$ m for gravity-spray towers. The injection of water at very high pressures, 2070 to 3100 kPa (300 to 450 psi), creates a fog of very fine droplets. Higher particle-collection efficiencies can be achieved in

such cases since collection mechanisms other than inertial impaction occur (Bethea 1978). However, these spray nozzles may use more power to form droplets than would a venturi operating at the same collection efficiency.

#### Gas Collection

Spray towers can be used for gas absorption, but they are not as effective as packed or plate towers. Spray towers can be very effective in removing pollutants if the pollutants are highly soluble or if a chemical reagent is added to the liquid. For example, spray towers are used to remove HCl gas from the tail-gas exhaust in manufacturing hydrochloric acid. In the production of superphosphate used in manufacturing fertilizer,  $SiF_4$  and HF gases are vented from various points in the processes. Spray towers have been used to remove these highly soluble compounds. Spray towers are also used for odor removal in bone meal and tallow manufacturing industries by scrubbing the exhaust gases with a solution of KMnO<sub>4</sub>. Because of their ability to handle large exhaust gas volumes in corrosive atmospheres, spray towers are also used in a number of flue gas desulfurization systems as the first or second stage in the pollutant removal process.

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

#### Maintenance Problems

The main advantage of spray towers over other scrubbers is that they are completely open; they have no internal parts except for the spray nozzles. This feature eliminates many of the scale buildup and plugging problems associated with other scrubbers. The primary maintenance problems are spray-nozzle plugging or eroding, especially when using recycled scrubber liquid. To reduce these problems, a settling or filtration system is used to remove abrasive particles from the recycled scrubbing liquid before pumping it back into the nozzles. (See Lesson 2 for additional information on spray nozzles.)

#### Summary

Spray towers are inexpensive control devices primarily used for gas conditioning (cooling or humidifying) or for first-stage particle or gas removal. They are also being used in many flue gas desulfurization systems to reduce plugging and scale buildup by pollutants. Many scrubbing systems use sprays either prior to or in the bottom of the primary scrubber to remove large particles that could plug it. Spray towers have been used effectively to remove large particles and highly soluble gases. The pressure drops across the towers are very low (usually less than 2.5 cm [1.0 in.] of water); thus, the scrubber operating costs are relatively low. However, the liquid pumping costs can be very high.

Spray towers are constructed in various sizes—small ones to handle small exhaust flows of  $0.05 \text{ m}^3/\text{s}$  (100 cfm) or less, and large ones to handle large exhaust flows of 50 m<sup>3</sup>/s (100,000 cfm) or greater. Because of the low gas velocity required, units handling large exhaust flow rates tend to be large in size. Operating characteristics of spray towers are presented in Table 4-1.

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p <sub>L</sub> )	Removal efficiency (%) and cut diameter	Applications
Gases Particles	1.3-7.6 cm of water (0.5-3.0 in. of water)	0.07-2.70 L/m <sup>3</sup> (0.5-20 gal/1000 ft <sup>3</sup> ) (5 gal/1000 ft <sup>3</sup> is normal; >10 when using pressure sprays)	70-2800 kPa (10-400 psig)	50-90*% (high efficiency only when the gas is very soluble) 2-8-μm cut diameter	Mining industry Chemical process industry Boilers and incinerators Iron and steel industry

### Table 4-1. Operating characteristics of spray towers.

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	Review Exercise	
1.	In a scrubber, the liquid and exhaust gas flow in opposite directions. a. cocurrent b. countercurrent c. crosscurrent d. crosshatch	
2.	In a spray tower, the the droplet is, the higher the theoretical collection efficiency will be. a. smaller b. larger c. higher d. lower	1. b. countercurrent
3.	Gas velocities in spray towers are usually kept very to prevent excessive liquid from becoming entrained in the exhaust gas stream leaving the tower. a. high b. low c. stable d. none of the above	2. a. smaller
4.	True or False? In general, countercurrent-flow spray towers must be larger than crosscurrent- or cocurrent-flow spray towers to accommodate the same volumetric flow rate.	3. b. low
		4. True

5.	In a spray tower, gas collection can be increased by increasing a. the size of the liquid droplets. b. the liquid-to-gas ratio (L/G).		
	d. all of the above		
6.	<ul> <li>Because spray towers contain few internal parts, they</li> <li>a. eliminate many potential problems due to plugging and scale buildup.</li> <li>b. have low pressure drops.</li> <li>c. are relatively simple and inexpensive.</li> <li>d. all of the above</li> </ul>	5.	b. the liquid-to-gas ratio (L/G).
7.	What are the main maintenance problems with spray towers?	6.	d. all of the above
8.	In spray towers, the pressure drops across the tower are usually $low/high$ and the liquid pumping costs can be very $low/high$ .	7.	plugging or erosion of the nozzle
		8.	low, high

## **Ejector Venturis**

The ejector, or jet, venturi scrubber uses a preformed spray, as does the simple spray tower. The difference is that only a single nozzle is used instead of many nozzles. This nozzle operates at higher pressures and higher injection rates than those in most spray chambers. The highpressure spray nozzle (up to 689 kPa or 100 psig) is aimed at the throat section of a venturi constriction. Figure 4-3 illustrates the ejector venturi design.

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

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



Figure 4-3. Ejector venturi scrubber.

#### **Particle Collection**

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

The turbulence that occurs in the throat area also causes the particles to contact the wet droplets and be collected. Particle collection efficiency increases with an increase in nozzle pressure and/or an increase in the liquid-to-gas ratio. In fact, ejector venturis operate at higher L/G ratios than most other particle scrubbers.

#### Gas Collection

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

#### Maintenance Problems

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

#### Summary

Because of their open design and the fact that they do not require a fan, ejector venturis are capable of handling a wide range of corrosive and/or sticky particles. However, they are not very effective in removing submicron particles. They have an advantage in being able to handle small, medium, and large exhaust flows. They can be used singly or in multiple stages of two or more in series, depending on the specific application. Multiple-stage systems have been used where extremely high collection efficiency of particles or gaseous pollutants was necessary. Multiple-stage systems provide increased gas-liquid contact time, thus increasing absorption efficiency. Table 4-2 lists the operating parameters for ejector venturis.

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p <sub>L</sub> )	Removal efficiency (%) and cut diameter	Applications
Gases	1.3-13 cm of water	7-13 L/m³	100-830 kPa	95% for very soluble gases	Pulp and paper industry Chemical process industry
Particles	1 (0.5-5 in. of water)	(50-100 gal/1000 ft <sup>3</sup> )	(15-120 psig)	l-μm cut diameter	Food industry Metals-processing industry

Table 4-2.	Operating	characteristics	of ejector	venturis.
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	Review Exercise	
1.	The ejector, or jet, venturi scrubber uses to move the process exhaust stream. a. multiple nozzles b. a single high-pressure nozzle c. a compressor d. a fan	
2.	For ejector venturis, particle collection efficiencies increase with an increase in a. nozzle pressure. b. liquid-to-gas ratio (L/G). c. pressure drop. d. all of the above	1. b. a single high-pressure nozzle
3.	What limits gas collection in ejector venturis?	2. d. all of the above
4.	Ejector venturis are subject to abrasion problems in the a. throat. b. nozzle. c. packing area. d. throat and nozzle.	3. high gas velocities
5.	True or False? Because of their open design and the fact that they do not require a fan, ejector venturis are capable of handling a wide range of corrosive and/or sticky particles.	4. d. throat and nozzle.
		5. True

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# Lesson 5 Wet-Film Scrubbers

## Lesson Goal and Objectives

#### Goal

To familiarize you with the operation, collection efficiency, and major maintenance problems of wet-film scrubbers.

#### **Objectives**

Upon completing this lesson, you should be able to-

- 1. describe the operation of wet-film scrubbers,
- 2. recall the collection efficiency of wet-film scrubbers for particles and gases,
- 3. recognize at least three different gas-liquid flow arrangements (designs) for wet-film scrubbers, and
- 4. recognize major operating and maintenance problems associated with each wet-film scrubber design.

## Introduction

In wet-film scrubbers, liquid is sprayed or poured over packing material contained between support trays. A liquid film coats the packing through which the exhaust gas stream is forced. Pollutants are collected as they pass through the packing, contacting the liquid film. Therefore, both gas and liquid phases provide energy for the gas-liquid contact. These scrubbers are commonly called packed towers.

A wet-film scrubber uses packing to provide a large contact area between the gas and liquid phases, to provide turbulent mixing of the phases, and to provide sufficient residence time for the exhaust gas to contact the liquid. These conditions are ideal for gas absorption. Large contact area and good mixing are also good for particle collection; however, once collected, the particles tend to accumulate and, thus, plug the packing bed. The exhaust gas is forced to make many changes in direction as it winds through the openings of the packed material. Large particles unable to follow the streamlines hit the packing and are collected in the liquid. As this liquid drains through the packing bed, the collected particles may accumulate, thus plugging the void spaces in the packed bed. Therefore, wet-film scrubbers are not used when particle removal is the only concern. Many other scrubber designs achieve better particle removal for the same power input (operating costs).

## **Gas Collection**

For gas absorption, wet-film scrubbers are the most commonly used devices. The wet film covering the packing enhances gas absorption several ways by providing:

- a large surface area for gas-liquid contact,
- turbulent contact (good mixing) between the two phases, and
- long residence time and repetitive contact.

Because of these features, packed towers are capable of achieving high removal efficiencies for many different gaseous pollutants.

Numerous operating variables affect absorption efficiency. Of primary importance is the solubility of the gaseous pollutants. Pollutants that are readily soluble in the scrubbing liquid can be easily removed under a variety of operating conditions. Some other important operating variables are discussed below.

Gas velocity—The rate of exhaust gas from the process determines the scrubber size to be used. The scrubber should be designed so that the gas velocity through it will promote good mixing between the gas and liquid phases. However, the velocity should not be too fast to cause flooding.

Liquid-injection rate—Generally, removal efficiency is increased by an increase in the liquid-injection rate to the vessel. The amount of liquid that can be injected is limited by the dimensions of the scrubber. Increasing liquid-injection rates will also increase the operating costs. The optimum amount of liquid injected is based on the exhaust gas flow rate.

**Packing size**—Smaller packing sizes offer a large surface area, thus enhancing absorption. However, smaller packing fits tighter, which decreases the open area between packing, thus increasing the pressure drop across the packing bed.

**Packing height**—As packing height increases, total surface area and residence time increase, enhancing absorption. However, more packing necessitates a larger absorption system, which increases capital cost.

## **Tower Designs**

Packed towers are typically designated by the flow arrangement used for gas-liquid contact or by the material used as packing for the bed.

The most common flow configuration for packed towers is *countercurrent* flow. Figure 5-1 shows a packed tower with this arrangement. The exhaust stream being treated enters the bottom of the tower and flows upward over the packing material. Liquid is introduced at the top of the packing by sprays or weirs, and it flows downward over the packing material. As the exhaust stream moves up through the packing, it is forced to make many winding changes in direction, resulting in intimate mixing of both the exhaust gas and liquid streams. This countercurrent-flow arrangement results in the highest theoretically achievable efficiency. The most dilute gas is contacted with the purest absorbing liquor, providing a maximized concentration difference (driving force) for the entire length of the column.



Figure 5-1. Countercurrent-flow packed tower.

The countercurrent-flow packed tower does not operate effectively if there are large variations in the liquid or gas flow rates. If either the liquid-injection rate or the gas flow rate through the packing bed is too high, a condition called *flooding* may occur. Flooding is a condition where the liquid is "held" in the pockets, or void spaces, between the packing and does not drain down through the packing. Flooding can be reduced by reducing the gas velocity through the bed or by reducing the liquid-injection rate.

In another flow arrangement used with packed towers, *cocurrent* flow, both the exhaust gas and liquid phases enter at the top-of the absorber and move downward over the packing material. This allows the absorber to be operated at higher liquid and gas flow rates since flooding is not a problem. The pressure drop is lower than with countercurrent flow since both streams move in the same direction. The major disadvantage is that removal efficiency is very limited due to the decreasing driving force (concentration differential) as the streams travel down through the column. This limits the areas of application for cocurrent absorbers. They are used almost exclusively in situations where limited equipment space is available, since the tower diameter is smaller than a countercurrent or plate tower for equivalent flow rates. Cocurrent flow is illustrated in Figure 5-2.



Figure 5-2. Cocurrent-flow packed tower.

In packed towers using the *crossflow* arrangement, the exhaust gas stream moves horizontally through the packed bed. The bed is irrigated by the scrubbing liquid flowing down through the packing material. The liquid and exhaust gas flow in directions perpendicular to each other. A typical crossflow packed tower is shown in Figure 5-3. (Inlet sprays aimed at the face of the bed may also be included. If included, these sprays scrub both the entering gas and the face of the packed bed.) The leading face of the packed bed is slanted in the direction of the oncoming gas stream. This ensures complete wetting of the packing by allowing the liquid at the front face of the packing time to drop to the bottom before being pushed back by the entering gas.

Crossflow absorbers are smaller and have a lower pressure drop than any other packed or plate tower for the same application (removal efficiency and flow rates). In addition, they are better suited than other wet-film scrubbers to handle exhaust streams with high particle concentrations. By adjusting the liquid flow rate, incoming particles can be removed and washed away in the front half of the bed. This also results in a liquid savings by enabling the crossflow packed tower to use less liquid in the rear sprays. This practice is carried one step further by actually constructing the tower into sections as shown in Figure 5-4. The front section can be equipped with water sprays and used for particulate matter removal. In the second section, sprays may contain a reagent in the scrubbing liquor for gas removal. The last section can be left dry to act as an entrainment separator. Crossflow packed towers do require complex design procedures since concentration gradients exist in two directions in the liquid: from top to bottom and from front to rear.



Figure 5-3. Crossflow packed tower.



Figure 5-4. Three-bed crossflow packed tower.

Another crossflow packed tower is the *fiber-bed* scrubber. The fiber-bed scrubber has packed beds that are made with fibrous material such as fiberglass or plastic (Figure 5-5). Liquid is sprayed onto the fiber beds to provide a wetted surface for pollutant removal and to wash away any collected material.



Figure 5-5. Fiber-bed scrubber.

## **Packing Material**

Packing material is the heart of the tower. It provides the surface over which the scrubbing liquid flows, presenting a large area for mass transfer to occur. Packing material represents the largest material cost of the packed tower. Pictured in Figure 5-6 are some of the more commonly used packings. These materials were originally made of stoneware, porcelain, or metal, but presently a large majority are being made of high-density thermoplastics (polyethylene and polypropylene). A specific packing is described by its trade name and overall size. For example, a column can be packed with 5-cm (2-in.) Raschig rings<sup>®</sup> or 2.5-cm (1-in.) Tellerettes<sup>®</sup>. The overall dimensions of packing materials normally range from 0.6 to 10 cm (0.25 to 4 in.).

Specific packing selected for an industrial application depends on the nature of the contaminants, geometric mode of contact, size of the absorber, and scrubbing objectives. The following factors provide a general guide for selecting packing materials (McDonald 1977):

Cost-Generally, plastic packing is less expensive than metal packing, with ceramic packing being the most expensive. Packing costs are expressed in dollars per cubic meter ( $\$/m^3$ ). Low pressure drop-Presure drop is a function of the volume of void space in a tower when filled with packing. Generally, the larger the packing size for a given bed size, the smaller the pressure drop.

**Corrosion resistance**-Ceramic or porcelain packings are commonly used in a very corrosive atmosphere.



Figure 5-6. Common packing materials.

Large specific area – A large surface area per cubic foot of packing,  $m^2/m^3$  (ft<sup>2</sup>/ft<sup>3</sup>), is desirable for mass transfer.

Structural strength – Packing must be strong enough to withstand normal loads during installation, service, physical handling, and thermal fluctuations. Ceramic packing may crack under sudden temperature changes.

Weight—Heavier packing may require additional support materials or heavier tower construction. Plastics have a big advantage in this area since they are much lighter than either ceramic or metal packings.

**Design flexibility**—The efficiency of a scrubber changes as the liquid and gas flow rates vary. Packing material must be able to handle the process changes without substantially affecting removal efficiency.

Arrangement – Packing material may be arranged in an absorber in one of two ways. The packing may be dumped into the column randomly or, in certain cases, systematically stacked, as bricks are laid atop each other. Randomly packed towers provide a higher surface area,  $m^2/m^3$  (ft<sup>2</sup>/ft<sup>3</sup>), but also cause a higher pressure drop than stacked packing. In addition to the lower pressure drop, the stacked packing provides better liquid distribution over the entire surface of the packing. However, the large installation costs required to stack the packing material usually make it impractical.

## **Exhaust Gas Distribution**

Uniform distribution of the exhaust gas through the packed beds is very important for efficient pollutant removal. This is accomplished by properly designing the support trays used to contain the packing in the bed. The support trays are essentially metal plates, or grids, that support the packing while allowing the exhaust gas to flow evenly into the bed. If the packed tower has multiple packing sections, each support grid would act as a distribution baffle, directing the exhaust gas into the next packing section.

## Liquid Distribution

As stated previously, one of the keys to effective packed tower operation is to intimately contact the gas stream with the liquid stream. This contact must be maintained throughout the entire column length. No packing material will adequately distribute liquid poured onto it at only one point. Liquid introduced into the tower in this manner tends to flow down over a relatively small cross section of the tower diameter. Known as *liquid channeling*, the liquid flows in little streams down through the tower without wetting the entire packing area. Liquid should be distributed over the entire cross-sectional top of the packing.

Once the liquid is distributed over the packing, it flows down (by the force of gravity) through the packing, following the path of least resistance. The liquid tends to flow toward the tower wall, where the void spaces are greater than in the center. Once the liquid hits the wall, it flows straight down the tower from that point (liquid channeling). A way must be provided to redirect the liquid from the tower wall back to the center of the column. This is usually done by using liquid redistributors, which funnel the liquid back over the entire surface of packing. It is recommended that redistributors be placed at intervals of no more than 3 m (10 ft) or 5 tower diameters, whichever is smaller (Zenz 1972).

Liquid can be distributed over the packing material by one of three devices: weirs, tubes, or spray nozzles. Figure 5-7 shows both the commonly used weir and perforated-tube liquid distributors. The drilled tube is often buried within the packing bed. This allows the liquid coming out of the holes to be distributed over the packing without being blown against the side walls of the tower. Burying the tube also allows the packing above the tube to act as an entrainment separator.





Figure 5-7a. Trough and weir liquid distributor.

Figure 5-7 b. Perforated-tube liquid distributor.

When packed towers are designed with spray nozzles, a few large nozzles will operate better than will many small nozzles. Large nozzles are less susceptible to plugging. Small nozzles that produce a finer spray are not needed in a packed tower because pollutant collection occurs on the wetted packing and not by the liquid droplets. The advantages and disadvantages of each liquid distributor are listed in Table 5-1.

Distributor	Advantages	Disadvantages
Weirs	Handle dirty liquids with a high solids content Can use river or unfiltered water Can be easily inspected and main- tained if access is available	Most costly to purchase Do not distribute liquid as uni- formly as other methods Weirs must be level
Tubes	Uniform liquid distribution Can be buried below packing surface Generally least expensive to purchase	Easily plugged, must use filter Difficult to determine if holes are plugged when tube is buried in the packing
Spray nozzles	Uniform liquid distribution Tower need not be plumb Can be easily inspected and main- tained if access is available	Highest pressure drops and opera- ting costs Easily plugged, must use filter

able 5-1. Liquid distributors for packed tower
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Source: Clark 1975.

## **Review Exercise**

1. 1 t H H a	in a packed tower, the gas stream being reated enters the bottom and flows upward through the packing while the liquid is introduced over the top of the packing and flows down through it. a. cocurrent b. crossflow	
2. 4 t	A packed tower cannot handle large varia- tions in liquid or gas flow rates because flooding may occur. a. cocurrent b. countercurrent c. crossflow d. fiber-bed	1. c. countercurrent
		2. b. countercurrent

3. Cocurrent packed towers usually have <u>higher/lower</u> pressure drops than do countercurrent packed towers.	2
4. True or False? Crossflow packed towers can handle flue gas containing a high concentration of particulate matte because they use liquid sprays that will remove and wash away particles in the front half of the bed.	3. lower
<ul> <li>5. Packing material is usually made of</li> <li>a. porcelain.</li> <li>b. polyethylene.</li> <li>c. polypropylene.</li> <li>d. all of the above</li> </ul>	4. True
6. Packed towers that have been randomly packed have <u>more/less</u> surface area and <u>higher/lower</u> pressure drop than do packed towers that have been systematically packed.	5. d. all of the above
<ul> <li>7. In a packed tower, liquid is distributed over the packing by using</li> <li>a. sprays.</li> <li>b. sprays and small venturis.</li> <li>c. sprays, weirs, and tubes.</li> <li>d. chevron-shaped sheets and sprays.</li> </ul>	6. more, higher
	7. c. sprays, weirs, and tubes.

## Maintenance Problems

A serious problem that can drastically affect the operation of a packed tower is the buildup of solids in the packing. This can occur as a result of a number of situations. If the incoming exhaust gas contains a high concentration of particulate matter, the beds can easily become plugged. One way to reduce this problem is to use precleaning sprays to remove particles before the exhaust gas enters the packed bed. Solids buildup can also occur as a result of a chemical reaction between the scrubbing liquid and gaseous pollutant, producing a solid compound. In this case, the packing may occasionally be flushed with a cleaning fluid to remove the solids. For example, potassium permanganate is occasionally used in scrubbing solutions to control odors. The use of potassium permanganate results in a residue buildup on the packing that must periodically be cleaned with an acid backwash. No matter what the cause, plugging presents an expensive maintenance problem. Tower internals are not easily accessible; cleaning requires shutting the system down and then removing, cleaning, and, finally, reinstalling the packing material.

Another critical problem in packed tower operation is maintaining the proper liquid and gas flow rates. If the liquid or gas flow rate increases (one in relation to the other), a point is reached where the rising exhaust gas starts to hold up the descending liquid. The liquid fills the upper portion of the packing until its weight causes it to fall. This condition, known as flooding, results in a high pressure drop, a pulsating airflow in the tower, and greatly reduced pollutant removal efficiencies. Optimum operating flow rates are normally at 60 to 75% of the flooding conditions. Conversely, a gas flow rate that is too low can also cause mixing problems. Too low a gas velocity can result in *gas channeling*. Gas channeling occurs when the gas does not distribute uniformly through the packing, but moves only through a small portion of the bed (following the path of least resistance). This normally occurs near the walls of the tower, where the void spaces are the greatest. Table 5-2 lists problems that could occur in daily operation of a packed tower and some probable causes of these problems.

Problem	Possible causes
Static pressure drop increases	Liquid flow rate to liquid distributor has increased and should be checked.
	Packing in irrigated bed could be partially plugged due to solids deposition, and may require cleaning.
	Entrainment separator could be partially plugged and may require cleaning.
	Packing support plate at bottom of packed section could be blinded, causing increased pressure drop, which will require cleaning.
	Packing could be settling due to corrosion or solids deposition, again requiring cleaning or additional packing.
	Airflow rate through absorber could have been increased by a change in damper set- ting, which may need readjustment.
Pressure drop decreases, slowly or rapidly	Liquid flow rate to distributor has decreased and should be adjusted accordingly.
	Airflow rate to scrubber has decreased due to a change in fan characteristics or due to a change in system damper settings.
	Partial plugging of spray or liquid distribu- tor, causing channeling through scrubber, could be occurring. Liquid distributor should be inspected to ensure that it is totally operable.
	Packing support plate could have been dam- aged and fallen into bottom of the absorber, allowing packing to fall to bottom and pro- duce a lower pressure drop. This should be checked.

Table 5-2. Potential operating problems and causes for packed towers.
Problem	Possible causes
Pressure or flow change in recycled liquid causing reduced liquid flow	Plugged strainer or filter in recycle piping, which may require cleaning. Plugged spray nozzles, which may require cleaning. Piping may be becoming partially plugged with solids and need cleaning. Liquid level in sump could have decreased, causing pump cavitation.
	Pump impeller could have been worn excessively. Valve in either suction or discharge side of pump could have been inadvertently closed.
High liquid flow	Break in the internal distributor piping. Spray nozzle that has been inadvertently "uninstalled." Spray nozzle that may have come loose or eroded away, creating a low pressure drop. Change in throttling valve setting on the dis- charge side of the pump, allowing larger liquid flow; reset to the proper conditions.
Excessive liquid carryover	Partially plugged entrainment separator, causing channeling and reentrainment of the collected liquid droplets. Airflow rate to absorber could have increased above the design capability, causing reentrainment. If a packed-type entrainment separator was used, packing may not be level, causing chan- neling and reentrainment of moisture. If a packed entrainment separator was used, and a sudden surge of air through the absorber occurred, this could have caused the packing to be carried out of absorber or to be blown aside, creating an open area "hole" through separator. Velocity through absorber has decreased to a point that absorption does not effectively take place, and low removal is achieved.

# Table 5-2. Potential operating problems and causes for packed towers (continued).

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Problem	Possible causes
Reading indicating low airflow	Packing in absorber may be plugged, causing a restriction to airflow.
	Liquid flow rate to absorber could have been increased inadvertently, again causing greater restriction and pressure drop, creating lower gas flow rate.
	Fan belts have worn or loosened, reducing airflow to equipment.
	Fan impeller could be partially corroded, reducing fan efficiency.
	Ductwork to or from absorber could be par- tially plugged with solids and may need cleaning.
	Damper in system has been inadvertently closed or setting changed.
	Break or leak in duct could have occurred due to corrosion.
Increase in airflow	Sudden opening of damper in system. Low liquid flow rate to absorber.
	Packing has suddenly been damaged and has fallen to bottom of absorber.
Sudden decrease in absorber efficiency	Liquid makeup rate to the absorber has been inadvertently shut off or throttled to a low level, decreasing absorber efficiency. If a chemical feed system is employed, system may have run out of chemical required; this
	could indicate malfunction of pH probes, if employed, requiring replacement.
	Set point on pH control may have to be adjusted to allow more chemical feed.
	Problem may exist with chemical metering pump, control valve, or line pluggage.
	Liquid flow rate to scrubber may be too low for effective removal.

Table 5-2. Potential operating problems and causes for packed towers (continued).

Source: MacDonald 1982.

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### Summary

Packed towers are mainly used to remove gaseous pollutants. Because of plugging problems, they are not used when particle removal is the only concern, or when a high concentration of particulate matter is in the exhaust gas. Packed towers are capable of very high efficiencies for removing many gaseous pollutants. For pollutants that are only slightly soluble, or if the gaseous pollutant removal efficiency must be greater than 99%, packed towers or plate towers can be used. Plate towers are used to control emissions from many of the same processes that would use packed towers. These units were described in Lesson 3.

The following list gives some factors used in comparing plate towers to packed towers:

- 1. Packed towers are not able to handle particulate matter or other solid materials in the flue gas as well as plate towers.
- 2. Plate towers are chosen for operations that require a large number of transfer units or that must handle large gas volumes. To achieve the same collection efficiency (transfer units), packed towers must have either deep packed beds or multiple beds. Packed towers can experience liquid channeling problems if the diameter or height of the tower is too large. Redistribution trays must be installed in large-diameter and tall packed towers to avoid channeling.
- 3. The total weight of a packed tower is more than that of a comparable plate tower.
- 4. Packed towers are much cheaper to construct than plate towers if corrosive substances are to be handled. Packed towers can be constructed with a fiberglass-reinforced polyester shell which is generally about half the cost of a carbon steel plate tower.
- 5. Packed towers cannot handle volume and temperature fluctuations as well as plate towers. Expansion or contraction due to temperature changes can crush or melt packing material.

In a packed tower, the optimum pressure drop through a packing section is 1.7 to 5.0 cm (0.2 to 0.6 in.) of water per foot of installed packing (Clark 1975). The overall pressure drops across packed towers are usually between 5 and 25 cm (2 and 10 in.) of water. Thus, packed towers are generally considered as medium-energy scrubbers.

Packed towers are most suited to applications where a high gas-removal efficiency is required and the exhaust gas is relatively free from particles. These include removing HCl, NH<sub>4</sub>, and SO<sub>2</sub> gases from a variety of process streams such as those from fertilizer manufacturing, chemical processing, acid manufacturing, steel making, and metal pickling operations. One important point that should be noted is that packed towers are not effective in removing submicron-sized particles, even if the particles are very soluble. Inorganic salts or fumes such as ammonium chloride or aluminum chloride are prime examples. These particles are usually so small that they flow with the exhaust gas through the packing bed and are not absorbed. Table 5-3 lists the general operating characteristics of wet-film scrubbers.

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p <sub>L</sub> )	Removal efficiency (%) and cut diameter	Applications
Gases	2-8.5 cm/m of column packing (0.25-1 in./ft	0.13-2.0 L/m <sup>3</sup> (1-15 gal/1000 ft <sup>3</sup> , depending on type of	34-100 kPa (5-15 psig)	Very high, 99 <sup>+</sup> %, depend- ing on operating conditions	Mainly used for gaseous pollu- tant removal Metal operations Acid plants Chemical process industries
T articles	of column packing)	flow and packing)		l.5-μm cut diameter	

Table 5-3. Operating characteristics of wet-film scrubbers.

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	Review Exercise	
1.	<ul> <li>Packed towers are frequently used for removing gaseous pollutants because</li> <li>a. the packing provides a large surface area for gas-liquid contact.</li> <li>b. they have relatively low pressure drops.</li> <li>c. the packing provides good mixing of gas and liquid and a long residence time.</li> <li>d. all of the above</li> </ul>	
2.	Increasing the liquid flow rate in a packed tower will usually <u>increase/decrease</u> the gas removal rate. $\tilde{\nu}$	1. d. all of the above
3.	If the gas flow rate through a packed tower is too low, may occur. a. flooding b. mixing c. gas channeling d. plugging	2. increase
4.	True or False? Packed towers remove particulate matter and other solids more easily and with less maintenance problems than do plate towers.	3. c. gas channeling
		4. False

<ul> <li>5. In a packed tower, liquid occasionally flows in little streams straight through the packing without wetting the packing surface. This condition is called</li> <li>a. flooding.</li> <li>b. liquid channeling.</li> <li>c. mixing.</li> <li>d. plugging.</li> </ul>	
<ul> <li>6. In processes having high-temperature flue gas, <u>plate/packed</u> towers are more suitable because their internal components will expand and contract.</li> </ul>	5. b. liquid channeling
<ul> <li>7. Packed towers are most suitable for industrial processes requiring high gas-removal efficiency, but not having a high concentration of particulate matter in the flue gas. I which of the following industrial processes would a packet tower be an appropriate control device?</li> <li>a. coal-fired boiler</li> <li>b. a pickling tank using HCl (in the steel industry)</li> <li>c. nitric acid plant</li> <li>d. ammonium chloride production</li> <li>e. both b and c</li> </ul>	6. plate In d
	7. e. both b and c

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# Lesson 6

## Combination Devices— Liquid-Phase and Gas-Phase Contacting Scrubbers

### Lesson Goal and Objectives

### Goal

To familiarize you with the operation, collection efficiency, and major maintenance problems of scrubbers that use energy from both the liquid and gas phases for contact.

### **Objectives**

Upon completing this lesson, you should be able to-

- 1. list four combination contacting scrubbers,
- 2. describe the operation of each combination contacting scrubber listed above,
- 3. recall the relative collection efficiency of each scrubber for both particles and gaseous pollutants, and
- 4. name the major operating or maintenance problems associated with each device.

### Introduction

A number of wet-collector designs use energy from both the gas stream and liquid stream to collect pollutants. Many of these combination devices are available commercially. A seemingly unending number of scrubber designs have been developed by changing system geometry and incorporating vanes, nozzles, and baffles. This lesson will describe several systems that incorporate features of both liquid-phase and gas-phase contacting wet collectors.

### Cyclonic Spray Scrubbers

Cyclonic spray scrubbers use the features of both the dry cyclone and the spray chamber to collect pollutants. Generally, the exhaust gas enters the chamber tangentially, swirls through the chamber in a corkscrew motion, and exits. At the same time, liquid is sprayed inside the chamber. As the exhaust gas swirls around the chamber, pollutants are captured when they impact on liquid droplets, are thrown to the walls, and washed back down and out.

Cyclonic scrubbers are generally low- to medium-energy devices, with pressure drops of 4 to 25 cm (1.5 to 10 in.) of water. Commercially available designs include the *irrigated cyclone* scrubber and the cyclonic spray scrubber. In the irrigated cyclone (Figure 6-1), the exhaust gas enters near the top of the scrubber into the water sprays. The exhaust gas is forced to swirl downward, then change directions, and return upward in a tighter spiral. The liquid droplets produced capture the pollutants, are eventually thrown to the side walls, and carried out of the collector. The "cleaned" gas leaves through the top of the chamber.

The cyclonic spray scrubber (Figure 6-2) forces the exhaust gas up through the chamber from a bottom tangential entry. Liquid sprayed from nozzles on a center post (manifold) is directed toward the chamber walls and through the swirling exhaust gas. As in the irrigated cyclone, liquid captures the pollutant, is forced to the walls, and washes out. The "cleaned" gas continues upward, exiting through the straightening vanes at the top of the chamber.



Figure 6-1. Irrigated cyclone scrubber.



Figure 6-2. Cyclonic spray scrubber.

Stationary vanes are used inside the cyclonic scrubber chamber for much the same purpose that they are used at the top—to alter the gas flow. But inside, they are designed to start or enhance the cyclonic gas flow.

### **Particle Collection**

Cyclonic spray scrubbers are more efficient than spray towers, but not as efficient as venturi scrubbers, in removing particles from the exhaust gas stream. Particles larger than 5  $\mu$ m are generally collected by impaction with 90% efficiency. The cut diameter ranges between 2 and 3  $\mu$ m for these devices. In a simple spray tower, the velocity of the particles in the exhaust gas stream is low: 0.6 to 1.5 m/s (2 to 5 ft/sec). By introducing the exhaust gas tangentially into the spray chamber, as does the cyclonic scrubber, exhaust gas velocities (thus, particle velocities) are increased to approximately 60 to 180 m/s (200 to 600 ft/sec). The velocity of the liquid spray is approximately the same in both devices. This increased particle-to-liquid relative velocity increases particle collection efficiency for this device over that of the spray chamber. Exhaust gas velocities of 60 to 180 m/s are equivalent to those encountered in a venturi scrubber. However, cyclonic spray scrubbers are not as efficient as venturis because they are not capable of producing the same degree of useful turbulence.

### Gas Collection

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

#### Maintenance Problems

The main maintenance problems with cyclonic scrubbers are nozzle plugging and corrosion or erosion of the side walls of the cyclone body. Nozzles have a tendency to plug from particles that are in the recycled liquid and/or particles that are in the exhaust gas stream. The best solution is to install the nozzles so that they are easily accessible for cleaning or removal. Due to high gas velocities, erosion of the side walls of the cyclone can also be a problem. Abrasionresistant materials may be used to protect the cyclone body, especially at the inlet.

#### Summary

The pressure drops across cyclonic scrubbers are usually 4 to 25 cm (1.5 to 10 in.) of water; therefore, they are low- to medium-energy devices and are most often used to control largesized particles. Relatively simple devices, they resist plugging because of their open construction. They also have the additional advantage of acting as entrainment separators because of their shape. Their biggest disadvantages are that they are not capable of removing submicron particles and they do not efficiently absorb most pollutant gases. Table 6-1 lists typical operating characteristics of cyclonic scrubbers.

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Pollutant	Pressure drop (Δp)	Liquid-10-gas ratio (L/G)	Liquid-inlet pressure (p <sub>L</sub> )	Removal efficiency (%) and cut diameter	Applications
Gases	4-25 cm of water	0.3-1.3 L/m <sup>3</sup> (2-10 gal/1000 ft <sup>3</sup> )	280-2800 kPa	Only effective for very soluble gases	Mining operations Drying operations Food processing Foundries
Particles	(1.5-10 in. of water)		(40-400 psig)	2-3-µm cut diameter	

	Review Exercise		
1.	Cyclonic spray scrubbers are more efficient than , but not as efficient as, in remov- ing particles. a. spray towers, venturi scrubbers b. venturi scrubbers, spray towers		
2.	In a cyclonic spray scrubber, particles are primarily collected a. as they hit the wetted walls. b. as they impact the liquid droplets. c. due to gravity. d. in the throat.	1.	a. spray towers, venturi scrubbers
3.	True or False? Cyclonic scrubbers are not often used to control gaseous emissions.	2.	b. as they impact the liquid droplets.
4.	The main maintenance problems associated with cyclonic scrubbers are and	3.	True
5.	Cyclonic scrubbers are energy devices. + a. high b. low- to medium-	4.	nozzle plugging (and) corrosion or erosion of the side walls in the chamber
6.	What are cyclonic scrubbers used most often to control? a. micron-sized particles b. large-sized particles c. gaseous emissions d. particles and gases simultaneously	5.	b. low- to medium-
		6.	b. large-sized particles

Table 6-1. Operating characteristics of cyclonic scrubbers.

### **Mobile-Bed Scrubbers**

Mobile-bed, also called moving-bed, scrubbers use energy from both liquid sprays and the gas stream to provide contact. Instead of having stationary packing, as in packed towers, they use a bed containing packing that is in constant motion. The gas stream provides the energy to keep the packing in motion while, at the same time, liquid is sprayed over the packing. Mobile-bed scrubbers can be classified as either *flooded* or *fluidized*, depending on the degree of packing movement. In a flooded-bed scrubber, the packing gently moves and rotates, whereas in a fluidized scrubber, the packing is suspended, or fluidized, within the bed.

Mobile-bed scrubbers were developed to provide the effective mass-transfer (absorption) characteristics of packed and plate towers, without the plugging problems. The wetted packing provides a large area for gas-to-liquid contact, promoting absorption. The movement of the bed cleans off any deposited particles. Therefore, these devices are primarily used when good collection efficiency for both particulate and gaseous pollutants is required.

A flooded-bed scrubber (Figure 6-3) contains a section of mobile packing (spheres) 10 to 20 cm (4 to 8 in.) deep. The spheres are usually made of plastic; however, glass or marble spheres have been used. The exhaust gas stream enters from the bottom while liquid is sprayed from the top and/or bottom over the packing. Bottom, or inlet, sprays are usually included to saturate the exhaust gas stream and remove any large particles. The gas velocity is such that it causes the packing materials to rotate and rub against each other. This rotating motion acts as a self-cleaning mechanism in addition to enhancing gas and liquid mixing.



Figure 6-3. Flooded-bed scrubber.

Bubbles formed in the bed create a layer of froth over the bed approximately twice as deep as the bed itself. This turbulent froth layer provides an additional surface for absorbing pollutant gases and collecting fine particles. Because of the high gas velocities, entrainment separators are required to prevent liquid-mist carryover.

A fluidized-bed scrubber is very similar to a flooded-bed scrubber. The difference is in the degree of movement of the packing. In a fluidized-bed scrubber, the exhaust gas velocity (1.8 to 4.8 m/s, or 6 to 16 ft/sec) is such that it keeps the packing in constant motion between a lower and upper retaining grid. This is shown in Figure 6-4. The packing is made of either polypropylene or polyethylene plastic balls that are hollow, resembling ping pong balls. The packed sections are usually 0.3 to 0.6 m (1 to 2 ft) thick with a froth zone about 0.6 m (2 ft) thick above the packing. These devices can have one to as many as six fluidized packed sections. When used for gas absorption, they are sometimes referred to as *turbulent-contact absorbers* (TCA).



Figure 6-4. Fluidized-bed scrubber.

### Particle Collection

In a mobile-bed scrubber, particles can be collected in three locations. First, sprays are used to remove coarse particles in the inlet below the bed. Particles are also captured when they impinge on the wetted surface of the packing. Finally, small particles are captured in the froth, or foam, layer above the bed. These devices will generally remove particles as small as 2 to 3  $\mu$ m in diameter and have been used extensively when the exhaust stream does not contain a substantial amount of particles in the submicron range. These devices usually contain one bed, unless gas absorption is a consideration. Adding additional beds or more packing does not substantially increase the particle collection efficiency (i.e., any particles not captured by the first stage will probably not be collected in any following stages). The pressure drop in mobile-bed scrubbers ranges from 5 to 15 cm (2 to 6 in.) of water per stage of packing.

#### **Gas Collection**

Mobile-bed scrubbers are capable of achieving high gaseous-polluant removal efficiencies. Their operation is very similar to the operation of packed towers. Liquid is sprayed over the mobile packing, providing a huge surface for the pollutant gas to contact the liquid. Movement of both the gas around the packing and the constantly sprayed liquid provides excellent mixing and contact time for absorption to occur. Mobile-bed scrubbers provide the same amount of absorption efficiency as do packed or plate towers without the associated plugging problems. Due to the high exhaust gas velocities through mobile-bed scrubbers, these units can handle five to six times the amount of exhaust gas handled by packed or plate towers of similar size (Bethea 1978). However, they are not as efficient as packed or plate towers per unit of energy consumed.

Absorption in mobile-bed scrubbers is enhanced by the same factors that affect packed towers. These factors are increasing the liquid-to-gas ratio, increasing the depth of packing, or increasing the number of stages. Increasing these factors increases the gas and liquid contact and the residence time. However, increasing these factors also increases the capital and/or operating costs of the system. As with any system, these process variables are set to achieve the desired removal efficiency at the minimum cost. For gas absorption, multiple stages are used and the liquid-to-gas ratios are high. For example, mobile-bed scrubbers have been used to remove SO<sub>2</sub> from boiler flue gas exhausts. Using a lime or limestone slurry, the liquid-injection rates are approximately 8 L/m<sup>3</sup> (60 gal/1000 ft<sup>3</sup>) of flue gas. This is compared to 0.4 L/m<sup>3</sup> (3.0 gal/1000 ft<sup>3</sup>) when these devices are used for particle removal (McIlvaine Company 1974).

### Maintenance Problems

Mobile-bed scrubbers are designed to minimize plugging and scale buildup problems through the constant motion of the packing spheres. However, these problems can still occur at the scrubber inlet (wet-dry interface) or on the packing support grid. Scale buildup in these areas can cause an uneven airflow distribution through the bed. Uneven airflows result in some areas of the packing bed having a high gas velocity, while the gas velocity is much lower in other areas. This can result in a decrease in collection efficiency and in excessive liquid carryover. Adjusting the inlet sprays can help solve this problem. As with any spray system. nozzles can also be a major maintenance problem. Nozzle maintenance is a special concern in lime or limestone scrubbing systems because of the large quantities of solids present in the recycled scrubbing liquor.

Deterioration of the spheres can also be a problem. Neither plastic nor marble balls are able to withstand high temperatures. The marble cracks and breaks while the plastic deforms. Most systems have safety mechanisms to prevent a total loss of water that would cause high temperatures. Deterioration of the balls from constant rubbing against each other can also be a problem. Glass balls can generally withstand abrasive conditions, whereas plastic balls cannot; therefore, they wear out quickly.

#### Summary

Mobile-bed scrubbers are used when high collection efficiency of particulate and gaseous pollutants is required. Typical applications would be for treating flue gases from industrial boilers, smelting operations, and kraft pulp mills. The main advantage of mobile-bed scrubbers is that they are capable of high-efficiency absorption without plugging. The main disadvantage is that they do not efficiently remove particles in the submicron range. A major maintenance problem is the effect of abrasive wear and high temperatures on packing balls, causing them to deteriorate.

Mobile-bed scrubbers are generally designed in one stage for particle collection, or in multiple stages for high-efficiency gas absorption. Gas velocities are much higher than those in packed or plate towers; therefore, mobile-bed scrubbers can be much smaller in size than either tower. Because of these high gas velocities, incorporating some type of entrainment separator is mandatory. Table 6-2 lists some general operating characteristics of mobile-bed scrubbers.

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p <sub>L</sub> )	Removal efficiency (%) and cut diameter	Applications
Gases Particles	5-15 cm of water per stage (2-6 in. of water per stage)	2.7-8.0 L/m <sup>3</sup> (20-60 gal/1000 ft <sup>3</sup> ) 0.4-0.7 L/m <sup>3</sup> (3-5 gal/1000 ft <sup>3</sup> )		99 <sup>+</sup> % of theoretical 2-3-μm cut	Mining operations Pulp mills Utility boilers Food industry

Table	6-2.	Operating	characteristics o	f mobile-bed	scrubbers.
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Review Exercise	
<ol> <li>Mobile-bed, or moving-bed, scrubbers were developed to provide the effective mass-transfer characteristics of  or towers without the plugging problems.</li> <li>a. spray (or) venturi</li> <li>b. packed (or) plate</li> <li>c. cyclonic (or) orifice</li> <li>d. ejector (or) spray</li> </ol>	
<ul> <li>2. In mobile-bed scrubbers, particles are collected</li> <li>a. by using inlet sprays.</li> <li>b. as they impinge on the wetted surface of the spheres.</li> <li>c. in a froth, or foam, layer above the bed.</li> <li>d. all of the above</li> </ul>	1. b. packed (or) plate
3. True or False? In mobile-bed scrubbers, adding stages or more packing will usually increase particle collection efficiency.	2. d. all of the above
<ul> <li>4. Mobile-bed scrubbers provide the gas absorption efficiency of packed or plate towers; however, they consume energy for the same unit operation.</li> <li>a. more &amp; a more &amp; a more &amp; c. the same a more a more</li> </ul>	3. False
<ul> <li>5. Gas absorption in mobile-bed scrubbers can be enhanced by</li> <li>a. increasing the L/G ratio.</li> <li>b. adding more packing height.</li> <li>c. adding stages.</li> <li>d. all of the above</li> </ul>	4. a. more
<ul> <li>6. When used for gas absorption, mobile-bed scrubbers operate at L/G ratios than when used to collect particles.</li> <li>a. much higher</li> <li>b. much lower</li> <li>c. the same</li> </ul>	5. d. all of the above
	6. a. much higher

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7.	Scale buildup or plugging at the mobile-bed scrubber inlet can cause that leads to a decrease in efficiency. a. a low liquid pH b. uneven gas flow distribution through the bed c. excessive liquid carryover d. low liquid flow		
8.	In mobile-bed scrubbers, the moving packing is made of a. glass. b. plastic. c. marble. d. any of the above	7.	b. uneven gas flow dis- tribution through the bed
9.	The biggest maintenance problem with mobile-bed scrub- bers is ball deterioration due to a. abrasive wear. b. high temperatures. c. both high temperatures and abrasive wear. d. none of the above	8.	d. any of the above
10.	True or False? A major limitation of mobile-bed scrubbers is that they are not effective in removing submicron- sized particles.	9.	c. both high tempera- tures and abrasive wear.
11.	In mobile-bed scrubbers, gas velocities are much lower/higher than in packed towers or plate towers; therefore, mobile-bed scrubbers can be much smaller/larger in size.	10.	True
		11.	higher, smaller

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### **Baffle Spray Scrubbers**

Baffle spray scrubbers are very similar to spray towers in design and operation. However, in addition to using the energy provided by the spray nozzles, baffles are added to allow the gas stream to atomize some liquid as it passes over them. A simple baffle scrubber system is shown in Figure 6-5. Liquid sprays capture pollutants and also remove collected particles from the baffles. Adding baffles slightly increases the pressure drop of the system.



Figure 6-5. Baffle spray scrubber.

#### Particle Collection

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

#### Gas Collection

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

#### Summary

These devices are most commonly used as precleaners to remove large particles (>10  $\mu$ m in diameter). The pressure drops across baffle scrubbers are usually low, but so are the collection efficiencies. Maintenance problems are minimal. The main problem is the buildup of solids on the baffles. Table 6-3 summarizes the operating characteristics of baffle spray scrubbers.

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p <sub>L</sub> )	Removal efficiency (%) and cut diameter	Applications
Gases	2.5-7.5 cm of water	0.13 L/m³	<100 kPa	Very low	Mining operations Incineration
Particles	(1-3 in. of water)	(1 gal/1000 ft <sup>3</sup> )	(<15 psig)	10-μm cut diameter	industries

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### Mechanically Aided Scrubbers

In addition to using liquid sprays or the exhaust stream, energy can be supplied to a scrubbing system by using a motor. The motor is used to drive a rotor or paddles which, in turn, generate water droplets for gas and particle collection. Systems designed in this manner have an advantage of requiring less space than do other scrubbers, but the overall power requirements tend to be higher than for other scrubbers of equivalent efficiency. This point might appear to contradict the contact power principle; however, significant power losses occur in driving the rotor. Power is not expended to provide for gas-liquid contact.

Fewer mechanically aided scrubber designs are available than are liquid- and gas-phase contacting collector designs. Two will be discussed here: *centrifugal-fan scrubbers* and *mechanically induced spray scrubbers*.

A centrifugal-fan scrubber can serve as both an air mover and a collection device. Figure 6-6 shows such a system, where water is sprayed onto the fan blades cocurrently with the moving exhaust gas. Some gaseous pollutants and particles are initially removed as they pass over the liquid sprays. The liquid droplets then impact on the blades to create smaller droplets for additional collection targets. Collection can also take place on the liquid film that forms on the fan blades. The rotating blades force the liquid (and any particles) off of the blades. The liquid droplets separate from the gas stream because of their centrifugal motion.



Figure 6-6. Centrifugal-fan scrubber.

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

Another mechanically aided scrubber, the induced-spray, consists of a whirling rotor submerged in a pool of liquid. The whirling rotor produces a fine droplet spray. By moving the process gas through the spray, particles and gaseous pollutants can subsequently be collected. Figure 6-7 shows an induced-spray scrubber that uses a vertical-spray rotor.

### **Particle Collection**

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

### Gas Collection

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



Figure 6-7. Mechanically induced spray scrubber.

### Maintenance Problems

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

#### Summary

Mechanically aided scrubbers have been used to control exhaust streams containing particulate matter. They have the advantage of being smaller than most other scrubbing systems, since the fan is incorporated into the scrubber. In addition, they operate with low liquid-togas ratios. The disadvantages are their generally high maintenance requirements, low absorption efficiency, and high operating costs. The performance characteristics of mechanically aided scrubbers are given in Table 6-4.

Pollutant	· Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p <sub>L</sub> )	Cut diameter	Applications
Particles	10-20 cm of water (4.0-8.0 in. of water)	0.07-0.2 L/m <sup>3</sup> (centrifugal) 0.5-1.5 gal/1000 ft <sup>3</sup> (centrifugal)	20-60 psig (centrifugal) <1-µm cut diameter Food product industries Chemical inc	Mining operations Food product industries Chemical industry	
		0.5-0.7 L/m <sup>3</sup> (spray rotor) 4-5 gal/1000 ft <sup>3</sup> (spray rotor)			steel mills

Table 6-4. Operating characteristics of mechanically aided scrubbers.

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

	Review Exercise	
1.	Adding baffles in a spray tower will generally help increase the particle removal efficiency, but also increases the a. L/G ratio. b. pressure drop. c. height of the unit. d. all of the above	
2.	Spray towers and baffle spray towers are generally not effective in removing particles smaller than a. 10 $\mu$ m. b. 50 $\mu$ m. c. 100 $\mu$ m. d. any of the above	1. b. pressure drop.
3.	Mechanically aided scrubbers use a rotor to generate water droplets. These devices usually require less	2. a. 10 μm.
4.	True or False? Mechanically aided scrubbers can serve as both an air mover and a collection device.	3. b. space, power requirements
		4. True

<ul> <li>5. In mechanically aided scrubbers, the majority of particle collection occurs</li> <li>a. in liquid droplets formed by the rotating blades.</li> <li>b. on the wetted blades.</li> <li>c. at the inlet sprays.</li> </ul>	
6. True or False? Mechanically aided scrubbers are generally not used for gas absorption, since several other designs provide better removal.	5. a. in liquid droplets formed by the rotating blades.
<ul> <li>7. Mechanically aided scrubbers generally have</li></ul>	6. True
8. True or False? Mechanically aided scrubbers operate at lower liquid-to-gas ratios than do most other scrubbers.	7. b. higher
	8. True

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# Lesson 7

## Equipment Associated with Scrubbing Systems

### Lesson Goal and Objectives

### Goal

To familiarize you with the operation of equipment associated with scrubbing systems.

### **Objectives**

Upon completing this lesson, you should be able to-

- 1. distinguish between forced- and induced-draft fans,
- 2. briefly describe the operation of a centrifugal fan,
- 3. list two maintenance problems associated with fans, pumps, ducts, and pipes in wet scrubbing systems,
- 4. list three types of pipes used in scrubbing systems and the advantages and disadvantages of each,

- 5. briefly describe quenchers, and
- 6. list five important variables that should be monitored in wet scrubbing systems.

### Introduction

Many components comprise a complete scrubbing system. To fully appreciate the operation of a scrubber, it is important to have a basic understanding of all the components of the system. For instance, fans and ducts are required to transport exhaust gas while pumps, nozzles, and pipes transport liquid to and from the scrubbing vessel. Water-recirculation and mistelimination systems are also necessary. Failure of any of these parts will cause problems for the entire scrubbing system. This lesson presents an overview of the equipment associated with scrubbing systems – covering their operation and some typical maintenance problems.

### Transport Equipment for Exhaust Gases and Scrubbing Liquids

Fans transport exhaust gas through ducts to and from the scrubber, while pumps transport liquids through pipes. Although not part of the scrubber chamber, they are essential to its operation.

#### Fans

Fans used in wet scrubbing systems are usually centrifugal. In centrifugal fans, exhaust gas is introduced into the center of a revolving wheel, or rotor, and exits at a right angle (90°) to the rotation of the blades (Figure 7-1). Centrifugal fans are classified by the type and shape of blades used in the fan. The forward-curved fans use blades that are curved toward the direction of the wheel rotation. The blades are smaller and spaced closer together than are the blades in other centrifugal fans. These fans are not usually used if the flue gas contains dust or sticky materials. They have been used for heating, ventilating, and air conditioning applications in industrial plants. Backward-curved fans use blades that are curved away from the direction of wheel rotation. The blades will clog when the fan is used to move flue gas containing dust and sticky fumes. They may be used on the clean-air discharge of air pollution control devices or to provide clean combustion air for boilers. Radial fans use straight blades that are attached to the wheel of the rotor. These fans are built for high mechanical strength and can be easily repaired. Fan blades may be constructed of alloys or coated steel to help prevent deterioration when handling abrasive and corrosive exhaust gas. Radial fans are used most frequently for air pollution control applications; however, backward-curved fans are also used on wet scrubbing systems. Airfoil fans use thick teardrop-shaped blades that are curved away from the wheel rotation. Airfoil fans can clog when handling dust or sticky materials.



Figure 7-1. Centrifugal fans.

Fans used for wet scrubbing systems can be located before or after the scrubber. When located before the scrubber, they are referred to as forced-draft, positive-pressure, or dirty-side fans. These fans normally move dry air, but can move moist air depending on process conditions. They are subject to abrasion and solids buildup when dust concentration is high. Abrasion on the fan can be reduced by using special wear-resistant alloys, by using replaceable liners on the wheel, or by reducing fan speed (using a large fan that moves slower). The solids buildup can sometimes be controlled by using a spray wash to periodically clean the wheel. If dirty-side fans are used, a cyclone or knockout chamber can reduce dust concentration.

Fans located after the scrubber are always operated wet, and are called induced-draft, negative-pressure, or clean-side fans. These fans are subject to corrosion and solids buildup from mist escaping from the entrainment separator. Corrosion problems can result when the exhaust gas contains acid-forming or soluble electrolytic compounds, especially if the temperature of the gas stream falls below the dew point of these compounds. Corrosion can be reduced by using proper construction materials and careful pH control in the scrubbing system. Solids buildup can occur when the mist escaping from the entrainment separator contains dissolved or settleable solids. As the mist enters the fan, evaporation occurs and some solids deposit on the wheel. If the buildup on the wheel is uniform, no problems occur until the buildup starts to flake off, knocking the fan out of balance (Wechselblatt 1975). Keeping entrainment separators operating efficiently or using clean water sprays on the fan blades will help reduce solids-buildup problems.

#### Ducts

Ducts, or ductwork, transport exhaust gas to and from the scrubber. Ducts are carefully designed to keep pressure losses at a minimum. In general, this requires sizing the duct properly and minimizing the number of bends, expansions, and contractions. Sizing the duct to suit the exhaust stream velocity will generally reduce the amount of dust that settles in the ductwork. Bends, expansions, and contractions cause pressure losses in the system and, consequently, increase operating costs.

Abrasion and corrosion are common problems of ductwork. Abrasion is generally more severe on ductwork leading into the scrubber, while corrosion affects ductwork leaving the scrubber. Using proper construction materials or linings greatly reduces corrosion or abrasion. For example, ductwork can be lined partially or fully with brick (especially at elbows) to prevent erosion due to abrasion. For ductwork exiting the scrubber, special alloys resistant to acid attack should be used. Also, ductwork can be insulated to prevent acids in the flue gas from condensing.

#### Pumps

A wide variety of pumps are used to transport both the scrubbing liquid and the sludge. The proper choice of a pump depends on flow rate, pressure, temperature, and material being pumped. Electric-motor-driven centrifugal pumps are the pumps most frequently used in wet scrubbing systems (Calvert et al. 1972). Figure 7-2 illustrates a simple centrifugal pump. The rotating impeller produces a reduction in pressure at the eye (center) of the impeller, causing liquid to flow into the impeller from the suction pipe. The liquid is then forced outward along the blades and discharged.



Figure 7-2. Centrifugal pump.

As with fans, abrasion and corrosion are the major maintenance problems associated with pumps in scrubbing systems. The impellers, housing, and seals are subject to potential corrosion and abrasion problems. Abrasion is caused by solids buildup in the scrubbing liquid. Bleeding this liquid and removing the solids before recycling it back through the pump (or scrubber) will reduce pump wear. Most vendors suggest that the solids content be less than 15% (EPA 1982). Special alloys or rubber linings can also be used to help reduce abrasion and corrosion.

#### Pipes

Pipes transport liquid to and from the scrubber. As with pumps, pipes are susceptible to abrasion, corrosion, and plugging. A wide variety of materials can be used to make pipes to reduce these problems. Some advantages and disadvantages of pipe materials commonly used are given in Table 7-1.

To prevent solids from building up in or plugging the pipe, a liquid slurry velocity in the scrubbing system of 1.2 to 2.1 m/s (4 to 7 ft/sec) is recommended as a reasonable compromise (Czuchra 1979).

Material	Advantages	Disadvantages	
Metals			
Cast iron	Flanged, threaded, or welded	Not resistant to corrosion	
Steel	Inexpensive		
Stainless steel	Easy to cut and install on site		
Copper alloys			
Linings used with metal pipes			
Hard rubber	Good resistance to many strong acids and alkalis	Cannot be cut to size on site	
Soft rubber	Resists abrasion	Must be precisely manufactured	
Glass	Resists acid and alkali attack	Fragile	
Thermoplastic	Resists corrosion	Not as abrasion resistant as	
PVC	Easily site-installed	rubber or stainless steel	
Polyethylene	Good resistance to temperature		
Polypropylene	and stress		
Nonmetals			
Plastic	Resists corrosion	May not be as heat resistant as other materials	
Fiberglass-reinforced pipe (FRP)	Resists chemical corrosion	Less abrasion resistant than	
	On-site installation	rubber-lined pipe	
		Operates at higher temperatures than a solid plastic pipe	

Table 7-1. Pipe materials for scrubber systems-advantages and disadvantages.

Adapted from Calvert et al. 1972.

### Conditioning Equipment for Exhaust Gases

#### Quenchers

Occasionally hot exhaust gas is quenched by water sprays before entering the scrubber. This can be accomplished by spraying liquid into the exhaust gas. Hot gases (those above ambient temperature) are often cooled to near the saturation level by sprays before they enter a scrubber. If not cooled, the hot gas stream can evaporate a large portion of the scrubbing liquor, adversely affecting collection efficiency. Some liquid droplets can evaporate before they have a chance to contact pollutants in the exhaust stream, and others can evaporate after contact, causing captured particles to become reentrained. In some cases, quenching can actually save money. Cooling the gases reduces the temperature and, therefore, the volume of gases, permitting the use of less expensive materials of construction and a smaller scrubber vessel and fan.

Quenchers are designed using the same principles as scrubbers. Increasing the gas-liquid contact in them increases their operation efficiency. Small liquid droplets cool the exhaust stream quicker than large droplets because they evaporate more easily. Therefore, less liquid is required. However, in most scrubbing systems, approximately one-and-a-half to two-and-a half times the theoretical evaporation demand is required to ensure proper cooling (Industrial Gas Cleaning Institute 1975). Evaporation also depends on time—it does not occur instantaneously. Therefore, the quencher should be sized to allow for an adequate exhaust-stream residence time. Normal residence times range from 0.15 to 0.25 seconds for gases under 540°C (1000°F) to 0.2 to 0.3 seconds for gases hotter than 540°C (Schifftner 1979).

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The cleanest water available should be used for presaturating. Quenching with recirculated scrubber liquor can reduce overall scrubber performance, since recycled liquid usually contains a high level of suspended and dissolved solids. As the liquid droplets evaporate, these solids become reentrained in the exhaust gas stream. Dissolved solids in the evaporating quench liquid can form fine particles that are difficult to collect in the scrubber (Kalika 1969). To help reduce this problem, makeup water can be added directly to the quench system rather than by adding all makeup water to a common sump (EPA 1982).

### **Construction Materials**

By now it should be obvious that scrubbing systems require special materials to prevent or reduce corrosion and abrasion. These are summarized in Table 7-2.

Material	Properties/uses	Corrosion resistance		
Metal				
Cast iron	High strength; low ductility; brittleness; hardness; low cost	Ordinary cast irons exhibit fair resistance to mildly corrosive environments; high-silicon cast irons exhibit excellent resis- tance in a variety of environ- ments (hydrofluoric acid is an important exception); cast irons are susceptible to galvanic cor- rosion when coupled to copper alloys or stainless steels		
Carbon steel	Good strength, ductility, and workability; low cost	Fair to poor in many environ- ments; low pH and/or high dis- solved solids in moist or immer- sion service leads to corrosion; properly applied protective coat- ings give appropriate protection in many applications; susceptible to galvanic corrosion when coupled to copper alloys or stain- less steels		
Martensitic stainless steel (410, 416, 420, 440c)	Chromium alloy, hardenable by heat treatment; typically used for machine parts; costs 2 to 5 times more than carbon steel	Good		
Ferritic stainless steel	Chromium alloy, not hardenable by heat treatment; costs 2 to 4 times more than carbon steel	Good; better than martensitic stainless steel; resists stress corro- sion; better chloride resistance than austenitic stainless steels		
405	Modified for weldability			
430	General purpose, often used for chimney liners	Good resistance to atmospheric corrosion		
442, 446	Used in high-temperature service			

Table 7-2. Construction materials for wet scrubber c	components.
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Material	Properties/uses	Corrosion resistance		
Austenitic stainless steel	Chromium and nickel alloy; not hardenable by heat; hardenable by cold working; nonmagnetic Types 201, 202, 301, 302, 303, 304, and 304L cost 3 to 5 times more than carbon steel; types 310, 316, 316L, and 321 cost 4 to 10 times more than carbon steel	Excellent; better than martensitic or ferritic stainless steel (except for halides)		
201, 202	Nitrogen added, used as a substi- tute for 301 and 302			
301	Good hardenability			
302	General purpose			
304	General purpose			
304L	Modified for weldability			
310	Used in high-temperature service			
316	Used in corrosive environments	Superior corrosion resistance;		
316L	Improved weldability	good acid resistance; resistant to hot organic acids; good pitting resistance		
Nickel alloy	Good strength; costs over 10 times more than carbon steel	Excellent resistance in most environments; not resistant in strong oxidizing solutions such		
		as ammonium and HNO <sub>3</sub>		
Inconel <sup>®</sup> * Monel <sup>®</sup> *		Good resistance to stress corrosion Good resistance to hydrofluoric acid		
Hastelloy <sup>®</sup> <sup>b</sup> and Chlorimet <sup>®</sup> <sup>c</sup>		Excellent overall resistance		
Titanium	High strength; light weight (60% that of steel); costs over 10 times more than carbon steel	Exceptional resistance at ambient temperatures; excellent resis- tance at other temperatures, except that crevice corrosion is possible in chloride solutions above 110°C (250°F)		

#### Table 7-2. Construction materials for wet scrubber components (continued).

<sup>a</sup>Registered trademark of Huntington Alloys, Inc. <sup>b</sup>Registered trademark of the Stalite Division of Cabot Corporation.

'Registered trademark of the Duriron Company, Inc.

Material	Properties/uses	Corrosion resistance	
Nonmetal			
Glass and glass linings	Brittleness, subject to damage by thermal shock; can be protected against breakage by coating with polyester fiberglass	Good resistance to hydrochloric and dilute sulfuric acid	
Brick linings		Acid resistant and abrasion	
Carbon brick	Used when fluorides are present; 540°C (1000°F) temperature limit	resistant; also provides thermal protection for inner materials	
Acid brick	870°C (1600°F) temperature limit		
Silicon carbide brick	1370°C (2500°F) temperature limit; high installation costs		
Porcelain and stoneware	Same properties but greater strength than glass; easily dam- aged by thermal shock	Good acid resistance	
Rubber	Excellent mechanical properties and abrasion resistance; temper- ture limit of approximately 105°C (220°F)	Resistant to dilute acids, alkalis, and salts, but some oxidizing media will attach to it	
Plastics Less resistance to mechanical abuse, lower strength, and higher expansion rates; cannot be used where temperatures con stantly exceed 105 °C (220 °F)		Excellent resistance to weak acids and alkalis; do not corrode and are not affected by slight changes in pH or oxygen content	

Table 7-2. Construction materials for wet scrubber components (continued).

Sources: EPA 1982 and Perry 1973.

### **Monitoring Equipment**

Having adequate equipment is imperative when monitoring the performance of a scrubber. Instrumentation on a wet scrubber can provide three distinct services:

- obtaining operational information by recording daily data to help detect any problems or misoperation that may occur,
- providing *operating input* for other devices to automatically operate some parts of the system, and
- providing for *safety* by sounding alarms and/or releasing interlocks to protect both the operators and equipment.

A monitoring system must be properly installed and maintained to provide reliable data. Monitors should be installed, operated, and calibrated according to the manufacturer's instructions. This is essential in obtaining reliable information. Because every scrubbing system is unique, the instrumentation and variables measured will vary from source to source. Table 7-3 lists monitors that are typically used in wet scrubbing systems.

Monitor	Measurements		
Thermometer or thermocouple	Measures inlet and outlet tempera- tures of gas to and from scrubber		
	Measures inlet and outlet tempera- tures of liquid to and from scrubber		
Flowmeter	Measures liquid flow rate to scrubber		
	Measures the amount of recycled liquid and bleed stream		
	Measures flow rate of fresh makeup liquid to scrubber		
Manometer	Measures pressure drop (inlet and outlet static pressure) across fan, scrubber vessel, and entrainment separator		
pH meter	Measures pH level in chemical feed stream, scrubbing liquid, recycle liquor, and bleed stream		
Ammeter	Monitors the current of the fans and pumps		

Table 7-3. Monitoring equipment for wet scrubbing systems.

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For any of these monitors, high and/or low settings can be chosen so that if the set value is exceeded, an alarm sounds, a bypass is opened, or an emergency system is activated. For example, sources scrubbing hot gases normally have a high-temperature alarm and/or an interlock system to automatically introduce emergency water or to bypass the scrubber if the high-temperature setting is exceeded.

Review Exercise	
<ol> <li>What is/are the most popular type(s) of centrifugal fan for wet scrubbing systems?         <ul> <li>a. radial fans</li> <li>b. backward-curved fans</li> <li>c. vane-axial fans</li> <li>d. a and b only</li> <li>e. all of the above</li> </ul> </li> </ol>	
<ul> <li>2. Fans located before the scrubber are referred to as <ul> <li> fans.</li> <li>a. positive-pressure</li> <li>b. dirty-side</li> <li>c. forced-draft</li> <li>d. all of the above</li> </ul> </li> </ul>	1. d. a and b only
<ul> <li>3. Fans located after the scrubber are always operated</li> <li>a. wet.</li> <li>b. dry.</li> </ul>	2. d. all of the above
<ul> <li>4. What is/are the primary maintenance problem(s) associated with fans?</li> <li>a. abrasion</li> <li>b. solids buildup</li> <li>c. corrosion</li> <li>d. all of the above</li> </ul>	3. a. wet.
5. True or False? In general, electric-motor-driven centrifugal pumps are the most frequently used pumps in wet scrub- bing systems.	4. d. all of the above
<ul> <li>6. What area(s) of the pump is/are most susceptible to abrasion or corrosion?</li> <li>a. impeller</li> <li>b. housing</li> <li>c. seals</li> <li>d. all of the above</li> </ul>	5. True
<ul> <li>7. To reduce pressure losses in ducts, the number of</li></ul>	6. d. all of the above
	7. d. all of the above

8.	What is a/are common problem(s) for pipes in most scrubbing systems? a. abrasion b. corrosion c. plugging d. all of the above		
9.	True or False? Cast iron and steel pipes are very resistant to attack by corrosive materials.	8.	d. all of the above
10.	The the liquid droplet produced by the quench spray, the more efficient the quencher is in cooling the exhaust gas stream. a. smaller b. larger c. rounder d. heavier	9.	False
11.	Quenchers must be sized to allow for an adequate of the exhaust gas, since evaporation does not occur instantaneously.	10.	a. smaller
12.	Quenching should be done with the water available. a. dirtiest b. cleanest c. highest-pH d. lowest-pH	11.	residence time
13.	List five monitors used in scrubbing systems.	12.	b. cleanest
		13.	<ul> <li>thermometer or thermocouple</li> <li>manometer</li> <li>pH meter</li> <li>flowmeter</li> <li>ammeter</li> </ul>

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# Lesson 8

## Wet Flue Gas Desulfurization Systems

### Lesson Goal and Objectives

#### Goal

To familiarize you with the operation of flue gas desulfurization (FGD) systems that use a scrubbing liquid to absorb  $SO_2$  present in the exhaust gas stream.

#### **Objectives**

Upon completing this lesson, you should be able to-

- 1. briefly describe five FGD wet scrubbing processes-four nonregenerable and one regenerable,
- 2. list six operating variables that affect wet scrubber operation in FGD systems,
- 3. recognize operating problems associated with each process above, and
- 4. recall some of the various scrubber designs and operating conditions associated with FGD processes.

### Introduction

One of the largest markets for wet scrubbing systems, in terms of money spent, is flue gas desulfurization (FGD). FGD refers to the removal of  $SO_2$  from the process exhaust stream. The majority of FGD systems have been applied to combustion sources such as utility and some industrial coal-fired boilers. FGD systems are also used to reduce  $SO_2$  emissions from some industrial plants such as smelters, acid plants, refineries, and pulp and paper mills.

FGD systems can be operated wet or dry. (Since dry systems do not incorporate wet scrubbers, they will not be discussed in this lesson.) In wet scrubbing systems, liquid absorbs  $SO_2$  in the exhaust stream. The scrubbing liquid contains an alkali reagent to enhance  $SO_2$  absorption. More than a dozen different reagents have been used, with lime and limestone being the most popular for utility boilers, and sodium-based reagents the most popular for industrial boilers (Table 8-1). Sodium-based solutions (sometimes referred to as clear solutions) provide better  $SO_2$  solubility and less scaling problems than lime or limestone. However, sodium reagents are much more expensive. Wet FGD scrubbers can further be classified as *nonregenerable* or *regenerable*. Nonregenerable processes, sometimes called throwaway processes, produce a sludge waste that must be disposed of properly. Most regenerable processes produce a product that may be sold to partially offset the cost of operating the FGD system. Regenerated products include elemental sulfur, and sulfuric acid. Based on the recent capacities listed in Table 8-1, 95% of the FGD processes are nonregenerable, or throwaway. The throwaway processes are simpler and presently more economical to use than those used to recover and sell products.

Process	Operational		Construction		Planned	
	No.	MW	No.	MW	No.	MW
Utility boilers-throwaway						
Dual alkali	3	1181	0	0	2	842
Dual alkali/limestone	1	20	0	0	0	0
Lime	22	8801	4	1995	11	6841
Limestone	32	11,464	17	7637	29	17,088
Limestone/alkaline fly ash	2	1480	0	0	0	0
Lime/alkaline fly ash	9	2613	2	1400	0	0
Lime/limestone	2	20	0	0	0	0
Lime/spray drying	1	110	3	1060	5	1813
Sodium carbonate	4	925	1	330	4	1900
Sodium carbonate/spray drying	0	0	1	440	0	0
Utility boilers-regenerable						
Aqueous carbonate/spray drying	0	0	1	100	0	0
Citrate	1	60	0	0	0	0
Lime	0	, 0	1	65	0	0
Limestone	0	0	0	0	0	0
Lime/limestone	0	· 0	0	0	0	0
Magnesium oxide	0	0	3	724	0 ·	0
Wellman-Lord	7	1540	1	534	0	0
Industrial boilers—throwaway						
Caustic wastestream	5	520	0	0	1	78
Double alkali	7	361	2	193	3	204
Lime/limestone	2	48	1	2	0	0
Sodium carbonate	9	1284	2	110	2	93
Sodium hydroxide	13	397	0	0	3	180
oourdin nydroxide	1.5	551	0	0		100

Table 8-1. FGD processes.

Sources: Smith et al. 1981 and Tuttle et al. 1979.

Note: The data for utility boilers are for 1980.

The data for industrial boilers are for 1978.

Most FGD systems employ two stages: one for fly ash removal and the other for  $SO_2$  removal. Attempts have been made to remove both the fly ash and  $SO_2$  in one scrubbing vessel; however, these systems experienced severe maintenance problems and low simultaneous removal efficiencies. The flue gas normally passes first through a fly ash removal device, either an electrostatic precipitator or a wet scrubber, and then into the  $SO_2$  absorber.

Many different types of absorbers have been used in FGD systems, including spray towers. venturis, plate towers, and mobile packed beds. Because of scale buildup, plugging, or erosion, which affect FGD dependability and absorber efficiency, the trend is to use simple scrubbers such as spray towers instead of more complicated ones. The configuration of the tower may be vertical or horizontal, and flue gas can flow cocurrently, countercurrently, or crosscurrently to the liquid. The chief drawback of spray towers is that they have a higher liquid-to-gas ratio requirement (for equivalent  $SO_2$  removal) than other absorber designs (Makansi 1982).

Numerous operating variables affect the  $SO_2$  removal rate of the absorber. Most of these variables were discussed in previous lessons; however, some are unique to FGD absorbers. The following list contains some of the important parameters affecting the operation of an FGD scrubber (Ponder et al. 1979 and Leivo 1978):

Liquid-to-gas ratio—The ratio of scrubber slurry to gas flow (L/G ratio). For a given set of system variables, a minimum L/G ratio is required to achieve the desired SO<sub>2</sub> absorption, based on the solubility of SO<sub>2</sub> in the liquid. High L/G ratios require more piping and structural design considerations, resulting in higher costs.

pH-Depending on the particular type of FGD system, pH must be kept within a certain range to ensure high solubility of SO<sub>2</sub> and to prevent scale buildup.

Gas velocity – To minimize equipment cost, scrubbers are designed to operate at maximum practicable gas velocities, thereby minimizing vessel size. Maximum velocities are dictated by gas-liquid distribution characteristics and by the maximum allowable liquid entrainment that the mist eliminator can handle. Gas velocities may be 1.5 to 10 m/s (5 to 30 ft/sec) in tower scrubbers and more than 30 m/s (100 ft/sec) in the throat of a venturi scrubber. A common range of the gas velocity for FGD absorbers is 2.0 to 3.0 m/s (7 to 10 ft/sec). The lower the velocity, the less the entrainment, but the more costly the scrubber will be.

Slurry holdup—For FGD processes using an alkali slurry for scrubbing, the system should be designed to provide adequate residence time for the  $SO_2$  to be absorbed by the alkali slurry. The main objective is to make sure that the maximum amount of alkali is utilized in the scrubber. Residence times in packed towers may be as long as 5 seconds. Residence times in venturi scrubbers are a few hundredths of a second, usually too short for high absorption efficiency of  $SO_2$  in systems using lime or limestone scrubbing slurries, unless additives or two scrubbing stages are used.

Gas distribution – A major problem that has occurred in commercial FGD scrubbers is maintaining a uniform gas flow. If the flow is not uniform, the scrubber will not operate at design efficiencies. In practice, uniform flow has been difficult to achieve. Typically, turning vanes near the scrubber inlet duct and compartmentalization have been used.

Scrubber designs – To promote maximum gas-liquid surface area and contact time, a number of scrubber designs have been used. Common ones are mobile-bed scrubbers, venturi-rod scrubbers, plate towers, and packed towers. Countercurrent packed towers are infrequently used because they have a tendency to become plugged by collected particles or to scale (when lime or limestone scrubbing slurries are used).

Turndown-To adjust to changes in boiler load. The scrubber must provide good gasliquid distribution, high liquid holdup for some processes, and high gas-liquid interfacial area for varying gas flow rates. Some scrubbers can be turned down to 50% of design, while others must be divided into sections that can be closed off. A variable-throat venturi can be used to accommodate turndown. In a large FGD installation, individual modules can be taken out of service.

It is important to note that the above list does not imply that these are the only parameters affecting  $SO_2$  absorption efficiency. Each FGD process has a unique set of operating criteria.
In addition to the set of factors just given, the coal properties greatly affect FGD system design for boiler operations. The major coal properties affecting FGD system design and operation are (Leivo 1978):

Heating value of coal—Affects flue gas flow rate. Flow rate is generally higher for lower heating value coals, which also contribute a greater water-vapor content to the flue gas. Moisture content—Affects the heating value and contributes directly to the moisture content and volume of the flue gas.

Sulfur content—The sulfur content, together with the allowable emission standards, determines the required  $SO_2$  removal efficiency, the FGD system complexity and cost, and also affects sulfite oxidation.

Ash content—May affect FGD system chemistry and increase erosion. In some cases, it may be desirable to remove fly ash upstream from the FGD system.

Chlorine content-May require high-alloy metals or linings for some process equipment and could affect process chemistry or require prescrubbing.

Another important design consideration associated with most FGD systems is that the flue gas exiting the absorber is saturated with water and still contains some  $SO_2$  (no system is 100% efficient). Therefore, these gases are highly corrosive to any downstream equipment—i.e., fans, ducts, and stacks. Two methods used to minimize corrosion are reheating the gases to above their dew point or choosing construction materials and design conditions that allow equipment to withstand the corrosive conditions. The selection of a reheating method or the decision not to reheat (thereby using special construction materials) are very controversial topics connected with FGD design (Makansi 1982). Both alternatives are expensive and must be considered on a by-site basis.

Four methods are currently used to reheat stack gases:

- 1. Indirect in-line reheating—The flue gas passes through a heat exchanger that uses steam or hot water.
- 2. Indirect-direct reheating-Steam is used to heat air (outside the duct) and then the hot air is mixed with the scrubbed gases.
- 3. Direct combustion reheating—Oil or gas is burned either in the duct or in an external chamber, and the resulting hot gases are mixed with the scrubbed gases.
- 4. Bypass reheating A portion of the untreated hot flue gas bypasses the scrubber and is mixed with the scrubbed gases.

None of the above methods has a clear advantage over the others (Makansi 1982). Systems using indirect in-line reheating have experienced severe corrosion and plugging problems; indirect-direct and direct combustion reheating are expensive because of added fuel costs; and bypass reheating is limited in the degree of reheating obtainable (due to  $SO_2$  emissions in the bypass).

This lesson will discuss five of the more popular FGD systems – four throwaway processes and one regenerable process. The process chemistry, system description, and operating experience involved in each will be presented.

	Review Exercise	
1.		-
2.	True or False? Almost all FGD systems use a single wet scrubber for both SO <sub>2</sub> and fly ash removal. $\overrightarrow{F}$	1. a. Sodium, lime or limestone
3.	Spray towers require higher (for equivalent SO <sub>2</sub> removal) than other absorber designs. a. pressure drops b. gas velocities c. liquid-to-gas ratios d. all of the above	2. False Most use two scrubbing stages.
4.	The lower the gas velocity, the <u>more/less</u> ) the entrain- ment; however, the scrubber system will be <u>more/less</u> costly.	3. c. liquid-to-gas ratios
5.	List five properties of the coal (or fuel) that will affect FGD operation.	4. less, more
6.	Because flue gas contains some SO <sub>2</sub> as it exits the absorbers, FGD systems generally use to pre- vent corrosion. a. additional absorbers b. reheaters c. special construction materials for downstream fans and ductwork d. both b and c	<ul> <li>5. • heating value</li> <li>• sulfur content</li> <li>• chlorine content</li> <li>• ash content</li> <li>• moisture content</li> </ul>
7.	<ul> <li>Match the reheating method with the proper description.</li> <li>1. Indirect in-line <ul> <li>a. A portion of the hot</li> <li>untreated flue gas is mixed</li> <li>with the scrubbed gases.</li> </ul> </li> <li>4. Bypass <ul> <li>b. Flue gas passes through a heat exchanger in the duct.</li> <li>c. Oil or gas is burned, and the hot gases are mixed with the scrubbed gases.</li> <li>d. Steam is used to heat air, and this hot air is mixed with the flue gas.</li> </ul> </li> </ul>	6. d. both b and c

7. 1. b 2. d 3. c 4. a

## Nonregenerable FGD Processes

Nonregenerable FGD processes generate a sludge or waste product. The sludge must be disposed of properly in a pond or landfill. The three most common nonregenerable processes used on utility boilers in the U.S. are lime, limestone, and double-alkali. Although the double-alkali process regenerates the scrubbing reagent, it is classified as throwaway since it does not produce a salable product and generates solids that must be disposed of in a landfill. Sodium-based throwaway systems (NaOH and Na<sub>2</sub>CO<sub>3</sub>) are overwhelmingly chosen for industrial boilers (see Table 8-1).

#### Lime Scrubbing

#### **Process Chemistry**

Lime scrubbing uses an alkaline slurry made by adding lime (CaO), usually 90% pure, to water. The alkaline slurry is sprayed in the absorber and reacts with the  $SO_2$  in the flue gas. Insoluble calcium sulfite  $(CaSO_3)$  and calcium sulfate  $(CaSO_4)$  salts are formed in the chemical reaction that occurs in the scrubber and are removed as sludge.

A number of reactions take place in the absorber. Before the calcium can react with the  $SO_2$ , both must be broken down into their respective ions. This is accomplished by slaking (dissolving) the lime in water and then spraying the slurry into the flue gas to dissolve the  $SO_2$ . Simplified reactions occur simultaneously and are illustrated below.

#### SO<sub>2</sub> dissociation:

S S E Lime (CaO) dissolution:

 $Ca(OH_2) \rightarrow Ca^{++} + 2OH^-$ 

 $CaO_{(solid)} + H_2O \rightarrow Ca(OH)_{2(aqueous)}$ 

$O_{2(gaseous)} \rightarrow SO_{2(aqueous)}$	
$O_2 + H_2O \rightarrow H_2SO_3$	
$H_2SO_3 \rightarrow H^+ + HSO_3^- \rightarrow 2H^+ + SO_3^-$	

Now that the SO<sub>2</sub> and lime are broken into their ions (SO<sub>3</sub> and Ca<sup>++</sup>), the following reaction occurs:

$$Ca^{++} + SO_3^{=} + 2H^+ + 2OH^- \rightarrow CaSO_{3(solid)} + 2H_2O.$$

In addition, the following reactions can also occur when there is excess oxygen:

$$SO_3^{=} + \frac{1}{2}O_2 \rightarrow SO_4^{=}$$
$$SO_4^{=} + Ca^{++} \rightarrow CaSO_{4(solid)}$$

From the above relationships and assuming that the lime is 90% pure, it will take 1.1 moles of lime to remove 1 mole of  $SO_2$  gas.

#### System Description

The equipment necessary for SO<sub>2</sub> emission reduction comes under four operations:

- 1. Scrubbing or absorption-accomplished with scrubbers, holding tanks, liquid-spray nozzles, and circulation pumps.
- 2. Lime handling and slurry preparation-accomplished with lime unloading and storage equipment, lime processing and slurry preparation equipment.
- 3. Sludge processing-accomplished with sludge clarifiers for dewatering, sludge pumps and handling equipment, and sludge solidifying equipment.
- 4. Flue-gas handling-accomplished with inlet and outlet ductwork, dampers, fans, and stack gas reheaters.

Figure 8-1 is a schematic of a typical lime FGD system. Flue gas from the boiler first passes through a particulate emission removal device then into the absorber where the  $SO_2$  is removed. The gas then passes through the entrainment separator to a reheater and is finally exhausted out of the stack. Individual FGD systems vary considerably, depending on the FGD vendor and the plant layout. ESPs or scrubbers can be used for particle removal with the various absorbers used for  $SO_2$  removal.



Figure 8-1. Typical process flow for a lime or limestone FGD system.

A slurry of spent scrubbing liquid and sludge from the absorber then goes to a recirculation tank. From this tank, a fixed amount of the slurry is bled off to process the sludge, and, at the same time, an equal amount of fresh lime is added to the recirculation tank. Sludge is sent to a clarifier, where a large portion of water is removed from the sludge and sent to a holding tank. Makeup water is added to the process-water holding tank, and this liquid is returned to the recirculation tank. The partially dewatered sludge from the clarifier is sent to a vacuum filter, where most of the water is removed (and sent to the process-water holding tank) and the sludge is sent to a settling pond. Table 8-2 lists operational data of lime FGD systems, showing the various absorbers used.

Company and plant	MW	W FGD vendor	Fly ash control	%S in	SO, absorber	Number of modules	L/G ratio		Pressure drop (Δp)		Efficiency (%)	
name	(gross)			coal		per boiler	L/m³	gal/1000 ft*	kPa	in. H <sub>t</sub> O	Design	Test
Pennsylvania Power Bruce Mansfield #1 Bruce Mansfield #2 Bruce Mansfield #3	917 917 917 917	Chemico Chemico Pullman Kellogg	lst-stage venturi lst-stage venturi ESP	3.0 3.0 3.0	Fixed-throat venturi Fixed-throat venturi Weir crosscurrent spray	6 6 6	6.0 6.0 	45.0 45.0 -	2.0 2.0 0.7	8.0 8.0 2.8	92.1 92.1 92.0	95.0 95.0 95.0
Columbus & Southern Ohio Electric Conesville #5 Conesville #6	411 411	Air Correction Division Air Correction Division	ESP ESP	4.67 4.67	Mobile bed Mobile bed	1 2	6.7 6.7	50.0 50.0	2.0 2.0	8.0 8.0	89.5 89.5	89.7 89.5
Duquesne Light Ehrama Phillips	510 408	Chemico Chemico	ESP Cyclone/ESP	2.20 1.92	Variable-throat venturi (plumb-bob type) Variable-throat venturi	5	5.3 5.8	40.0 40.0	4.0 4.0	16.0 16.0	83.0 83.0	86.0 90.0
Kentucky Utilities Green River	64	American Air Filter	Cyclone/ variable-throat venturi	4.0	Mobile bed	1	4.5	34.0	1.0	4.0	80.0	80.0
Louisville Gas & Electric Cane Run #4 Cane Run #5 Mill Creek #1 Mill Creek #3 Paddy's Run #6	188 200 358 442 72	American Air Filter Combustion Engineering Combustion Engineering American Air Filter Combustion Engineering	ESP ESP ESP ESP	8.75 8.75 8.75 8.75 8.75 2.50	Mobile bed Countercurrent spray Mobile bed Mobile bed (marbles)	2 2  4 2	8.0 7.4 12.7 8.7 2.2	60.0 55.0 95.0 65.0 16.5	1.0 0.1 1.6 2.9	40.0 0.5  6.5 11.5	85.0 85.0 85.0 85.0 90.0	87.5 91.0 86.6 85.7 90.0
Kansas City Power & Light Hawthorn #3 Hawthorn #4	90 90	Combustion Engineering Combustion Engineering		0.6 0.6	Mobile bed (marbles) Mobile bed (marbles)	2 2	8.5 8.5	26.0 26.0	2.7 2.7	11.0 11.0	70.0 70.0	70.0 70.0
Monongahela Power Pleasants #1 Pleasants #2	618 618	B&W B&W	ESP ESP	8.7 4.5	Sieve tray Sieve tray	4 4	7.4 7.4	55.0 55.0	1.2	5.0	90.0 90.0	90.0 90.0
Utah Power & Light Hunter #1 Hunter #2 Huntington #1	400 400 430	Chemico Chemico Chemico	ESP FSP ESP	0.55 0.55 0.55	Countercurrent spray Countercurrent spray Countercurrent spray	4 4 4 4	5.7 5.7 5.7	43.0 43.0 43.0	0.6 0.6 0.6	2.5 2.5 2.5	80.0 80.0 80.0	80.0 80.0 80.0

#### Table 8-2. Operational data for lime FGD systems on utility boilers.

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#### **Operating Experience**

Early lime FGD systems were plagued with many operational and maintenance problems. Scale buildup and plugging of absorber internals and associated equipment were prominent problems. However, scaling and plugging in lime FGD systems were not as severe as with other calcium-based FGD systems (EPA 1981). Scale buildup ( $CaSO_4$ ) on spray nozzles and entrainment separators was particularly troublesome. New spray nozzle designs and careful control of the recirculating slurry have reduced internal scrubber scaling (EPA 1975). Problems with the entrainment separators have also been reduced by careful separator design, installing adequate wash sprays, and monitoring the pressure drop across them. Additional techniques used to reduce scale buildup are (Leivo 1978):

Control of pH-If a lime FGD system is operated above a pH of 8.0 to 9.0, there is a risk of sulfite scaling. Automatic contol of the feed by on-line pH sensors has been successful. Holding tank residence time—By providing retention time in the scrubber recirculation tank, the supersaturation of the liquor can be decreased before recycling to the scrubber. Typical residence times of 5 to 15 minutes have been used in some full-scale systems. Control of suspended solids concentration—The degree of supersaturation can be minimized by keeping an adequate supply of seed crystals in the scrubber slurry. Typical levels in newer installations range from 5 to 15% suspended solids. Solids are generally controlled by regulating the slurry bleed rate.

Liquid-to-gas ratio—High liquid-to-gas ratios can reduce scaling problems because the absorber outlet slurry is more dilute, containing less calcium sulfates and calcium sulfites that cause scaling.

Another problem concerned stack gas reheaters. Stack gas is reheated to avoid condensation on and corrosion of the ductwork and stack, and to enhance plume rise and pollutant dispersion. Reheating is accomplished by using steam coils in the stack, by using hot air supplied by auxiliary oil heaters in the stack, or by other methods previously mentioned. Some reheater failures were caused by acid attack to reheater components. Other reheaters vibrated too much, causing structural deterioration.

Corrosion of scrubber internals, fans and ductwork, and stack linings have been reduced by using special materials such as rubber- or plastic-coated steel and by carefully controlling slurry pH with monitors. Additional operation and maintenance problems and solutions are found in *Proceedings: Symposium on Flue Gas Desulfurization, Volumes I and II* (EPA: March 1978, July 1979, and 1981), and *Lime FGD Systems Data Book* (Ponder et al. 1979).

	Review Exercise	
1.	List three nonregenerable FGD processes.	
2.	Reacting lime with water is referred to as a. clarifying. b. slaking. c. raking. d. thickening.	<ul><li>lime</li><li>limestone</li><li>double-alkali</li></ul>
3.	What is $CaSO_3$ in the following reaction? $Ca^{++} + SO_3^{\pm} + 2H^{+} + 2OH^{-} \rightarrow CaSO_3 + 2H_2O$ a. solid (sludge) b. liquid c. gas	2. b. slaking.
4.	Lime FGD systems use a(an) to remove fly ash from the flue gas before it enters the absorber. a. venturi scrubber b. electrostatic precipitator c. mechanical collector with precipitator or scrubber d. any of the above	3. a. solid (sludge)
5.	Most lime FGD systems on utility boilers operate at L/G ratios of a. 0.4 to 1.3 L/m <sup>3</sup> (3 to 10 gal/1000 ft <sup>3</sup> ). b. 3.0 to 8.0 L/m <sup>3</sup> (25 to 60 gal/1000 ft <sup>3</sup> ). c. 13 to 26 L/m <sup>3</sup> (100 to 200 gal/1000 ft <sup>3</sup> ). d. none of the above	4. d. any of the above
6.	In early lime FGD systems, scale buildup and plugging of the were particularly troublesome. a. spray nozzles b. entrainment separator c. scrubber internals d. all of the above	5. b. 3.0 to 8.0 L/m <sup>3</sup> (25 to 60 gal/1000 ft <sup>3</sup> ).
7.	Operating a lime FGD system at a pH above 8.0 to 9.0 a. reduces scale buildup. b. increases the risk of scale buildup. c. is recommended. d. eliminates nozzle plugging.	6. d. all of the above
8.	High/Low liquid-to-gas ratios reduce the potential for scale buildup.	<ol> <li>b. increases the risk of scale buildup.</li> </ol>
		8. High

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## 9. Stack gas is reheated to a. avoid condensation.

- b. enhance plume rise.
- c. give better pollutant dispersion.
- d. all of the above

9. d. all of the above

#### Limestone Scrubbing

#### **Process Chemistry**

Limestone scrubbers are very similar to lime scrubbers. The use of limestone  $(CaCO_3)$  instead of lime requires different feed preparation equipment and higher liquid-to-gas ratios (since limestone is less reactive than lime). Even with these differences, the processes are so similar that an FGD system can be set up to use either lime or limestone in the scrubbing liquid.

The basic chemical reactions occurring in the limestone process are very similar to those in the lime-scrubbing process. The only difference is in the dissolution reaction that generates the calcium ion. When limestone is mixed with water, the following reaction occurs:

$$CaCO_{3(solid)} + H_2O \rightarrow Ca^{++} + HCO_3^- + OH^-.$$

The other reactions are the same as those for lime scrubbing.

#### System Description

The equipment necessary for  $SO_2$  absorption is the same as that for lime scrubbing, except in the slurry preparation. The limestone feed (rock) is reduced in size by crushing it in a ball mill. Limestone is sent to a size classifier. Pieces larger than 200 mesh are sent back to the ball mill for recrushing. Limestone is mixed with water in a slurry supply tank. Limestone is generally a little cheaper than lime, making it more popular for use in large FGD systems. Table 8-3 lists operations data for limestone FGD systems. Note the similarities in equipment and operating conditions to those of lime FGD systems.

Company and plant	MW	FGD vendor	Fly ash control	%S in coal	SO <sub>1</sub> absorber	Number of modules	L/G ratio		Pressure drop (Δp)		Efficiency (%)	
name	(gross)					per boiler	L/m¹	gal/1000 ft*	kPa	in. H <sub>z</sub> O	Design	Test
Alabama Electric Tombigbee #2 Tombigbee #3	255 255	Peabody Peabody	ESP ESP	1.15 1.15	Countercurrent spray Countercurrent spray	2 2	9.4 9.4	70.0 70.0	1.0 1.0	4.0 4.0	59.5 59.5	85.0 85.0
Arizona Electric Power Apache #2 Apache #3 Cholla #1 Cholla #2	195 195 119 264	Research-Cottrell Research-Cottrell Research-Cottrell Research-Cottrell	ESP ESP Cyclone/venturi Cyclone/venturi	0.50 0.50 0.50 0.50	Spray/packed bed Spray/packed bed Spray/packed bed Spray/packed bed	2 2 1 4	2.8 2.8 6.5 6.5	20.6 20.6 48.9 48.9	1.5 1.5 0.1 0.1	6.0 6.0 0.5 0.5	42.5 42.5 58.5 75.0	97.0 97.0 92.0 85.0
Basin Electric Power Laramie River #1 Laramie River #2	570 570	Research Cottrell Research Cottrell	ESP ESP	0.81 0.81	Spray/packed bed Spray/packed bed	5 5	8.0 8.0	60.0 60.0		_ _	90.0 90.0	90.0 90.0
Central Illinois Light Duck Creek #1	416	Environeering	ESP	3.66	Rod deck packed tower	4	6.7	50.0	2.0	8.0	85.0	85.0
Colorado Ute Electrical Craig #1 Craig #2	447 455	Peabody Peabody	ESP ESP	0.45 0.45	Countercurrent spray Countercurrent spray	4 4	6.7 6.7	50.0 50.0	1.6 1.6	6.5 6.5	85.0 85.0	85.0 85.0
Commonwealth Edison Powerton	450	Air Correction Division – UOP	ESP	8.58	Mobile bed (TCA)	3	8.0	60.0	3.0	12.0	74.0	75.5
Indianapolis Power & Light Petersburg #3	532	Air Correction Division – UOP	ESP	8.25	Mobile bed (TCA)	4	6.7	50.0	1.7	7.0	85.0	85.0
Kansas City Power & Light La Cygne Jeffery #1 Jeffery #2 Lawrence #4 Lawrence #5	820 720 700 125 420	B&W Combustion Engineering Combustion Engineering Combustion Engineering Combustion Engineering	Variable venturi ESP ESP Rod venturi Rod venturi	5.39 0.32 0.30 0.55 0.55	Sieve tray Countercurrent spray Countercurrent spray Countercurrent spray Countercurrent spray	8 6  2 2	5.0 4.1 4.1 4.0 2.5	37.7 30.4 30.4 30.0 19.0	1.5 1.0 1.0 0.6 0.6	6.0 6.0 6.0 2.5 2.5	80.0 80.0 80.0 73.0 52.0	80.0 60.0 60.0 73.0 52.0

#### Table 8-3. Operational data for limestone FGD systems on utility boilers.

Note: A dash ( - ) indicates that no data are available.

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#### Table 8-3. Operational data for limestone FGD systems on utility boilers (continued).

Company and plant	MW	FGD vendor	Fly ash control	%S in	SO <sub>z</sub> absorber o	Number of modules per boiler	L/G ratio		Pressure drop (Δp)		Efficiency (%)	
name	(gross)			coal			L/m•	gal/1000 ft <sup>4</sup>	kPa	in. H <sub>t</sub> O	Design	Test
Salt River Project Coronado #1 Coronado #2	350 350	Pullman Kellogg Pullman Kellogg	ESP ESP	1.00 1.00	Weir crosscurrent spray Weir crosscurrent spray	2 2		_ _	0.4 0.4	1.5 1.5	66.0 66.0	82.0 82.0
South Carolina Public Service Winyah #2 Winyah #3	280 280	B&W B&W	ESP ESP	1.70 1.70	Venturi/sieve tray Countercurrent spray	2 2	6.3 —	47.5 —	1.1	4.5	45.0 90.0	90.0 90.0
South Mississippi Electric R. D. Morrow #1 R. D. Morrow #2	200 200	Environeering Environeering	ESP ESP	1.30 1.30	Rod deck packed tower Rod deck packed tower	1	6.6 6.6	49.0 49.0	2.0 2.0	8.0 8.0	52.7 52.7	85.0 85.0
Southern Illinois Marion #4	173	B&W	ESP	3.75	Countercurrent spray	2	9.9	74.0	1.5	6.0	89.4	89.4
Springfield City Southwest #1	194	Air Correction Division – UOP	ESP	3.50	Mobile bed (TCA)	2	5.5	41.0	1.5	6.0	80.0	87.0
Springfield Water, Light & Power Dallman #3	205	Research-Cottrell	Cyclone/ESP	3.30	Spray/packed bed	2	_		0.2	0.7	95.0	95.0
TVA Widows Creck #8	550	TVA	ESP/venturi	<b>3</b> .70	Mobile packed bed and grid packing	1 3	8.0	60.0	0.5	2.0	70.0	
<b>Texas Power &amp; Light</b> Sandow #4	545	Combustion Engineering	ESP	1.60	Countercurrent spray	3	-	-		-	75.0	
Texas Utilities Martin Lake #1 Martin Lake #2 Martin Lake #3 Monticello	793 793 793 800	Research-Cottrell Research-Cottrell Research-Cottrell Chemico	ESP ESP ESP ESP	0.90 0.90 0.90 1.50	Spray/packed bed Spray/packed bed Spray/packed bed Countercurrent spray	6 6 6 3	  9.4	- - 70.0	1.1 1.1 1.1 1.2	4.5 4.5 4.5 5.0	71.0 71.0 71.0 74.0	95.0 95.0 95.0 74.0

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#### **Operating Experience**

Early limestone FGD systems had scrubber operating problems similar to those of lime scrubbing systems. Plugged and clogged nozzles, scrubber internals, and mist eliminators (entrainment separators) resulted from inefficient SO<sub>2</sub> absorption by limestone in the scrubber. Increased absorption efficiency is achievable at high pH values since more alkali is available to dissolve the SO<sub>2</sub> gas. However, scale buildup will occur if the scrubber is operated at very high pH values. The pH levels can be maintained by carefully controlling limestone and water feed rates. Low pH reduces removal efficiency; high pH causes scale buildup on scrubber internals.

As can be seen from Tables 8-2 and 8-3, the SO<sub>2</sub> removal efficiencies for various lime and limestone FGD installations range from 50 to 92%. These FGD systems were designed to meet existing air pollution regulations. Lime and limestone FGD systems are capable of removing SO<sub>2</sub> with efficiencies in excess of 90% (Devitt et al., March 1978; EPA 600/7-78-032a). The addition of small amounts of soluble *magnesium* (<1% by weight) to the scrubber liquor can greatly increase SO<sub>2</sub> removal efficiencies to as high as 99% (Dewitt et al., March 1978; EPA 600/7-78-032a). Magnesium is added in the form of magnesium oxide, magnesium sulfate, or dolomitic lime (used in lime scrubbing systems). Magnesium compounds are more soluble than calcium compounds and react rapidly with SO<sub>2</sub>.

EPA is currently working on a program that uses an additive of *adipic acid* to limestone FGD systems. Adipic acid can increase  $SO_2$  removal efficiencies from 85% to as high as 97% (EPA, August 1980). Adipic acid is a crystalline powder derived from petroleum. EPA experiments have shown that when a limestone slurry reacts with  $SO_2$  in the scrubber, the slurry becomes very acidic. This acidity limits the amount of  $SO_2$  that can be absorbed. Adding adipic acid to the slurry slightly increases the slurry's initial acidity, but prevents it from becoming highly acidic during the absorption of  $SO_2$ . The net result is an improvement in the scrubbing efficiency.

EPA research has shown that adipic acid can reduce the total limestone consumption by as much as 15%, thus reducing operating costs. Adipic acid is nontoxic (it is used as a food additive) and does not have any adverse environmental impacts. Adipic acid has been tested in full-scale tests at an electrical generating station, and its benefits have been verified (Mobley and Chang 1981).

Another scrubber operating problem occurring in lime and limestone FGD systems is that calcium sulfite in the sludge settles and filters poorly. It can be removed from the scrubber slurry only in a semiliquid or paste-like form. A process improvement called *forced oxidation* was developed by IERL-RTP to address this problem. In forced oxidation, air is blown into the scrubber slurry tank that contains primarily calcium sulfite and water. The air oxidizes the calcium sulfite to calcium sulfate.

$$CaSO_3 + H_2O + \frac{1}{2}O_2 - CaSO_4 + H_2O$$

Calcium sulfate formed by this reaction grows to a larger crystal size than calcium sulfite. As a result, calcium sulfate is easily filtered, forming a drier and more stable material that can be disposed of in a landfill. This material  $(CaSO_4)$  can also be used for cement, gypsum wallboard, or as a fertilizer additive.

Forced oxidation can also help control scale buildup problems on scrubber internals. This process helps control scale by removing calcium sulfite from the slurry in the form of calcium sulfate, which is more easily filtered. This will prevent calcium sulfites and calcium sulfates from being recirculated in the absorber. However, if forced oxidation is used on a closed-loop water system, there is a potential for increasing the concentrations of chlorides and other impurities in the recycled water that previously were thrown away with the sludge.

	Review Exercise	
1.	Limestone FGD systems generally operate at <u>higher/lower</u> liquid-to-gas ratios than lime FGD systems because $SO_2$ is <u>more/less</u> / reactive with a limestone slurry.	
2.	True or False? The chemistry for $SO_2$ removal in a lime- stone slurry is very different from that for $SO_2$ removal in a lime slurry.	l. higher, less
3.	The major difference in equipment for a limestone FGD system (compared to a lime FGD system) is in the a. fly ash collection equipment. b. type of absorber. c. slurry feed preparation. d. all of the above	2. False
4.	True or False? Limestone is generally less expensive to pur- chase than is lime.	3. c. slurry feed preparation.
5.	The addition of to the slurry of a limestone FGD system has increased SO <sub>2</sub> removal rates in experimen- tal studies. a. magnesium oxide b. magnesium sulfate c. adipic acid d. any of the above	4. True
6.	In lime/limestone FGD systems, calcium sulfite formed as part of the sludge is difficult to remove from the slurry. One method used to eliminate this problem is to convert the calcium sulfite to calcium sulfate by the process called a. forced oxidation. b. Wellman-Lord. c. double-alkali. d. direct reduction.	5. d. any of the above
		6. a. forced oxidation.

#### Dual-Alkali Scrubbing

Dual-, or double-, alkali scrubbing is a throwaway FGD process that uses a sodium based alkali solution to remove  $SO_2$  from combustion exhaust gas. The sodium alkali solution absorbs  $SO_2$ , and the spent absorbing liquor is regenerated with lime or limestone. Calcium sulfites and sulfates are precipitated and discarded as sludge. The regenerated sodium scrubbing solution is returned to the absorber loop. The dual-alkali process has reduced plugging and scaling problems in the absorber because sodium scrubbing compounds are very soluble. Dual-alkali systems are capable of 95%  $SO_2$  reduction.

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Particulate matter is removed prior to  $SO_2$  scrubbing by an electrostatic precipitator or a venturi scrubber. This is done to prevent fly ash erosion of the absorber internals and to prevent any appreciable oxidation of the sodium solution in the absorber due to catalytic elements in the fly ash (EPA, March 1978).

#### **Process Chemistry**

The sodium alkali solution is usually a mixture of sodium carbonate  $(Na_2CO_3)$ , also called soda ash, sodium sulfite  $(Na_2SO_3)$ , and sodium hydroxide (NaOH), also called caustic. The SO<sub>2</sub> reacts with the alkaline components to primarily form sodium sulfite and sodium bisulfite  $(NaHSO_3)$ . The following are the main absorption reactions (EPA 1981):

2 NaOH + SO<sub>2</sub> 
$$\rightarrow$$
 Na<sub>2</sub>SO<sub>3</sub> + H<sub>2</sub>O  
NaOH + SO<sub>2</sub>  $\rightarrow$  NaHSO<sub>3</sub>  
Na<sub>2</sub>CO<sub>3</sub> + SO<sub>2</sub> + H<sub>2</sub>O  $\Rightarrow$  2NaHSO<sub>3</sub>  
Na<sub>2</sub>CO<sub>3</sub> + SO<sub>2</sub>  $\rightarrow$  Na<sub>2</sub>SO<sub>3</sub> + CO<sub>2</sub>  
Na<sub>2</sub>SO<sub>3</sub> + SO<sub>2</sub> + H<sub>2</sub>O  $\rightarrow$  2NaHSO<sub>3</sub>.

In addition to the above reactions, some of the  $SO_3$  present may react with alkaline components to produce sodium sulfate. For example,

$$2NaOH + SO_3 \rightarrow Na_2SO_4 + H_2O$$

Throughout the system, some sodium sulfite is oxidized to sulfate by:

calcium sludge and a regenerated sodium solution.

$$2Na_2SO_3 + O_2 \rightarrow 2Na_2SO_4$$
.

After reaction in the absorber, spent scrubbing liquor is bled to a reactor tank for regeneration. Sodium bisulfite and sodium sulfate are inactive salts and do not absorb any SO<sub>2</sub>. Actually, it is the hydroxide ion (OH<sup>-</sup>), sulfite ion (SO<sup> $\frac{1}{3}$ </sup>), and carbonate ion (CO<sup> $\frac{1}{3}$ </sup>) that absorb SO<sub>2</sub> gas. Sodium bisulfite and sodium sulfate are reacted with lime or limestone to produce a

 $2NaHSO_{3} + Ca(OH)_{2} \rightarrow Na_{2}SO_{3} + CaSO_{3} \cdot \frac{1}{2}H_{2}O^{\downarrow} + \frac{3}{2}H_{2}O^{\downarrow} \\ (lime) \qquad (sludge)$   $Na_{2}SO_{3} + Ca(OH)_{2} + \frac{1}{2}H_{2}O \rightarrow 2NaOH + CaSO_{3} \cdot \frac{1}{2}H_{2}O^{\downarrow} \\ (lime) \qquad (sludge)$   $Na_{2}SO_{4} + Ca(OH)_{2} \rightarrow 2NaOH + CaSO_{4}\downarrow \\ (lime) \qquad (sludge)$ 

At the present time, lime regeneration is the only process that has been used on commercial dual-alkali installations.

#### System Description

The dual-alkali process uses two loops—absorption and regeneration. In the absorption loop, the sodium solution contacts the flue gas in the absorber to remove  $SO_2$ . As shown in Figure 8-2, the scrubbing liquor from the bottom of the absorber is mixed with regenerated solution and sprayed in at the top of the absorber. A bleed stream from the recirculating liquid is sent to the reactor tank in the regeneration loop. The bleed stream is mixed with a



Figure 8-2. Typical process flow for a dual-alkali FGD system.

lime slurry in a reactor tank, where insoluble calcium salts are formed and the absorbent is regenerated. The sludge from the reactor is then sent to a clarifier, or thickener, where the calcium sludge is drawn off the bottom, filtered, and washed with water. From the filter, the sodium solution is recycled to the thickener, and the sludge is discarded. From the thickener, the regenerated sodium solution is sent to a holding tank where the sodium compounds and makeup water are added.

Some sodium sulfate solution is unreacted in the regeneration step. Additional sodium is added to the regenerated solution in the form of soda ash or caustic soda. This regenerated absorbent is now ready to be used again.

#### **Operating Experience**

The dual-alkali process has been installed and operating on both utility and industrial boilers for a number of years. It is the third most popular FGD system used on industrial boilers (see Table 8-1). Corrosion of, erosion of, and scale buildup on system equipment have not been major operating problems at dual-alkali FGD installations in the U.S. (EPA 1981). Operating data for the dual-alkali systems are presented in Table 8-4. Note the much lower L/G ratios of these systems compared to those of lime and limestone systems. This is because the sodium solution is more efficient in absorbing SO<sub>2</sub> than are either lime or limestone slurries.

Company and plant	MW	FGD vendor	Fly ash control	ash control in SO. abso	SO <sub>1</sub> absorber of modules per boiler	L/G ratio		Pressure drop (Δp)		Efficiency (%)		
name	(gross)	rGD venuor	Fly ash control	coal		per boiler	L/m¹	gal/1000 ft'	kPa	in. H <sub>t</sub> O	Design	Test
Central Illinois Public Service Newton #1	617	Buell-Envirotech	ESP	2.50	Mobile bed	4	1.8	10.0	1.5	6.0	90.0	90.0
Louisville Gas & Electric Cane Run #6	299	Combustion Equipment Associates	ESP	4.80	Sieve plates	2	1.3	10.0	2.5	9.9	95.0	95.0
Southern Indiana Gas & Electric A. B. Brown #1	265	FMC	ESP	<b>3</b> .55	Disc and donut trays	2	1.3	10.0	2.5	10.0	85.0	85.0
Caterpillar Tractor East Peoria, IL Joliet, IL Morton, IL Mossville, IL	105 34 19 70	FMC Zurn Zurn FMC	Cyclone Cyclone Cyclone Cyclone Cyclone	3.20 3.20 3.20 -	Venturi Dustraxtor Dustraxtor Venturi	4 2 2 4	2.2  1.2	16.0  8.6				90.0 90.0 90.0 90.0
Firestone Tire Pottstown, PA	4	FMC	Cyclone	8.00	Venturi	1	1.8	10.0	-	_		90.5
General Motors Parma, OH	32	GM Environmental	Cyclone	_	Bubble-cap plates	4	2.6	20.0	0.9	8.0	_	90.0

Table 8-4. Operational data for dual-alkali FGD systems on utility and industrial boilers.

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Note: A dash (--) indicates that no data are available.

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Some operating problems include regenerating scrubbing liquor and controlling the solids content of the sludge. Sodium sulfate, one of the compounds in the spent scrubbing liquor, is difficult to regenerate because it does not react efficiently with hydrated lime in the presence of sodium sulfite (Leivo 1978). Process conditions must be carefully controlled to adjust for the amounts of sodium sulfate and sodium sulfite that are formed in the spent scrubbing liquid. Another problem occurring in dual-alkali systems is that the solids content of the sludge can vary greatly, causing problems in handling and stabilizing the sludge for final disposal (Makansi 1982).

Review Exercise	
<ol> <li>Dual-alkali processes generally use a solution to absorb the SO<sub>2</sub> from the flue gas and then react it with a slurry to regenerate the absorbing solution.</li> <li>a. sodium, citrate</li> <li>b. citrate, lime or limestone</li> <li>c. sodium, lime or limestone</li> <li>d. lime or limestone, sodium</li> </ol>	
2. $SO_2$ is <u>more/less</u> soluble in a sodium alkali solution than in a lime or limestone slurry.	1. c. sodium, lime or limestone
3. True or False? The sodium solution used in FGD systems is often a mixture of different sodium compounds.	s 2. more
<ul> <li>4. Solutions of sodium compounds are referred to as clear liquor solutions because the compounds are</li> <li>a. blue.</li> <li>b. soluble.</li> <li>c. insoluble.</li> <li>d. transparent.</li> </ul>	3. True
<ul> <li>5. In the dual-alkali process, the sodium reagent is regenerated by reacting the spent solution with lime. As part of this reaction, insoluble are formed in the regeneration vessel.</li> <li>a. sodium salts</li> <li>b. calcium salts</li> <li>c. magnesium salts</li> <li>d. citrate salts</li> </ul>	4. b. soluble.
	5. b. calcium salts

<ul> <li>6. Compared to lime and limestone scrubbing systems, dual-alkali absorbers have a much lower</li> <li>a. pressure drop.</li> <li>b. gas velocity.</li> <li>c. liquid-to-gas ratio.</li> <li>d. all of the above</li> </ul>	
<ol> <li>True or False? Using sodium-based scrubbing solutions (as compared to calcium-based) helps eliminate scale buildup.</li> </ol>	6. c. liquid-to-gas ratio.
	7. True

#### Sodium-Based Once-Through Scrubbing

Sodium-based once-through (throwaway) scrubbing systems are the overwhelming choice for FGD systems installed on industrial boilers (see Table 8-1). These systems use a clear liquid absorbent of either sodium carbonate, sodium hydroxide, or sodium bicarbonate. According to Makansi (1982), sodium-based systems are favored for treating flue gas from industrial boilers because:

- sodium alkali is the most efficient of the commercial reagents in removing SO<sub>2</sub>, and the chemistry is relatively simple.
- they are soluble systems as opposed to slurry systems making for scale-free operation and fewer components.
- such systems can handle the wider variations in flue-gas composition resulting from the burning of many different fuels by industry.
- the systems are often smaller, and operating costs are a small percentage of total plant costs.
- in some cases, these plants have a waste caustic stream or soda ash available for use as the absorbent.

These systems have been applied to only a few large utility boilers because:

- the process consumes a premium chemical (NaOH or Na<sub>2</sub>CO<sub>3</sub>) that is much more costly per pound than calcium-based reagents.
- the liquid wastes contain highly soluble sodium salt compounds. Therefore, the huge quantities of liquid wastes generated by large utilities would have to be sent to ponds to allow the water to evaporate.

#### Process Chemistry

The process chemistry is very similar to that of the dual-alkali process, except the absorbent is not regenerated.

#### System Description

A basic sodium-based throwaway FGD system is illustrated in Figure 8-3. Exhaust gas from the boiler may first pass through an ESP or baghouse to remove particulate matter. Sodium chemicals are mixed with water and sprayed into the absorber. The solution reacts with the  $SO_2$  in the flue gas to form sodium sulfite, sodium bisulfite, and a very small amount of sodium sulfate. A bleed stream is taken from the scrubbing liquor recirculation stream at a rate equal to the amount of  $SO_2$  that is being absorbed. The bleed stream is sent to a neutralization tank and aeration tower before being sent to a lined disposal pond.



Figure 8-3. Typical process flow for a sodium-based throwaway (single-alkali) FGD system.

Some coal-fired units use ESPs or baghouses to remove fly ash before the gas enters the scrubber. In these cases, the absorber can be a plate tower or spray tower that provides good scrubbing efficiency at low pressure drops. For simultaneous  $SO_2$  and fly ash removal, venturi scrubbers can be used. In fact, many of the industrial sodium-based throwaway systems are venturi scrubbers originally designed to remove particulate matter. These units were slightly modified to inject a sodium-based scrubbing liquor. Although removal of both particles and  $SO_2$  in one vessel can be economically attractive, the problems of high pressure drops and using a scrubbing medium to remove fly ash must be considered. However, in cases where the particle concentration is low, such as from oil-fired units, simultaneous particulate and  $SO_2$  emisson reduction can be effective.

#### **Operating Experience**

Presently, 93 sodium-based throwaway FGD systems are in operation in the U.S. They have been installed on 158 industrial boilers and 4 utility boilers. Table 8-5 lists operating data for some of these systems. These systems are generally simpler to operate and maintain than lime or limestone systems. Therefore, reported operating problems have not been as severe or as frequent with the sodium-based system as with calcium-based systems.

Control of pH, as with other FGD systems, is of prime concern to maximize absorption efficiency. Troubles with controlling pH can cause scale buildup and plugging of the sample lines (at high pH, the liquor absorbs  $CO_2$  and forms carbonate scale in systems where a high amount of calcium or magnesium is present) (Makansi 1982). Other problems include ineffective entrainment separation, nozzle plugging, and failure of dampers, duct liners, and stack liners.

Company and plant	MW	) FGD vendor	Fly ash control	%S	SO <sub>t</sub> absorber	Number of modules per boiler	L/G ratio		Pressure drop (Ap)		Efficiency (%)	
name	(gross)			coal			L/m³	gal/1000 ft³	kPa	in. H <sub>2</sub> O	Design	Test
Nevada Power Reid Gardner #1	125	Combustion Equipment	Cyclone/venturi	1.00	Sieve plate	1	0.2	1.6	0.7	8.0	90.0	
Reid Gardner #2	125	Combustion Equipment	Cyclone/venturi	1.00	Sieve plate	1	0.2	1.6	0.7	3.0	90.0	91.2
Reid Gardner #8	125	Combustion Equipment Association	Cyclone/venturi	1.00	Sieve plate	1	0.2	1.6	0.7	8.0	85.0	91.2
Pacific Power & Light Jim Bridger #4	550	Air Correction Division UOP	ESP	0.56	Sieve plate	3	2.7	20.0	_	_	91.0	91.0
Alyeska Pipeline Valdez, AK	25	FMC	_	0.10	Disc-and-donut trays	1	1.6	12.0				96.0
Belridge Oil McKittrick, CA	6	C-E NATCO		1.10	Eductor venturi with	1	_	_		_		90.0
McKittrick, CA	6	Heater Technology	-	1.10	Eductor venturi with	1	5.4	40.0	-	-	-	90.0
McKittrick, CA	6	Thermotics	_	1.10	Eductor venturi with variable disk	1	4.0	<b>30</b> .0	_	_	*****	90.0
Chevron, USA Bakersfield, CA	124	Koch Engineering		1.10	Flexitrays	3	1.1	8.0			_	90.0
Double Barrel Bakerstield, CA	6	C-E NATCO		1.10	Spray tower/ tray tower	1	8.3	25.0	_			95.0
FMC Green River, WY	223	FMC	ESP	1.00	Disc-and-donut trays	2	2.7	20.0		_		95.0
General Motors St. Louis, MO Dayton, OH Tonowanda, NY	32 18 46	A. D. Little Entoleter FMC	None . None . Cyclone	3.20 2.00 1.20	Impingement plate Vane cage Variable-throat venturi	1 2 4	0.8 2.7	6.0 20.0		- 7.0		90.0 86.0 95.0

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Note: A dash ( ) indicates that no data are available.

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Company and plant	MW FGD vendor	FGD vendor	Fly ash control	%S in	SO. absorber	Number of modules	L/G ratio		Pressure drop (Δp)		Efficiency (%)	
name	(gross)			coal		per boiler	L/m'	gal/1000 ft*	kPa	in. H <sub>2</sub> O	Design	Test
Getty Oil Bakersfield, CA	36	FMC	None	1.10	Disc-and-donut tray/ flexitray	1	1.1	8.4		_		90.0
Bakersfield, CA	445	In-house	None	1.10	Flexitray	9	1.2	9.0		- 1		96.0
Orcutt, CA	2:5	In-house	None	4.00	Packed tower	1		-		-	-	94.0
ITT Raynier Fernandina Beach, FL	88	Neptune Airpol	Cyclone	2.50	Variable-throat venturi	2	-	-	5.5	22.0		85.0
Kerr-McGee Trona, CA	245	Combustion Equipment Association	_	0.5-5	Plate tower	2		-	1.5	6.0		98.0
Mead Paperboard Stevenson, AL	50	Neptune Airpol	Venturi	3.00	Bubble-cap plates	1	-	-	_			95.0
Northern Ohio Sugar Freemont, OH	20	Great Western Sugar	None	1.00	Variable-throat venturi	2	_		_			
Reichhold Chemicals Pensacola, FL	40	Neptune Airpol	None	2.00	Venturi	2		_	6.0	24.0	_	
Texasgulf Granger, WY	70	Swemco	Cyclone/ESP	0.75	Sieve plate	2	_	_	_		_	90.0

#### Table 8-5. Operational data for sodium-based once-through FGD systems on utility and industrial boilers (continued).

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Review Exercise	
<ol> <li>What is the most popular FGD system for industrial boilers?         <ul> <li>a. lime</li> <li>b. limestone</li> <li>c. Wellman-Lord</li> <li>d. sodium-based throwaway</li> </ul> </li> </ol>	
2. True or False? The three sodium compounds used most often in throwaway systems are sodium hydroxide, sodium carbonate, and sodium bicarbonate.	1. d. sodium-based throwaway
<ul> <li>3. Sodium-based once-through FGD systems are favored for industrial boilers because <ul> <li>a. sodium is the most efficient of the commercial reagents.</li> <li>b. they operate without scale buildup occurring.</li> <li>c. they are often smaller and cheaper than other systems.</li> <li>d. all of the above</li> </ul></li></ul>	2. True
<ul> <li>4. Large utilities have not used sodium-based once-through systems because of the expense of the sodium reagent and the <ul> <li>a. limited efficiency.</li> <li>b. low fly ash removal.</li> <li>c. wastes contain soluble salts that cannot be discharged into rivers or lakes.</li> <li>d. all of the above</li> </ul> </li> </ul>	3. d. all of the above
5. True or False? In a sodium-based once-through FGD sys- tem, the flue gas may first pass through a baghouse or ESP.	4. c. wastes contain soluble salts that cannot be discharged into rivers or lakes.
<ul> <li>6. A problem that must be considered when trying to remove both SO<sub>2</sub> and fly ash in the same scrubber is that <ul> <li>a. pressure drops are higher.</li> <li>b. the scrubbing liquid, if recirculated, can contain a high level of fly ash.</li> <li>c. SO<sub>2</sub> absorption efficiency is always lower.</li> <li>d. a. and b. above</li> </ul> </li> </ul>	5. True
	6. d. a. and b. above

÷

7.	True or False? Sodium-based once-through systems are generally simpler to operate and maintain than lime or limestone FGD systems.	6. d. a. and b. above
8.	At high pH values, the scrubbing liquid in the sodium system absorbs and can form carbonate scale if significant amounts of calcium and magnesium are present. a. $SO_2$ b. $CO_2$ c. $O_2$ d. $CaCO_3$	7. True
		8. b. CO <sub>2</sub>

## **Regenerable FGD Processes**

Regenerable FGD processes remove  $SO_2$  from the flue gas and generate a salable product. Regenerable products include elemental sulfur, sulfuric acid, or, in the case of lime or limestone scrubbing, gypsum (used for wallboard). Regenerable processes do not produce a sludge, thereby eliminating the sludge disposal problem. Most regenerable processes also:

- have the potential for consistently obtaining a high SO<sub>2</sub> removal efficiency, usually exceeding 90%,
- utilize the scrubbing reagent more efficiently than nonregenerable processes, and
- use scrubbing liquors that do not cause scaling and plugging problems in the scrubber.

The major drawback of using these processes is that these systems are usually more complicated in design and are more expensive to install and operate.

Two regenerable processes presently operating in the U.S. are the Wellman-Lord and the magnesium oxide. The Wellman-Lord process has been widely used in both sulfuric acid and petroleum refining industries and has been installed on a number of industrial and utility boilers. The magnesium oxide process has been tested at a number of utility boilers, but the Philadelphia Electric Company's Eddystone and Cromby Stations are the only utility boilers presently operating this process. The Wellman-Lord process is the only major commercial regenerable FGD process used in the U.S. and will be the only one covered in detail in this section. The citrate and magnesium oxide processes are covered in more detail in APTI Course 415, Control of Gaseous Emissions—Student Manual (EPA 450/2-81-006).

#### Wellman-Lord

The Wellman-Lord process is a regenerable FGD process used to reduce  $SO_2$  emissions from utility and industrial boilers and produces a usable product. This process is sometimes referred to as the Wellman-Lord/Allied Chemical process, Allied Chemical referring to the regeneration step.

#### **Process Chemistry**

In the Wellman-Lord process, the  $SO_2$  is absorbed by an aqueous sodium sulfite solution which forms a sodium bisulfite solution according to the following equation:

$$SO_2 + Na_2SO_3 + H_2O \rightarrow 2Na_2HSO_3$$
.

Some oxidation occurs in the absorber to form sodium sulfate, which is unreactive with  $SO_2$  gas.

$$Na_2SO_3 + \frac{1}{2}O_2 \rightarrow Na_2SO_4$$

The formation of sodium sulfate depletes the supply of sodium sulfite available for scrubbing. This can be made up by adding sodium carbonate to the scrubbing slurry to combine with sodium bisulfite according to the following chemical reaction:

$$Na_2CO_3 + 2NaHSO_3 \rightarrow 2Na_2SO_3 + CO_2^{\dagger} + H_2O_1$$

The absorbent is then regenerated by evaporating the water from the bisulfite solution.

$$2NaHSO_3 \rightarrow Na_2SO_3 + H_2O + SO_2(concentrated)$$

The concentrated  $SO_2$  produced in the regeneration step is then sent to the Allied process for conversion to elemental sulfur or sulfuric acid.

A typical process flow of one Wellman-Lord system is shown in Figure 8-4. The process equipment includes an electrostatic precipitator for removing particulate matter; a venturi scrubber for cooling flue gas and removing  $SO_3$  and chlorides; an  $SO_2$  absorber; an evaporator-crystallizer for regenerating the absorbent; and the Allied Chemical process for reducing concentrated  $SO_2$  gas into elemental sulfur or sulfuric acid. The absorber is a plate tower.  $SO_2$  gas is scrubbed with a sodium sulfite solution at each plate. A mist eliminator removes entrained liquid droplets from gas exiting the absorber. There is a direct-fired natural gas reheating system in the absorber stack to reheat cleaned gas for good dispersion of the steam plume.



Figure 8-4. Typical process flow for a Wellman-Lord FGD system.

The solution (sodium bisulfite), collected at the bottom of the absorber, overflows into an absorber surge tank. This solution is pumped through a filter to remove any collected particulate matter. A small side-stream is sent to a purge treatment system where sodium sulfate is removed. The solution is then pumped to the evaporator for regeneration of the sodium sulfite solution.

The evaporator is a forced-circulation vacuum evaporator. Solution is recirculated in the evaporator, where low-pressure steam evaporates water from the sodium bisulfite solution. When sufficient water is removed, sodium sulfite crystals form and precipitate. Concentrated  $SO_2$  gas (95% by volume) is removed by the steam. The sodium sulfite crystals form a slurry that is withdrawn continuously and sent to a dissolving tank, where condensate from the evaporator is used to dissolve the sodium sulfite crystals into a solution. This solution is pumped back into the top stage of the absorber (EPA 1977). The water vapor is removed from the evaporator's overhead  $SO_2/H_2O$  vapors by water-cooled condensers. The  $SO_2$  is compressed by a liquid-ring compressor and sent to the Allied Chemical  $SO_2$  reduction plant.

#### **Operating Experience**

The Wellman-Lord process has ben installed on two 350-MW coal-fired boilers at the Public Service of New Mexico power plant at San Juan. This system was supplied by Davy Powergas and is similar to the system supplied on the Mitchell power plant in Indiana. The San Juan plant uses a five-stage tray tower instead of the three-stage tray tower of the Mitchell plant. The Wellman-Lord process has also been used to control SO<sub>2</sub> emissions at Claus tail-gas plants, sulfuric acid plants, and on industrial boilers. A listing of selected installations is given in Table 8-6. SO<sub>2</sub> removal efficiency ranges from 85 to 90%, with a high of 98% on units installed in Japan (EPA, March 1978; EPA 600/7-78-032b).

Company and landing	Food and only in	Gas vol	Initial		
Company and location	reed gas origin	m³/s	scfm	date	
Olin Corporation Paulsboro, NJ	Sulfuric acid plant	20.1	43,000	1970	
Standard Oil of California El Segundo, CA	Claus plant	13.4	28,000	1972	
Allied Chemical Corporation Calumet, IL	Sulfuric acid plant	13.4	28,000	1973	
Olin Corporation Curtis Bay, MD	Sulfuric acid plant	34.8	74,000	1973	
Standard Oil of California Richmond, CA	Claus plant	13.4	28,000	1975	
Standard Oil of California El Segundo, CA	Claus plant	13.4	28,000	1975	
Standard Oil of California Richmond, CA	Claus plant	13.4	28,000	1976	
Northern Indiana Public Service Company Gary, IN	115-MW coal-fired boiler system with 80% load factor and recovery capacity	105.0	223,000	1977	
Public Service Company of New Mexico Waterflow, NM	375-MW coal-fired boiler system, San Juan Station No. 1		1 700 000	1070	
Public Service Company of New Mexico Waterflow, NM	375-MW coal-fired boiler system, San Juan Station No. 2	040.0	1,780,000	1978	
Getty Oil Company Delaware City, DE	60-MW mixed-fuel boiler system, Delaware City No. 1				
Getty Oil Company Delaware City, DE	60-MW mixed-fuel boiler system, Delaware City No. 2	235.0	520,000	1980	
Getty Oil Company Delaware City, DE	60-MW mixed-fuel boiler system, Delaware City No. 3				
Public Service Company of New Mexico Waterflow, NM	550-MW coal-fired boiler system, San Juan Station No. 3	)	9 400 000	1091	
Public Service Company of New Mexico Waterflow, NM San Juan Station No. 4			2,400,000	1301	

#### Table 8-6. Wellman-Lord installations in the United States.

Review Exercise	2
<ol> <li>Regenerable FGD processes generate a salable product such as         <ul> <li>a. sulfur.</li> <li>b. sulfuric acid.</li> <li>c. gypsum.</li> <li>d. all of the above</li> </ul> </li> </ol>	
2. List three advantages that the regenerable process has over the nonregenerable FGD process.	1. d. all of the above
<ul> <li>3. In the Wellman-Lord process, an aqueous solution of absorbs SO<sub>2</sub>.</li> <li>a. Na<sub>2</sub>SO<sub>3</sub></li> <li>b. Na<sub>2</sub>HSO<sub>3</sub></li> <li>c. Na<sub>2</sub>SO<sub>4</sub></li> <li>d. CaO</li> </ul>	<ul> <li>2. • avoids sludge disposal problem</li> <li>• utilizes reagent better</li> <li>• uses clear liquid solutions (reduces scaling)</li> </ul>
<ul> <li>4. In the regenerating reaction of the Wellman-Lord process water is evaporated from the sodium bisulfite solution, regenerating the sodium sulfite and producing <ul> <li>a. elemental sulfur.</li> <li>b. concentrated SO<sub>2</sub> gas.</li> <li>c. gypsum.</li> <li>d. all of the above</li> </ul> </li> </ul>	ess, 3. a. Na2SO3 (sodium sulfite)
5. True or False? In the Wellman-Lord process, the flue gamay pass through a particle removal device before enter the absorber.	as 4. b. concentrated $SO_2$ gas.
<ul> <li>6. In the Wellman-Lord process, a prescrubber is used to</li> <li>a. humidify the gas stream.</li> <li>b. remove chlorides.</li> <li>c. both a and b</li> <li>d. none of the above</li> </ul>	5. False The flue gas must be pretreated.
	6. c. both a and b

### Summary

FGD systems have been installed and operated on many industrial and utility boilers and on some industrial processes for a number of years. These systems are capable of removing approximately 70 to 90% of the SO<sub>2</sub> in the flue gas, depending on the operating conditions of the system. Some systems have achieved an SO2-removal efficiency of greater than 95%. The most popular FGD systems used on utility boilers are lime and limestone scrubbing. Approximately 75% of the FGD systems installed on utility boilers are either lime or limestone scrubbing. The use of dual-alkali systems on utility boilers is attractive because of their ability to remove  $SO_2$  very efficiently and because of the reduced scaling problems associated with these systems. Wellman-Lord FGD systems have been used to reduce  $SO_2$  emissions from utility and industrial boilers and from a number of industrial processes. These systems have the advantage of regenerating the scrubbing liquor and producing a salable product instead of a sludge that can be a disposal problem. However, these systems are more expensive to install and operate than are lime, limestone, or dual-alkali systems. The throwaway-sodium FGD systems have been used mostly on industrial boilers. These systems use a sodium scrubbing liquor that is very efficient in absorbing  $SO_2$  emissions, but produce liquid wastes that can cause waste disposal problems. FGD systems used on utility boilers generate large quantities of liquid wastes. Therefore, throwaway-sodium systems have mainly been used on industrial boilers.

Over the past 15 years, a wealth of material has been written and documented concerning FGD control technology. The authors of this manual suggest that the readers turn to the many publications from EPA-IERL concerning this subject, particularly the proceedings from the FGD symposia sponsored by the EPA.

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# Lesson 9

## Design Review of Scrubbers Used for Particulate Pollutants

## Lesson Goal and Objectives

#### Goal

To familiarize you with the factors to be considered when reviewing particulate-pollutant scrubber design plans for the permit process.

#### **Objectives**

Upon completing this lesson, you should be able to-

- 1. recall at least four important scrubber design factors,
- 2. estimate the collection efficiency of a venturi scrubber using appropriate equations and graphs, and
- 3. use the *cut power method* to estimate the cut diameter necessary for achieving a specified collection efficiency.

## Introduction

The design of a scrubber involves many factors including space restriction, pollutant collection efficiency, pressure drop (gas-side), particle size, exhaust gas flow rate, liquid-to-gas ratio, and many construction details such as using corrosion-resistant materials, baffles, nozzles, venturi throats, water sprays, packing, plates, orifices, entrainment separators, inlets, and outlets. These have been discussed in detail in the previous lessons. Officers who review scrubber design plans for air pollution control agencies should consider these factors during the review process.

In Lesson 1, and throughout this course, scrubbers are categorized by the manner in which exhaust gas and liquid are brought into contact. Scrubbers can also be grouped by the kinds of pollutants they collect: those that are mainly used to collect particulate emissions and those that are mainly used to collect gaseous emissions.

Because all scrubbers can be used to collect both particulate and gaseous pollutants, the choice of the most appropriate type can sometimes be difficult. Therefore, this lesson will point out those scrubber design features that are important when choosing a scrubber to remove particulate pollutants. This lesson will also look at a few equations that can be used to estimate pressure drop and collection efficiency.

## Wet Scrubbers Used to Remove Particles

Venturi scrubbers are the most popular scrubbers used to remove particulate matter. Other scrubbers used include cyclonic, orifice, mechanically aided, and spray towers. Typical gasside pressure drops and L/G ratios for these devices are given in Table 9-1.

Scrubber	Pressure	drop, Δp	Liquid-to-gas ratio*		
Scrubber	kPa	in. H <sub>1</sub> O	L/m³	gal/1000 ft <sup>3</sup>	
Venturi	1.5-25.0	5.0-100.0	0.4-5.0	3.0-40.0	
Spray tow <del>er</del>	0.12-0.75	0.5-3.0	0.7-2.7	5.0-20.0	
Cyclonic spray	0.4-4.0	1.5-10.0	0.3-1.3	2.0-10.0	
Moving bed (good for removing particulate and gaseous pollutants)	0.5-6.0	2.0-24.0	0.4-8.0	3.0-60.0	
Orifice (self-induced spray)	0.5-4.0	2.0-10.0	0.07-0.7	0.5-5.0	
Mechanically aided (fan)	1.0-2.0	4.0-8.0	0.07-0.5	0.5-4.0	

Table 9-1. Ranges of pressure drops and liquid-to-gas (L/G) ratios for various wet scrubbers.

\*Higher L/G reflects those used for gas absorption.

Wet scrubbers remove particles from an exhaust stream by contacting the particles with liquid, usually water. A number of factors affect particle removal efficiency, including:

- particle-size distribution
- liquid flow rate
- exhaust gas flow rate
- method of contacting
- pressure drop across the scrubber.

As with gaseous pollutant removal (absorption), efficient particle removal requires contact between the exhaust stream (containing particles) and the scrubbing liquid. However, particle removal occurs instantaneously upon contact with the liquid, whereas efficient absorption requires a long contact time. Therefore, efficient particle removal requires high relative velocities (gas versus liquid velocity).

### Estimating Collection Efficiency and Pressure Drop

A number of theories have been developed from basic particle-movement principles to explain the action of wet scrubbing systems. Many of these start from firm scientific concepts, but yield only qualitative results when predicting collection efficiencies or pressure drops. The interaction of particulate matter having a given particle-size distribution with water droplets having another size distribution is not easy to express in quantitative terms. As a result of this complexity, experimentally determined parameters are usually needed to approach reality (Beachler and Jahnke 1981).

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Venturi	1.5-25.0	5.0-100.0	0.4-5.0	3.0-40.0	
Spray tower	0.12-0.75	0.5-3.0	0.7-2.7	5.0-20.0	
Cyclonic spray	0.4-4.0	1.5-10.0	0.3-1.3	2.0-10.0	
Moving bed (good for removing particulate and gaseous pollutants)	0.5-6.0	2.0-24.0	0.4-8.0	3.0-60.0	
Orifice (self-induced spray)	0.5-4.0	2.0-10.0	0.07-0.7	0.5-5.0	
Mechanically aided (fan)	1.0-2.0	4.0-8.0	0.07-0.5	0.5-4.0	

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#### **Collection Efficiency**

Collection efficiency is frequently expressed in terms of penetration. Penetration is defined as the fraction of particles (in the exhaust stream) that passes through the scrubber uncollected. Penetration is the opposite of the fraction of particles collected, and is expressed as:

(Eq. 9-1)  $Pt = 1 - \eta$ 

Where: Pt = penetration $\eta = collection efficiency.$ 

Wet scrubbers usually have an efficiency curve that fits the relationship of:

(Eq. 9-2)  $\eta = 1 - e^{-f(system)}$ 

Where: η = collection efficiency e = exponential function f(system) = some function of the scrubbing system variables.

By substituting for efficiency, penetration can be expressed as:

(Eq. 9-3)  

$$Pt = 1 - \eta$$
  
 $= 1 - (1 - e^{-f(system)})$   
 $= e^{-f(system)}.$ 

In testing the design of a specific scrubber, the vendor can measure operating variables and the collection efficiency of the unit. These data can then be used to evaluate the efficiency of the system. An equation for the scrubbing system variables, f(system), can be developed for that particular design. Scrubber vendors and various consultants have, in fact, developed equations and assembled data that can be used to design and evaluate their specific scrubbers. Unfortunately, much of this information is proprietary. In addition, an equation that has been designed for a venturi scrubber may not work well for evaluating the design of an orifice or cyclonic scrubber. In other words, there is not one specific equation that can be used to estimate the collection efficiency of every scrubbing system. A number of equations used for predicting collection efficiency can be found in the Wet Scrubber System Study (Calvert et al. 1972).

#### Model for Estimating Venturi Scrubber Efficiency

One method used to predict particle collection efficiency in a venturi scrubber is called the *infinite-throat model* (Yung et al. 1977). This model is a refined version of the Calvert correlation given in the *Wet Scrubber System Study, Volume I, Scrubber Handbook* (Calvert et al. 1972). The equations presented in the infinite-throat model assume that all particles are captured by the water in the throat section of the venturi. Two studies found that this method correlated very well with actual scrubber operating data (Yung et al. 1977 and Calvert et al. 1978).

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The equations listed in the model can be used to predict the penetration (Pt) for one particle size (diameter). To get an overall penetration ( $\overline{Pt}$ ), you must integrate over the entire particle-size distribution. Equation 9-4 (penetration for one particle size) was solved for the overall penetration assuming a log-normal particle-size distribution. These results are plotted in Figures 9-1 through 9-3 (Yung et al. 1977). In these figures,  $\overline{Pt}$ , overall penetration, is plotted versus B, a dimensionless parameter characterizing the liquid-to-gas ratio, with  $K_{pg}$ , a dimensionless inertial parameter for mass-median diameter. Each figure has been plotted for a different geometric standard deviation, i.e., 2.5, 5.0, and 7.5. By knowing the particle-size distribution of the dust from an industrial source and the operating conditions of the scrubber, the collection efficiency (penetration) can be estimated using Figures 9-1, 9-2, or 9-3.

Equation number	Equation				
Eq. 9-4	$\ln \Pr(d_p) = -B  \frac{4 K_{po} + 4.2 - 5.02 K_{po}^{0.5} \left(1 + \frac{0.7}{K_{po}}\right) \tan^{-1} \sqrt{\frac{K_{po}}{0.7}}}{K_{po} + 0.7}$				
	Where: Pt(d <sub>p</sub> ) = penetration for one particle size B = parameter characterizing the liquid-to-gas ratio, dimensionless K <sub>po</sub> = inertial parameter at throat entrance dimensionless				
	Note: Equation 9-4 was developed assuming that the venturi has an infinite- sized throat length. This is valid only when $l$ is greater than 2.0. $l = \frac{3l_r C_o \varrho_s}{2d_s \varrho_l}$				
	Where: $l =$ throat length parameter, dimensionless $l_r =$ venturi throat length, cm $C_D =$ drag coefficient for the liquid at the throat entrance, dimensionless $Q_s =$ gas density, g/cm <sup>3</sup> $d_s =$ droplet diameter, cm $Q_l =$ liquid density, g/cm <sup>3</sup>				
Eq. 9-5 Nukiyama Tanasawa equation	$d_{d} = \frac{50}{v_{gr}} + 91.8(L/G)^{1.5}$ Where: $d_{d}$ = droplet diameter, cm $v_{gr}$ = gas velocity in the throat, cm/s L/G = liquid-to-gas ratio, dimensionless				

## Infinite-Throat Model for Predicting Venturi Scrubber Performance (using metric units)

## Infinite-Throat Model for Predicting Venturi Scrubber Performance (continued)

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Equation number	Equation				
Eq. 9-6	$\mathbf{B} = (\mathbf{L}/\mathbf{G}) \ \frac{\boldsymbol{\varrho}_l}{\boldsymbol{\varrho}_{\boldsymbol{g}} \mathbf{C}_{\boldsymbol{D}}}$				
	Where: $B = parameter characterizing liquid-to-gas ratio,dimensionlessL/G = liquid-to-gas ratio, dimensionless\varrho_t = liquid density, kg/m^3\varrho_s = gas density, kg/m^3C_D = drag coefficient for the liquid at the throatentrance, dimensionless$				
Eq. 9-7	$K_{po} = \frac{d_p^2 v_{g\tau}}{9 \mu_g d_d}$				
	Where: $K_{po}$ = inertial parameter at the throat entrance, dimensionless $d_p$ = particle aerodynamic resistance diameter, cmA $v_{gr}$ = gas velocity in the throat, cm/s $\mu_q$ = gas viscosity, g/cm·s $d_d$ = droplet diameter, cm				
Eq. 9-8	$K_{pg} = \frac{d_{pg}^2 v_{gr}}{9 \mu_g d_d}$				
	Where: $K_{pg}$ = inertial parameter for mass-median diameter, dimensionless $d_{pg}$ = particle aerodynamic geometric mean diameter, cmA $v_{gr}$ = gas velocity in the throat, cm/s $\mu_{g}$ = gas viscosity, g/cm •s $d_{d}$ = droplet diameter, cm				
Eq. 9-9	$C_{o} = 0.22 + \frac{24}{N_{Reo}} \left(1 + 0.15 N_{Reo}^{0.6}\right)$				
	Where: $C_D = drag$ coefficient for the liquid at the throat entrance, dimensionless $N_{R\infty} = Reynolds$ Number for the liquid droplet at the throat inlet, dimensionless				

Equation number	Equation				
Eq. 9-10	$N_{Rec} = \frac{v_{gr} d_d}{v_g}$				
	Where: $N_{Rec}$ = Reynolds Number for the liquid at the throat entrance, dimensionless $v_{sr}$ = gas velocity in the throat, cm/s $\nu_{s}$ = gas kinematic viscosity, cm <sup>2</sup> /s $d_{s}$ = droplet diameter, cm				
Eq. 9-11	$\mathbf{d}_{pg} = \mathbf{d}_{ps} (\mathbf{C}_{f} \times \boldsymbol{\varrho}_{p})^{0.5}$				
	Where: $d_{pg}$ = particle aerodynamic geometric mean diameter, $\mu$ mA $d_{pg}$ = particle physical, or Stokes, diameter, $\mu$ m $C_f$ = Cunningham slip correction factor, dimensionless $Q_p$ = particle density, g/cm <sup>3</sup>				
Eq. 9-12	$C_f = 1 + \frac{(6.21 \times 10^{-4})T}{d_{ps}}$				
	Where: C <sub>f</sub> = Cunningham slip correction factor, dimensionless T = absolute temperature, K d <sub>ps</sub> = particle physical, or Stokes, diameter, μm				

## Infinite-Throat Model for Predicting Venturi Scrubber Performance (continued)

Source: Yung et al. 1977.




Source: Yung et al. 1977.



Figure 9-2. Overall penetration, Pt, versus B with  $K_{pe}$  as a parameter, where the geometric standard deviation,  $\sigma_{gm}$ , is equal to 5.0.



Figure 9-3. Overall penetration,  $\overline{Pt}$ , versus B with  $K_{pe}$  as a parameter, where the geometric standard deviation,  $\sigma_{im}$ , is equal to 7.5.

Example 9-1 will illustrate how to use the infinite-throat model to predict the performance of a venturi scrubber. When using the equations given in the model, make sure that the units for each equation are consistent.

# Example 9-1

Cheeps Disposal Inc. is planning to install a hazardous-waste incinerator that will burn both liquid and solid waste materials. The exhaust gas from the incinerator will pass through a quench spray and then into a venturi scrubber. Caustic will be added to the scrubbing liquor to remove any HCl from the flue gas and to control the pH of the scrubbing liquor. The uncontrolled particulate emissions leaving the incinerator are estimated to be 1100 kg/h (maximum average). The local air pollution regulation states that particulate emissions must not exceed 10 kg/h. Using the following data, estimate the overall collection efficiency of the scrubbing system.

Mass-median particle size (physical),  $d_{ps} = 9.0 \ \mu m$ Geometric standard deviation,  $\sigma_{gm} = 2.5$ Particle density,  $\varrho_p = 1.9 \ g/cm^3$ Gas viscosity,  $\mu_g = 2.0 \times 10^{-4} \ g/cm \cdot s$ Gas kinematic viscosity,  $\nu_g = 0.2 \ cm^2/s$ Gas density,  $\varrho_g = 1.0 \ kg/m^3$ Gas flow rate,  $Q_G = 15 \ m^3/s$ Gas velocity in venturi throat,  $v_{gr} = 9000 \ cm/s$ Gas temperature (in venturi),  $T_g = 80 \ cm/s$ Water temperature,  $T_l = 30 \ cm/s$ Liquid density,  $\varrho_l = 1000 \ kg/m^3$ Liquid flow rate,  $Q_L = 0.014 \ m^3/s$ Liquid-to-gas ratio,  $L/G = 0.0009 \ L/m^3$ 

#### Solution

1. The mass-median particle size (physical),  $d_{ps}$ , is 9.0  $\mu$ m. Since the particle aerodynamic geometric mean diameter,  $d_{pg}$ , is not known, you must use Equation 9-11 to calculate  $d_{pg}$ and Equation 9-12 to calculate the Cunningham slip correction factor,  $C_f$ .

(Eq. 9-12) 
$$C_f = 1 + \frac{(6.21 \times 10^{-4})T}{9}$$

(Eq. 9-11)  $d_{pg} = d_{ps} (C_f \times \varrho_p)^{0.5}$ 

- Note: This step would not have been required if the particle diameter had been given as the aerodynamic geometric mean diameter,  $d_{pg}$ , and expressed in units of  $\mu$ mA.
- Calculate the droplet diameter, d<sub>d</sub>, from Equation 9-5 (Nukiyama Tanasawa equation).

(Eq. 9-5) 
$$d_d = \frac{50}{v_{sr}} + 91.8(L/G)^{1.5}$$

= 1.024  $d_{pg} = 9 \ \mu m (1.024 \times 1.9 \ g/cm^3)^{0.5}$ = 12.6 \mumber mA = 12.6 \times 10^{-4} cmA

 $C_f = 1 + \frac{(6.21 \times 10^{-4})(273 + 80)}{9}$ 

- $d_{d} = \frac{50}{9000 \text{ cm/s}} + 91.8(0.0009)^{1.5}$ = 0.0080 cm
- 3. Calculate the inertial parameter for the massmedian diameter,  $K_{pg}$ , using Equation 9-8.
  - (Eq. 9-8)  $K_{pg} = \frac{d_{pg}^2 v_{gr}}{9 \mu_r d_d}$

$$K_{pg} = \frac{(12.6 \times 10^{-4} \text{ cm})^2 (9000 \text{ cm/s})}{9(2.0 \times 10^{-4} \text{ g/cm} \cdot \text{s})(0.008 \text{ cm})}$$
  
= 992

 Calculate the Reynolds Number, N<sub>Reo</sub>, using Equation 9-10.

(Eq. 9-10) 
$$N_{Rec} = \frac{v_{gr} d_d}{v_g}$$
  $N_{Rec} = \frac{(9000 \text{ cm/s})(0.008 \text{ cm})}{0.2 \text{ cm}^2/\text{s}}$   
= 360

5. Calculate the drag coefficient for the liquid at the throat entrance,  $C_D$ , using Equation 9-9.

(Eq. 9-9) 
$$C_D = 0.22 + \frac{24}{N_{Reo}} (1 + 0.15 N_{Reo}^{0.6})$$
  $C_D = 0.22 + \frac{24}{360} (1 + 0.15 (360)^{0.6})$   
= 0.628

6. Now calculate the parameter characterizing the liquid-to-gas ratio, B, using Equation 9-6.

(Eq. 9-6) 
$$B = (L/G) \frac{\varrho_l}{\varrho_g C_D}$$

$$B = (0.0009) \frac{1000 \text{ kg/m}^3}{(1.0 \text{ kg/m}^3)(0.628)}$$
$$= 1.43$$

7. The geometric standard deviation, σ<sub>gm</sub>, is 2.5. The overall penetration, Pt, can be found from Figure 9-4.
B = 1 K<sub>pg</sub> = Read



Source: Yung et al. 1977.

Figure 9-4. Overall penetration,  $\overline{Pt}$ , for Example 9-1, where the standard deviation,  $\sigma_{em}$ , is equal to 2.5.

- 8. The collection efficiency can be calculated using the equation below.
- $\eta = 1 \overline{Pt}$ = 0.992 = 99.2%

$$\sigma_{gm} = 2.5$$
  
B = 1.43  
K<sub>pg</sub> = 992  
Read  $\overline{Pt} = 0.008$ 

9-10

9. The local regulations state that the particulate emissions cannot exceed 10 kg/h. The required collection efficiency can be calculated by using the equation below.

$\eta_{required} =$	$\frac{\text{dust}_{in} - \text{dust}_{out}}{\text{dust}_{in}}$	$\eta_{required} = 0$	1100 kg/h - 10 kg/h 1100 kg/h		
Where:	dust <sub>in</sub> = dust concentration leading into the venturi dust <sub>our</sub> = dust concentration leaving the venturi	= ( = 9	).991 99.1 <i>%</i>		
The estimated efficiency of the venturi scrub- ber is slightly higher than the required efficiency.					

Note: Figures 9-1 through 9-3 can also be used to determine some of the required operating variables. This can be done by solving the example problem in reverse. By entering the figures at the required efficiency (or  $\overline{Pt}$ ), one can obtain various sets of  $K_{pg}$  and B values. These values for  $K_{pg}$  and B can be used to calculate the required L/G ratio or  $v_{rr}$  for a specific collection efficiency.

# Cut Power Method

One empirical correlation that has been used to predict the collection efficiency of a scrubber is the cut power method. In this method, developed by Calvert, penetration is a function of the cut diameter of the particles to be collected by the scrubber. The cut diameter is the diameter of the particles that are collected by the scrubber with at least 50% efficiency. Since scrubbers have limits to the size of particles they can collect, knowledge of the cut diameter is useful in evaluating the scrubbing system.

In the cut power method, penetration is a function of the particle diameter and is given as:  $Pt = e^{-A_{cur} d_p}^{B_{cur}}$ 

(Eq. 9-13)

Where: Pt = penetration

> $A_{cur}$  = parameter characterizing the particle-size distribution  $B_{cur}$  = empirically determined constant, depending on the scrubber design  $d_p$  = aerodynamic diameter of the particle.

Penetration, calculated by Equation 9-13, is given for only one particle size  $(d_p)$ . To obtain the overall penetration, the equation can be integrated over the log-normal particle-size distribution. Calvert has developed a method of determining the cut diameter required to achieve a given collection efficiency. By mathematically integrating Pt over a log-normal distribution of particles and by varying the geometric standard deviation,  $\sigma_{gm}$ , and the geometric mean particle diameter,  $d_{pg}$ , the overall penetration,  $\overline{Pt}$ , can be obtained. Figure 9-5 plots the overall penetration as a function of the required cut diameter,  $(d_p)_{cur}$  (Calvert 1972).

Figure 9-5 was developed using Equation 9-13,  $Pt = e^{-A_{cut} d_p^{B_{cut}}}$ , where B = 2. For plate towers, B = 2, but is only  $\approx 2$  for venturis under certain conditions. For centrifugal scrubbers,  $B \approx 0.7$  and, therefore, Figure 9-5 should not be used as is. Further limitations and models developed for specific devices using the cut power method are discussed by Calvert (1972). The application of these models to actual operating systems has not been documented adequately in the open literature.

Example 9-2 will illustrate how to use the cut power method to estimate the cut diameter for a venturi scrubber.

# Example 9-2

Given similar conditions as in Example 9-1, estimate the cut diameter for a venturi scrubber. The data below are approximate.

Geometric standard deviation,  $\sigma_{gm} = 2.5$ Particle aerodynamic geometric mean diameter,  $d_{pg} = 12.6 \ \mu mA$ Required efficiency,  $\eta = 99.1\%$  or 0.991

#### Solution

- 1. For an efficiency of 99.1%, the overall penetration can be calculated from  $\overline{Pt} = 1 - \eta$ .
- $\overline{Pt} = 1 0.991$ = 0.009
- The overall penetration is 0.009, and the geometric standard deviation is 2.5. Using Figure 9-5, read (d<sub>p</sub>)<sub>cur</sub>/d<sub>pg</sub>.

$$Pt = 0.009$$
$$\sigma_{gm} = 2.5$$
$$(d_p)_{cut}/d_{pg} \approx 0.09$$



Figure 9-5. Penetration versus cut diameter.

3. The cut diameter,  $(d_p)_{cur}$ , is calculated from

$$\frac{(\mathbf{d}_p)_{cut}}{\mathbf{d}_{pg}} = 0.09$$

 $(d_p)_{cut} = (0.09) d_{pg}.$ 

From the information presented in Lesson 2, a venturi scrubber is capable of operating with a cut diameter of 1.13  $\mu$ mA. However, the pressure drop and other operating conditions of the scrubber must be maintained to achieve a high collection efficiency.

# Contact Power Theory

A more general theory for estimating collection efficiency is the contact power theory. This theory is based on a series of experimental observations made by Lapple and Kamack (1955). The fundamental assumption of the theory is:

"When compared at the same power consumption, all scrubbers give substantially the same degree of collection of a given dispersed dust, regardless of the mechanism involved and regardless of whether the pressure drop is obtained by high gas flow rates or high water flow rates." (Lapple and Kamack 1955)

In other words, collection efficiency is a function of how much power the scrubber uses, and not of how the scrubber is designed. This has a number of implications in the evaluation and selection of wet collectors. Once it is realized that a certain amount of power is needed for a required collection efficiency, the claims about specially located nozzles, baffles, etc. can be evaluated more objectively. The choice between two different scrubbers with the same power requirements may depend primarily on ease of maintenance.

Semrau (1959 and 1963) developed the contact power theory from the work of Lapple and Kamack (1955). The theory, as developed by Semrau, is empirical in approach and relates the total pressure loss,  $P_{T}$ , of the system to the collection efficiency.

The total pressure loss is expressed in terms of the power expended to inject the liquid into the scrubber plus the power needed to move the process gas through the system.

(Eq. 9-14) 
$$P_T = P_G + P_A$$

Where:  $P_T = \text{total contacting power, } kWh/1000 \text{ m}^3 (hp/1000 \text{ acfm})$ 

 $P_G$  = power input from gas stream, kWh/1000 m<sup>3</sup> (hp/1000 acfm)

 $P_L$  = power input from liquid injection, kWh/1000 m<sup>3</sup> (hp/1000 acfm)

[Note: The total pressure loss,  $P_r$ , should not be confused with penetration, Pt, defined in the previous section. Penetration is the symbol used by Calvert to express the fraction of particulate matter escaping from a collector.]

 $(d_p)_{cut} = (0.09)(12.6 \ \mu mA)$ = 1.13 \ \mu mA The power expended in moving the gas through the system,  $P_G$ , is expressed in terms of the scrubber pressure drop.

(Eq. 9-15) 
$$P_G = 2.724 \times 10^{-4} \Delta p$$
, kWh/1000 m<sup>3</sup> (metric units)

or

 $P_G = 0.1575 \Delta p$ , hp/1000 acfm (English units)

Where:  $\Delta p = pressure drop, kPa (in. H_2O)$ 

The power expended in the liquid stream,  $P_L$ , is expressed as:

(Eq. 9-16) 
$$P_L = 0.28 \ p_L (Q_L/Q_G), \ kWh/1000 \ m^3 \ (metric units) \ or \ P_L = 0.583 \ p_L (Q_L/Q_G), \ hp/1000 \ acfm \ (English units)$$

Where:  $p_L = \text{liquid inlet pressure, 100 kPa (lb/in.<sup>2</sup>)}$   $Q_L = \text{liquid feed rate, m<sup>3</sup>/h (gal/min)}$  $Q_G = \text{gas flow rate, m<sup>3</sup>/h (ft<sup>3</sup>/min)}.$ 

The constants given in the expressions for  $P_G$  and  $P_L$  incorporate conversion factors to put the terms on a consistent basis.

The total power can therefore be expressed as:

(Eq. 9-17) 
$$P_T = P_G + P_L$$
  
= 2.724 × 10<sup>-4</sup>  $\Delta p$  + 0.28 p<sub>L</sub> (Q<sub>L</sub>/Q<sub>G</sub>), kWh/1000 m<sup>3</sup>  
or  
= 0.1575  $\Delta p$  + 0.583 p<sub>L</sub> (Q<sub>L</sub>/Q<sub>G</sub>), hp/1000 acfm.

The problem now is to correlate this with scrubber efficiency.

Equation 9-2 of this lesson shows that efficiency is an exponential function of the system variables for most types of collectors.

(Eq. 9-18) 
$$\eta = 1 - e^{-f(system)}$$

Semrau defines the function of the system variables, f(system), as:

(Eq. 9-19)

 $f(system) = N_r = \alpha P_T^{\beta}$ 

Where:  $N_r =$  number of transfer units

 $P_T$  = total contacting power

 $\alpha$  and  $\beta$  = empirical constants which are determined from experiment and depend on the characteristics of the particles.

The efficiency then becomes:

(Eq. 9-20) 
$$\eta = 1 - e^{-\alpha P_T^{\beta}}$$
.

Table 9-2 gives values of  $\alpha$  and  $\beta$  for different industries. The values of  $\alpha$  and  $\beta$  can be used in either the metric or English units.

Aerosol	α	β
Talc dust	2.97	0.362
Phosphoric acid mist	1.33	0.647
Foundry cupola dust	1.35	0.621
Open-hearth steel furnace fume	1.26	0.569
Odorous mist	0.363	1.41
Hot black liquor gas	0.522	0.861
Lime kiln dust (raw)	1.47	1.05
Black liquor furnace fume	1.75	0.620
Ferrosilicon furnace fume	0.870	0.459
Lime kiln dust (prewashed)	0.915	1.05
Black liquor fume	0.740	0.861
Copper sulfate	0.390	1.14
Copper sulfate	0.562	1.06
Talc dust	2.70	0.362
Talc dust	1.16	0.655
	Aerosol Talc dust Phosphoric acid mist Foundry cupola dust Open-hearth steel furnace fume Odorous mist Hot black liquor gas Lime kiln dust (raw) Black liquor furnace fume Ferrosilicon furnace fume Lime kiln dust (prewashed) Black liquor fume Copper sulfate Copper sulfate Talc dust Talc dust	AerosolαTalc dust2.97Phosphoric acid mist1.33Foundry cupola dust1.35Open-hearth steel furnace fume1.26Odorous mist0.363Hot black liquor gas0.522Lime kiln dust (raw)1.47Black liquor furnace fume1.75Ferrosilicon furnace fume0.870Lime kiln dust (prewashed)0.915Black liquor fume0.740Copper sulfate0.390Copper sulfate0.562Talc dust2.70Talc dust1.16

#### Table 9-2. Parameters $\alpha$ and $\beta$ for the contact power theory.

Source: Semrau 1960.

The contact power theory cannot predict efficiency from a given particle-size distribution as can the cut power method. The contact power theory gives a relationship which is independent of the size of the scrubber. With this observation, a small pilot scrubber could first be used to determine the pressure drop needed for the required collection efficiency. The fullscale scrubber design could then be scaled up from the pilot information.

# Example 9-3

A wet scrubber is to be used to control particulate emissions from a foundry cupola. Stack test results reveal that the particulate emissions must be reduced by 85% to meet emission standards. If a 100-acfm pilot unit is operated with a water flow rate of 0.5 gal/min at a water pressure of 80 psi, what pressure drop ( $\Delta p$ ) would be needed across a 10,000-acfm scrubber unit?

# Solution

1.	From Table 9-2, read the $\alpha$ and $\beta$ parameters for foundry cupola dust.	$\alpha = 1.35$ $\beta = 0.621$
2.	Calculate the number of transfer units, $N_r$ , using Equation 9-18.	
	(Eq. 9-18) $\eta = 1 - e^{-N_r}$	$N_r = \ln \frac{1}{1 - 0.85}$
	$N_r = \ln \frac{1}{1 - \eta}$	$= \ln 6.66$ = 1.896

3. Calculate the total contacting power,  $P_r$ , using Equation 9-19.

4.

(Eq. 9-19) $N_t = \alpha P_T^{\beta}$	$1.896 = 1.35 P_T^{0.621}$
-	$1.896 - P^{0.621}$
	$\frac{1.35}{1.35} = F_T^{-1.11}$
	$1.404 = P_T^{0.621}$
	$\ln 1.404 = 0.621 \ln P_T$
	$0.3393 = 0.621 \ln P_T$
	$0.5464 = \ln P_r$
	$P_T = 1.73 \text{ hp}/1000 \text{ acfm}$
Calculate the pressure drop, $\Delta p$ , using Equa-	
tion 9-17.	$P_r = 0.1575 \Delta p + 0.583 p_L \left(\frac{Q_L}{Q_G}\right)$
(Eq. 9-17) $P_T = 0.1575 \Delta p + 0.583 p_L \left(\frac{Q_L}{Q_g}\right)$	$1.73 = 0.1575 \Delta p + 0.583(80) \left(-\frac{1}{2}\right)$

From the data in Table 9-2, you can see that the usefulness of Equation 9-20 is limited due to the lack of  $\alpha$  and  $\beta$  values. However, the concept of the contact power theory is still a very useful tool in evaluating scrubber design. Since the theory does correlate well with operating data, and it is independent of scrubber size, the theory has applications in scaling up designs from pilot plant data. In addition, the basic principle of the contact power theory can be applied to specific sources of interest. For example, in a regulatory analysis of wet scrubbing systems for coal-fired utility boilers, Figure 9-6 was developed using the contact power theory (Kashdan 1979). This figure plots power consumption versus outlet dust loading (instead of transfer units) for the operating points of 12 utility boilers. The curve fits the equation  $y = 0.68x^{-1.41}$ , where y = outlet grain loading and x = theoretical power consumption calculated using Equation 9-17. The good fit is quite remarkable given the variety of coals, boilers, process variables, inlet particle-size distribution, and scrubber designs among the different plants (Kashdan 1979).

 $\Delta p = 9.5$  in.  $H_2O$ 

The concept of the contact power theory does have limitations. It does not apply to a number of new wet collecting systems where a combination of collecting mechanisms are used, such as condensation scrubbers. Also, the theory applies best when the power is applied in one scrubbing area (McIlvaine 1977), such as in a venturi scrubber. Multiple-staged devices and packed towers will have collection efficiencies varying from those of a venturi scrubber for a given power input.



Source: Kashdan 1979.

Figure 9-6. Correlation of scrubber outlet dust loading with theoretical power consumption.

#### **Pressure Drop**

As discussed earlier, a number of factors affect particle capture in a scrubber. One of the most important, especially for the contact power theory, is pressure drop. Pressure drop is the difference in pressure between the inlet and the outlet of the scrubber. The pressure drop represents the energy expended in the scrubbing process. From the contact power theory, the higher the pressure drop, the more efficient the scrubber. However, the higher the pressure drops just high enough to ensure adequate collection of particles.

The following factors affect the pressure drop in a scrubber:

- scrubber design and geometry
- gas velocity
- liquid-to-gas ratio.

As with calculating collection efficiency, no one equation can predict the pressure drop for all scrubbing systems.

Many theoretical and empirical relationships are available for estimating the pressure drop across a scrubber. Generally, the most accurate are those developed by scrubber manufacturers for *their* particular scrubbing systems. Due to the lack of validated models, it is recommended that users consult the vendor's literature to estimate pressure drop for the particular scrubbing device of concern.

One expression was developed for venturis and is widely accepted. The correlation proposed by Calvert is (Yung et al. 1977):

(Eq. 9-21)	$\Delta p = 8.24 \times 10^{-4} (v_{gr})^2 (L/G)$	(metric units)
	or	
	$\Delta p = 4.0 \times 10^{-5} (v_{gr})^2 (L/G)$	(English units)
Where:	$\Delta p = pressure drop, cm H_2O$ (in. $H_2O$ )	
	$v_{gr} =$ velocity of gas in the venturi throat,	cm/s (ft/sec)

L/G = liquid-to-gas ratio, dimensionless,  $L/m^3$  (gal/1000 ft<sup>3</sup>).

Using Equation 9-21 for the conditions given in Example 9-1, we get:

$$v_{sr} = 9000 \text{ cm/s}$$
  
 $L/G = 0.0009 \text{ L/m}^3$   
 $\Delta p = 8.24 \times 10^{-4} (9000)^2 (0.0009)$   
 $= 60 \text{ cm } H_2O$ 

# Using Pilot Methods to Design Scrubbers

The semi-empirical theories previously discussed are useful for scrubber design and evaluation exercises because they can give qualitatively correct information. However, they have a number of practical limitations. It is not common practice to choose scrubber systems based only on this information. The uncertainties involved in particle-size determinations and the questions associated with using empirically determined parameters restrict the use of theoretical methods. Basically, too many variables are involved and accounting for them all in a simple theory is too difficult. The time and expense needed to obtain good input data for these methods may be better spent in developing pilot plant information.

Scrubbers that work primarily through impaction mechanisms have certain performance characteristics (such as efficiency and pressure drop) which are independent of scale. This consequence of the contact power principle provides the basis for using pilot systems. By using a small-scale scrubber (100 to 1000 cfm) on the exhaust gas stream, the effectiveness of the equipment for removing the actual particles in the gas can be experimentally determined.

Pilot systems ranging from 170 m<sup>3</sup>/h (100 cfm) units to one-tenth the size of full-scale plants have been developed in the past. McIlvaine (1977) has compared the effectiveness of the various design methods. His work is summarized in Table 9-3.

Description	Expense (relative scale)	Time (months)
Most reliable		
1/10 size full-scale play	nts 100-1000	12-24
2000-cfm pilot units	30	3-6
100-cfm pilot units	5	2-3
Empirical curves based similar processes	on 0.2	0.2
Impactor in situ partic sizing	le 2	1
Least reliable		

Table 9-3. Methods for predicting	g venturi scrubber	pressure requirements.
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The design of a wet collector system for a particulate-emission problem requires more than the application of a few design equations. The experience of scrubber manufacturers with specific industry installations, coupled with the use of pilot units, provides more reliable ways to determine the size of a system for a wide range of operating conditions. In many cases, theoretical models can complement such studies and provide qualitative data for wet collector evaluations.

# Review of Design Criteria for Permits

The principal design criteria are the exhaust flow to the scrubber, measured in units of  $m^3/min$  (ft<sup>3</sup>/min, or acfm), and the dust concentration, measured in units of  $g/m^3$  (lb/ft<sup>3</sup>, or gr/ft<sup>3</sup>). The exhaust volume and dust loading are set by the process exhaust conditions. Once these criteria are known, the vendor can begin to design the scrubber for the specific application. A thorough review of the design plans should consider the factors presented below.

Dust properties—type, shape, density, and size of the dust particles; average and maximum concentrations in the process exhaust stream. If the scrubber is to be installed on an existing source, a stack test to measure dust concentration and particle-size distribution (cut diameter and standard deviation) should be performed. If the scrubber is installed on a new source, these data could be obtained from a similar installation.

Exhaust gas characteristics—average and maximum exhaust flow rates to the scrubber; chemical properties such as dew point, corrosiveness, pH, and solubility of the pollutants to be removed should be measured or accurately estimated.

Liquid flow—the type of scrubbing liquid and the rate at which the liquid is supplied to the scrubber. If the scrubbing liquid is to be recirculated, the pH and amount of suspended solids should be monitored to ensure continuous reliability of the scrubbing system.

**Pressure drop**—the pressure drop (gas-side) at which the scrubber will operate; the scrubber design should also include a means for monitoring the pressure drop across the system, usually by manometers.

Removal of entrained liquid—mists and liquid droplets that become entrained in the "scrubbed" exhaust stream should be removed before exiting the stack. Some type of entrainment separator, or mist eliminator, should be included in the design.

Emission requirements—collection efficiency in terms of grain loading and opacity regulations for particulate matter and concentration regulations for gaseous pollutants; collection efficiency can be high (95 to 99%) if the scrubber is properly designed. The agency review engineer can use the equations given in this lesson to estimate the scrubber efficiency. However, these equations can only predict the general collection efficiency of the system, and they should not be used as the basis to either accept or reject the design plans submitted for the permit process.

# Summary

When checking the design plans for the permit process, the agency engineer should check its files or another agency's files for similar applications for scrubber installations. A review of these data will help determine if the scrubber design specifications submitted by the industrial source's officials are adequate to achieve particle removal efficiency for compliance with the regulations. The agency engineer should require the source owner/operator to conduct stack tests (once the source is operating) to determine if the source is in compliance with local, State, and Federal regulations. The agency engineer should also require that the source owner/operator submit an operation and maintenance schedule that will help keep the scrubber system on line.

	Review Exercise	
1.	The scrubber used most often to remove particulate matter from exhaust streams is a <u>whynn</u> scrubber.	
2.	True or False? Efficient particle removal requires low gas-to-liquid (relative) velocities.	1. venturi
3.	<ul> <li>The term <i>penetration</i> is defined as</li> <li>a. the fraction of particles collected in a scrubber.</li> <li>b. the amount of gaseous pollutants absorbed in the scrubbing liquor.</li> <li>c. the fraction of particles that passes through a scrubber uncollected.</li> </ul>	2. False
4.	<ul> <li>The cut power method is an empirical correlation used to predict the penetration. The penetration is a function of a. the cut diameter of the particles that are collected by the scrubber.</li> <li>b. the cut-throat velocity of the scrubber.</li> <li>c. the amount of power that is supplied to the scrubber.</li> <li>d. the pressure drop across the scrubber.</li> </ul>	<ol> <li>c. the fraction of par- ticles that passes through a scrubber uncollected.</li> </ol>
5.	<ul> <li>Cut diameter is</li> <li>a. the cut-off size of the particles that are not collected.</li> <li>b. the diameter of the particles that are collected with at least 100% efficiency.</li> <li>c. the diameter of the particles that are collected with at least 50% efficiency.</li> </ul>	4. a. the cut diameter of the particles that are collected by the scrubber.
6.	<ul> <li>In the equation used in the contact power theory,</li> <li>P<sub>T</sub> = P<sub>G</sub> + P<sub>L</sub>, the symbol P<sub>T</sub> represents <ul> <li>a. the penetration of the system.</li> </ul> </li> <li>b. the collection efficiency.</li> <li>c. the total pressure loss, or contacting power, of the scrubbing system.</li> </ul>	5. c. the diameter of the particles that are collected with at least 50% efficiency.
7.	According to the contact power theory, the lower/higher the pressure drop is across the scrubbing system, the higher the collection efficiency will be.	6. c. the total pressure loss, or contacting power, of the scrubbing system.
8.	Which of the following factors affect the pressure drop of a scrubbing system? a. scrubber design and geometry b. gas velocity c. liquid-to-gas ratio d. all of the above	7. higher
		8. d. all of the above

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# Lesson 10

# Design Review of Absorbers Used for Gaseous Pollutants

# Lesson Goal and Objectives

# Goal

To familiarize you with the factors to be considered when reviewing absorber design plans for the permit process.

# **Objectives**

Upon completing this lesson, you should be able to-

- 1. recall at least four scrubber design factors,
- 2. estimate the liquid flow rate, the diameter, and the packing height of a packed tower using appropriate tables and equations, and
- 3. estimate the number of plates and the height of a plate tower using appropriate tables and equations.

# Introduction

The design of an absorber used to reduce gaseous pollutants from process exhaust streams involves many factors including the pollutant collection efficiency, pollutant solubility in the absorbing liquid, liquid-to-gas ratio, exhaust flow rate, pressure drop, and many construction details of the absorbers such as packing, plates, liquid distributors, entrainment separators, and corrosion-resistant materials. These have been discussed in detail in the previous lessons. Air pollution control agency officers who review design plans for absorbers should consider these factors during the review process.

The previous lessons stated that all wet scrubbing systems are able to collect particulate and gaseous pollutants emitted from process exhaust streams. However, spray towers, plate towers, packed towers, and moving-bed scrubbers are generally used to reduce gaseous pollutants. This lesson will focus on equations used to estimate liquid flow rate, the diameter and the height of a packed tower, and the diameter and number of plates used in a plate tower to achieve a specified pollutant removal efficiency.

Absorbers remove gaseous pollutants by dissolving them into a liquid called the absorbent. In designing absorbers, optimum absorption efficiency can be achieved by:

- providing a large interfacial contact area,
- providing for good mixing between the gas and liquid phases,
- allowing sufficient residence, or contact, time between the phases, and
- choosing a liquid in which the gaseous pollutant is very soluble.

# Absorption

Absorption refers to the transfer of a gaseous pollutant from a gas phase to a liquid phase. More specifically, in air pollution control, absorption involves the removal of objectionable gaseous pollutants from a process stream by dissolving them in a liquid.

Some common terms used when discussing the absorption process follow:

Absorbent-the liquid, usually water, into which the pollutant is absorbed.

Solute, or absorbate-the gaseous pollutant being absorbed, such as SO<sub>2</sub>, H<sub>2</sub>S, etc.

Carrier gas-the inert portion of the gas stream, usually air, from which the pollutant is to be removed.

Interface—the area where the gas phase and the absorbent contact each other.

Solubility-the capability of a gas to be dissolved in a liquid.

Absorption is a mass-transfer operation. In absorption, mass transfer of the gaseous pollutant into the liquid occurs as a result of a concentration difference (of the pollutant) between the liquid and gas phases. Absorption continues as long as a concentration difference exists where the gaseous pollutant and liquid are not in equilibrium with each other. The concentration difference depends on the solubility of the gaseous pollutant into the liquid.

# Solubility

A very important factor affecting the amount of a pollutant, or solute, that can be absorbed is its solubility. Solubility is a function of both the temperature and, to a lesser extent, the pressure of the system. As temperature increases, the amount of gas that can be absorbed by a liquid decreases. From the ideal gas law: as temperature increases, the volume of a gas also increases; therefore, at the higher temperature, less gas is absorbed due to the increased volume it occupies. Pressure affects the solubility of a gas in the opposite manner. By increasing the pressure of a system, the amount of gas absorbed generally increases.

The solubility of a specific gas in a given liquid is defined at a designated temperature and pressure. Table 10-1 presents data on the solubility of  $SO_2$  gas in water at 101 kPa, or 1 atm, and various temperatures. In determining solubility data, the partial pressure (in mm Hg) is measured with the concentration (in grams of solute per 100 grams of liquid) of the solute in the liquid. The data in Table 10-1 were taken from *The International Critical Tables*, a good source of information concerning gas-liquid systems.

Solubility data are obtained at equilibrium conditions. This involves putting measured amounts of a gas and a liquid into a closed vessel and allowing it to sit for a period of time. Eventually, the amount of gas absorbed into the liquid will equal the amount coming out of the solution. At this point, there is no net transfer of mass to either phase, and the concentration of the gas in both the gaseous and liquid phases remains constant. The gas-liquid system is at equilibrium.

Grams of SO <sub>1</sub> per 100 g H <sub>2</sub> O	10°C	20°C	30°C	40°C	50°C	60°C	70°C
0.0	_	-			_		-
0.5	21	29	42	60	83	111	144
1.0	42	59	85	120	164	217	281
1.5	64	90	129	181	247	328	426
2.0	86	123	176	245	333	444	581
2.5	108	157	224	311	421	562	739
3.0	130	191	273	378	511	682	897
3.5	153	227	324	447	603	804	-
4.0	176	264	376	518	698		-
4.5	199	300	428	588	793		-
5.0	223	338	482	661	-	-	—

Table 10-1. Partial pressure of SO, in aqueous solution, mm Hg.

Equilibrium conditions are important in operating an absorption tower. If equilibrium were to be reached in the actual operation of an absorption tower, the collection efficiency would fall to zero at that point since no net mass transfer could occur. The equilibrium concentration, therefore, limits the amount of solute that can be removed by absorption. The most common method of analyzing solubility data is to use an equilibrium diagram. An equilibrium diagram is a plot of the mole fraction of solute in the liquid phase, denoted as x, versus the mole fraction of solute in the gas phase, denoted as y. Equilibrium lines for the SO<sub>2</sub> and water system given in Table 10-1 are plotted in Figure 10-1. Figure 10-1 also illustrates the temperature dependence of the absorption process. At a constant mole fraction of solute in the gas (y), the mole fraction of SO<sub>2</sub> that can be absorbed in the liquid (x) increases as the temperature decreases.



Figure 10-1. Equilibrium lines for SO<sub>2</sub>-H<sub>2</sub>O systems at various temperatures.

Under certain conditions, *Henry's law* may also be used to express equilibrium solubility of gas-liquid systems. Henry's law is expressed as:

(Eq. 10-1) p = Hx
Where: p = partial pressure of solute at equilibrium, Pa x = mole fraction of solute in the liquid, mole fraction H = Henry's law constant, Pa/mole fraction.

From Equation 10-1 you can see that H has the units of pressure per concentration. Henry's law can be written in a more useful form by dividing both sides of Equation 10-1 by the total pressure,  $P_T$ , of the system. The left side of the equation becomes the partial pressure divided by the total pressure, which equals the mole fraction in the gas phase, y. Equation 10-1 now becomes:

(Eq. 10-2) y=H'x
Where: y = mole fraction of gas in equilibrium with liquid H' = Henry's law constant, mole fraction in vapor per mole fraction in liquid x = mole fraction of the solute in the liquid. Note: H' now depends on the total pressure.

Equation 10-2 is the equation of a straight line, where the slope (m) is equal to H'. Henry's law can be used to predict solubility only when the equilibrium line is straight. Equilibrium lines are usually straight when the solute concentrations are very dilute. In air pollution control applications, this is usually the case. For example, an exhaust stream that contains a 1000-ppm SO<sub>2</sub> concentration corresponds to a mole fraction of SO<sub>2</sub> in the gas phase of only 0.001. Figure 10-2 demonstrates that the equilibrium lines are still straight at this low concentration of SO<sub>2</sub>.



Figure 10-2. Equilibrium diagram for SO<sub>2</sub>-H<sub>2</sub>O system for the data given in Example 10-1.

Another restriction on using Henry's law is that it does not hold true for gases that react or dissociate upon dissolution. If this happens, the gas no longer exists as a simple molecule. For example, scrubbing HF or HCl gases with water causes both compounds to dissociate in solution. In these cases, the equilibrium lines are curved rather than straight. Data on systems that exhibit curved equilibrium lines must be obtained from experiments.

Henry's law constants for the solubility of several gases in water are listed in Table 10-2. The units of Henry's law constants are atmospheres per mole fraction. The smaller the constant, the more soluble the gas. Table 10-2 demonstrates that  $SO_2$  is approximately 100 times more soluble in water than  $CO_2$  is in water. The following example illustrates how to develop an equilibrium diagram from solubility data.

20°C	30°C
80.4	92.4
53.6	62.0
48.3	60.9
40.1	47.5
26.4	31.0
1.42	1.86
0.014	0.016
	20°C 80.4 53.6 48.3 40.1 26.4 1.42 0.014

Table 10-2. Henry's law constants for gases in HzO.\*

\*Expressed in  $H \times 10^{-5}$ , atm/mole fraction.

#### Example 10-1

Given the data in Table 10-3 for the solubility of  $SO_2$  in pure water at 303 K (30 °C) and 101.3 kPa (760 mm Hg), calculate y and x, plot the equilibrium diagram, and determine if Henry's law applies.

Table 10-3.	Equilibrium	data.
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cso <sub>2</sub> (g of SO <sub>1</sub> per 100 g of H <sub>2</sub> O)	psoz (partial pressure of SOz)	y (mole fraction of SO <sub>2</sub> in gas phase)	x (mole fraction of SO <sub>2</sub> in liquid phase)
0.5	6 kPa (42 mm Hg)		
1.0	11.6 kPa (85 mm Hg)		
1.5	18.3 kPa (129 mm Hg)		
2.0	24.3 kPa (176 mm Hg)		
2.5	30.0 kPa (224 mm Hg)		
3.0	36.4 kPa (273 mm Hg)		

# Solution

1. The data must first be converted into mole fraction units. The mole fraction of  $SO_2$  in the gas phase, y, is obtained by dividing the partial pressure of  $SO_2$  by the total pressure of the system.

$$y = \frac{p_{so_2}}{P_T}$$

The mole fractions of  $SO_2$  in the gas phase are tabulated in Table 10-4.

2. The mole fraction of the solute  $(SO_2)$  in the liquid phase, x, is obtained by dividing the moles of  $SO_2$  dissolved into the solution by the total moles of liquid.

$$x = \frac{\text{moles of SO}_{z} \text{ in solution}}{\text{moles of SO}_{z} \text{ in solution} + \text{moles of H}_{z}O}$$

The mole fractions of the solute in the liquid phase are tabulated in Table 10-4.

moles of SO<sub>2</sub> in solution =  $c_{so_2}/64$  g SO<sub>2</sub> per mole moles of H<sub>2</sub>O = 100 g of H<sub>2</sub>O/18 g H<sub>2</sub>O per mole = 5.55 moles

1

$$x = \frac{\frac{c_{so_2}}{64}}{\frac{c_{so_2}}{64} + 5.55}} = \frac{\frac{0.5}{64}}{\frac{0.5}{64} + 5.55}}{= 0.0014}$$

 $y = \frac{6 \text{ kPa}}{101.3 \text{ kPa}}$ 

= 0.06

#### Table 10-4. Equilibrium data for Example 10-1.

$c_{so_2} = \frac{g \text{ of } SO_2}{100 \text{ g } H_2O}$	psoz (kPa)	y = p/101.3	$x = \frac{c_{so_2}/64}{c_{so_2}/64 + 5.55}$
0.5	6.0	0.060	0.0014
1.0	11.6	0.115	0.0028
1.5	18.3	0.180	0.0042
2.0	24.3	0.239	0.0056
2.5	30.0	0.298	0.0070
3.0	36.4	0.359	0.0084

3. The mole fraction of  $SO_2$  in air, y, is plotted against the mole fraction of  $SO_2$  dissolved in water, x, in Figure 10-2.



Figure 10-2. Equilibrium diagram for SO<sub>2</sub>-H<sub>2</sub>O system

for the data given in Example 10-1.

The plot in Figure 10-2 is a straight line; therefore, Henry's law applies. The slope of the line  $(\Delta y / \Delta x)$ , Henry's law constant (H'), is approximately equal to 42.7. Slope =  $\frac{\Delta y}{\Delta x}$ =  $\frac{0.2}{0.00}$ 

 $lope = \frac{\Delta y}{\Delta x} = \frac{0.239 - 0.180}{0.0056 - 0.0042} \approx 42.7$ 

Review Exercise				
1.	Of the wet collectors listed below, which is/are the best device(s) for removing gaseous pollutants from process exhaust streams? a. packed tower b. plate tower c. venturi scrubber d. centrifugal scrubber e. a and b			
2.	<ul> <li>In the absorption process, the solute is the</li> <li>a. inert portion of the gas stream.</li> <li>b. area where the gas phase and liquid phase come into contact with each other.</li> <li>c. gaseous pollutant that is absorbed.</li> <li>d. capability of a gas to be dissolved in a liquid.</li> </ul>	1. e. a and b		
3.	A very important factor affecting the amount of a pollu- tant that can be absorbed is its	<ol><li>c. gaseous pollutant that is absorbed.</li></ol>		
4.	In an absorber, as the temperature of the system increases, the amount of pollutant that can be absorbed increases/decreases.	3. solubility		
5.	A plot of the mole fraction of the solute in the liquid phase versus the mole fraction of the solute in the gas phase is called a. the partial pressure. b. an equilibrium diagram. c. a concentration gradient.	4. decreases		
6.	What is one form of the equation for Henry's law? a. $x = Hp$ b. $H = xp$ c. $H = x/y$ d. $y = H'x$	5. b. an equilibrium diagram.		
7.	In describing the solubility of various gases in water, the smaller/larger Henry's law constant is, the more soluble the gas is.	6. d. $y = H'x$		
		7. smaller		

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# Absorber Design

# Theory

The first step in designing an air pollution control device is to develop a mathematical expression describing the observed phenomenon. A valid mathematical expression describing absorber performance makes it possible to determine the proper absorber size for a given set of conditions, and predict how a change in operating conditions affects absorber performance. A number of theories, or models, attempt to analytically describe the absorption mechanism. However, in practice, none of these analytical expressions can solely be used for design calculations. Experimental or empirical data must also be used to obtain reliable results.

The most widely used model for describing the absorption process is the *two-film*, or *double-resistance*, theory, which was first proposed by Whitman in 1923. The model starts with the three-step mechanism of absorption previously discussed in Lesson 1. From this mechanism, the rate of mass transfer was shown to depend on the rate of migration of a molecule in either the gas or liquid phase. The two-film model starts by assuming that the gas and liquid phases are in turbulent contact with each other, separated by an interface area where they meet. This assumption may be correct, but no mathematical expressions adequately describe the transport of a molecule through both phases in turbulent motion. Therefore, the model proposes that a mass-transfer zone exists to include a small portion (film) of the gas and liquid phases on either side of the interface. The mass-transfer zone is comprised of two films, a gas film and a liquid film on their respective sides of the interface. These films are assumed to flow in a laminar, or streamline, motion. In laminar flow, molecular motion occurs by diffusion, and can be categorized by mathematical expressions. This concept of the two-film theory is illustrated in Figure 10-3.



Figure 10-3. Visualization of two-film theory.

According to the two-film theory, for a molecule of substance A to be absorbed, it must proceed through a series of five steps. The molecule must:

1. migrate from the bulk-gas phase to the gas film,

- 2. diffuse through the gas film,
- 3. diffuse across the interface,
- 4. diffuse through the liquid film, and finally
- 5. mix into the bulk liquid.

The theory assumes that complete mixing takes place in both gas and liquid bulk phases and that the interface is at equilibrium with respect to molecules transferring in or out. This implies that all resistance to movement occurs when the molecule is diffusing through the gas and liquid films, hence the name *double-resistance* theory. The partial pressure (concentration) in the gas phase changes from  $p_{AG}$  in the bulk gas to  $p_{AI}$  at the interface.

A gas concentration is expressed by its partial pressure. Similarly, the concentration in the liquid changes from  $c_{AI}$  at the interface to  $c_{AL}$  in the bulk phase as mass transfer occurs. The rate of mass transfer then equals the amount of molecule A transferred multiplied by the resistance molecule A encounters in diffusing through the films.

(Eq. 10-3) 
$$N_A = k_g (p_{AG} - p_{AI})$$

(Eq. 10-4) 
$$N_A = k_i (c_{AI} - c_{AL})$$

Where:

 $N_{A} = \text{rate of transfer of component A, g-mol/h•m² (lb-mole/hr•ft²)} \\ k_{g} = \text{mass-transfer coefficient for gas film, g-mol/h•m²•Pa (lb-mole/hr•ft³•atm)} \\ k_{t} = \text{mass-transfer coefficient for liquid film, g-mol/h•m²•Pa (lb-mole/hr•ft³•atm)} \\ p_{AG} = \text{partial pressure of solute A in the gas} \\ p_{AI} = \text{partial pressure of solute A at the interface} \\ c_{AI} = \text{concentration of solute A in the liquid} \\ \end{cases}$ 

The mass-transfer coefficients,  $k_s$  and  $k_i$ , represent the flow resistance the solute encounters in diffusing through each film respectively (Figure 10-4). An analogy is the resistance electricity encounters as it flows through a circuit.

Equations 10-3 and 10-4 define the general case of absorption and are applicable to both curved and straight equilibrium lines. In practice, Equations 10-3 and 10-4 are difficult to use, since it is impossible to measure the interface concentrations,  $p_{AI}$  and  $c_{AI}$ . The interface is a fictitious state used in the model to represent an observed phenomenon. The interface concentrations can be avoided by defining the mass-transfer system at equilibrium conditions and combining the individual film resistances into an overall resistance. If the equilibrium line is straight, the rate of absorption is given by the equations below.

(Eq. 10-5) 
$$N_A = K_{OG}(p_{AG} - p_A^*)$$

(Eq. 10-6) 
$$N_A = K_{OL}(c_A^* - c_{AL})$$

Where:

- $N_A$  = rate of transfer of component A, g-mol/h•m<sup>2</sup> (lb-mole/hr•ft<sup>2</sup>)  $p_A^*$  = equilibrium partial pressure of solute A at operating conditions
- $c_{4}^{*}$  = equilibrium concentration of solute A at operating conditions
- $K_{og}$  = overall mass-transfer coefficient based on gas phase, g-mol/h•m<sup>2</sup>•Pa (lb-mole/hr•ft<sup>2</sup>•atm)
- $K_{oL}$  = overall mass-transfer coefficient based on liquid phase, g-mol/h•m<sup>2</sup>•Pa (lb-mole/hr•ft<sup>2</sup>•atm)
- $p_{AG}$  = partial pressure of solute A in the gas

 $c_{AL}$  = concentration of solute A in the liquid



Figure 10-4. Resistance to motion encountered by a molecule being absorbed.

An important fact concerning Equations 10-5 and 10-6 is that they impose an upper limit on the amount of solute that can be absorbed. The rate of mass transfer depends on the concentration departure from equilibrium in either the gas  $(p_{AG} - p_A^*)$  or liquid  $(c_A^* - c_{AL})$  phase. The larger these concentration differences are, the greater the rate of mass transfer. If equilibrium is ever reached  $(p_{AG} = p_A^* \text{ or } c_{AL} = c_A^*)$ , absorption stops and no net transfer occurs. Thus, the equilibrium concentrations determine the maximum amount of solute that is absorbed.

At equilibrium, the overall mass-transfer coefficients are related to the individual masstransfer coefficients by the equations below.

(Eq. 10-7) 
$$\frac{1}{K_{oG}} = \frac{1}{k_s} + \frac{H'}{k_t}$$

(Eq. 10-8) 
$$\frac{1}{K_{OL}} = \frac{1}{k_l} + \frac{1}{H' k_s}$$

H' is Henry's law constant (the slope of the equilibrium). Equations 10-7 and 10-8 are useful in determining which phase controls the rate of absorption. From Equation 10-7, if H' is very small (which means the gas is very soluble in the liquid), then  $K_{OG} \approx k_{z}$ , and absorption is said to be gas-film controlled. The major resistance to mass transfer is in the gas phase. Conversely, if a gas has limited solubility, H' is large, and Equation 10-8 reduces to  $K_{OL} \approx k_{l}$ . The mass-transfer rate is liquid-film controlled and depends on the solute's dispersion rate in the liquid phase. Most systems in the air pollution control field are gas-phase controlled since the liquid is chosen so that the solute will have a high degree of solubility. The discussion so far has been based on the two-film theory of absorption. Other theories offer different descriptions of gas molecule movement from the gas to the liquid phase. Some of the significant mass-transfer models follow. For these theories, the mass-transfer rate equation does not differ from that of the two-film model. The difference lies in the way they predict the mass-transfer coefficient. It has been shown that the rate of mass transfer depends on a *concentration difference* multiplied by a *resistance factor*. Like most theories describing how something functions, absorption theories provide a basic understanding of the process, but due to the complexities of "real life" operations, it is difficult to apply them directly. Concentrations can easily be determined from operating (c and p) and equilibrium ( $c_{\star}^{\star}$  and  $p_{\star}^{\star}$ ) data of the system. Mass-transfer coefficients are very difficult to determine from theory. Theoretically predicted values of the individual mass-transfer coefficients ( $k_{\star}$  and  $k_{\star}$ ) based on the two-film theory, do not correlate well with observed values. Overall mass-transfer coefficients are more easily determined from experimental or operational data. However, the overall coefficients apply only when the equilibrium line is straight.

# Mass-Transfer Models\*

Film Theory (Whitman 1923)—First, and probably the simplest, theory proposed for mass transfer across a fluid. Details of this model are discussed in the text because it is the most widely used.

Penetration Theory (Higbie 1935)—Assumes that the liquid surface in contact with the gas consists of small fluid elements. After contact with the gas phase, the fluid elements return to the bulk of the liquid and are replaced by another element from the bulk-liquid phase. The time each element spends at the surface is assumed to be the same.

Surface-Renewal Theory (Danckwerts 1951)—Improves on the penetration theory by suggesting that the constant exposure time be replaced by an assumed time distribution. Film-Penetration Theory (Toor and Marchello 1958)—Combination of the film and penetration theories. Assumes that a laminar film exists at the fluid interface (as in the film theory), but further assumes that mass transfer is an unsteady process.

Mass-transfer coefficients are often expressed by the symbols  $K_{00}a$ ,  $k_ia$ , etc., where "a" represents the surface area available for absorption per unit volume of the column. This allows for easy determination of the column area required to accomplish the desired separation. These mass-transfer coefficients are developed from experimental data and are usually reported in one of two ways: as an empirical relationship based on a function of the liquid flow, gas flow, or slope of the equilibrium line; or correlated in terms of a dimensionless number, usually either the Reynolds or Schmidt Number. Figure 10-5 compares the effect on the mass-transfer coefficient for SO<sub>2</sub> in water using two types of packing materials (Perry 1973). Packing A consists of one-inch rings and packing B consists of three-inch spiral tiles. Similar figures are used extensively to compare different absorbers or similar absorbers with varying operating conditions. It should be noted that these estimated mass-transfer coefficients are system and packing-type dependent and, therefore, do not have widespread applicability. The *Chemical Engineers' Handbook* gives a comprehensive listing of empirically derived coefficients. In addition, manufacturers of packed and plate towers have graphs in their literature similar to the one in Figure 10-5.

<sup>\*</sup>Source: Diab and Maddox 1982.



Figure 10-5. Comparison of overall absorption coefficient for SO<sub>2</sub> in water.

Although the science of absorption is considerably developed, much of the work in practical design situations is empirical in nature. The following section will apply the principles discussed to the design of gas absorption equipment. Emphasis has been placed on presenting information that can be used to estimate absorber size and liquid flow rate.

Review Exercise				
1.	In the double-resistance, or two-film, theory, a zone exists that includes a gas and liquid phase on either side of the interface. a. soluble b. mass-transfer c. droplet			
2.	True or False? The two-film theory implies that all resis- tance to movement occurs when the molecule (gaseous pollutant) is diffusing through the gas and liquid films.	1. b. mass-transfer		
3.	In absorption equations, the concentration of a gaseous pollutant is usually expressed by its a. diffusion rate. b. total pressure. c. partial pressure.	2. True		
		3. c. partial pressure.		

4.	In calculating the rate of mass transfer of pollutant A, $N_A$ , using the equation $N_A = K_{OG}(p_{AG} - p_A^*)$ , the term $K_{OG}$ is the a. equilibrium concentration of pollutant A. b. mass-transfer coefficient for the gas film. c. mass-transfer coefficient for the liquid film. d. overall mass-transfer coefficient based on the gas phase.		
5.	True or False? Overall mass-transfer coefficients are only valid when a plot of the equilibrium data yields an equili- brium line that is straight.	4. d.	overall mass-transfer coefficient based on the gas phase.
		5. T	rue

# Procedures

The effectiveness of an absorption system depends on the solubility of the gaseous contaminant. For very soluble gases, almost any type of absorber will give adequate removal. However, for most gases, only absorbers that provide a high degree of turbulent contact and a long residence time are capable of achieving high absorption efficiencies. The two most common high-efficiency absorbers are plate and packed towers. Both of these devices are used extensively to control gaseous pollutants. Absorber design calculations presented in this lesson will focus on these two devices.

Numerous procedures are used to design an absorption system. These procedures range in difficulty and cost from short-cut "rules of thumb" equations to in-depth design procedures based on pilot plant data. Procedures presented here will be based on the short-cut "rules of thumb." The approaches discussed in this lesson are for single component systems (i.e., only one gaseous pollutant).

To design an absorption system, certain parameters are set by either operating conditions or regulations. The gas stream to be treated is usually the exhaust from a process in the plant. Therefore, the volume, temperature, and composition of the gas stream are given parameters. The outlet composition of the contaminant is set by the emission standard which must be met. The temperature and inlet composition of the absorbing liquid are also usually known. The main unknowns in designing the absorption system are:

- the flow rate of liquid required,
- the diameter of the vessel needed to accommodate the gas and liquid flow, and
- the height of absorber required to achieve the needed removal.

Procedures for estimating these three unknowns will be discussed in the following sections.

#### Material Balance

In designing or reviewing the design of an absorption control system, the first task is to determine the flow rates and composition of each stream entering the system. From the law of conservation of mass, the material entering a process must either accumulate or exit. In other words, "what comes in must go out." A material balance is used to help determine flow rates and compositions of individual streams. Figure 10-6 illustrates the material balance for a typical countercurrent-flow absorber. The solute is the "material" in the material balance.



Figure 10-6. Material balance for countercurrent-flow absorber.

The following procedure to set up a material balance and determine the liquid flow rate will focus on a countercurrent gas-liquid flow pattern. This is the most common flow pattern used to achieve high-efficiency gas absorption. For cocurrent flow, only a slight modification of this procedure is required. Equations for crosscurrent flows are very complicated since they involve a gradient pattern that changes in two directions. They will not be presented here.

X = mole fraction of solute in pure liquid

Y = mole fraction of solute in inert gas

 $L_m =$ liquid flow rate, g-mol/h (lb-mole/hr)

 $G_m = gas$  flow rate, g-mol/h (lb-mole/hr)

Engineering design work is usually done on a solute-free basis (X, Y) to make the material balance calculations easier. The solute-free basis is defined in Equations 10-9 and 10-10.

(Eq. 10-9) 
$$Y = \frac{y}{1-y}$$
  
(Eq. 10-10)  $X = \frac{x}{1-x}$ 

In air pollution control systems, the percent of pollutant transferred, y and x, is generally small. Therefore, from Equations 10-9 and 10-10,  $Y \approx y$  and  $X \approx x$ . In this lesson, it is assumed that X and Y are always equal to x and y respectively. If y (inlet gas concentration) ever becomes larger than a few percent by volume, this assumption is invalid and will cause errors in the material balance calculations.

An overall mass balance across the absorber in Figure 10-7 yields Equation 10-11.

(Eq. 10-11) Ib mole in = lb mole out  $G_m(in) + L_m(in) = G_m(out) + L_m(out).$ 



Figure 10-7. Typical operating line diagram.

For convenience, the top of the absorber is labeled as point 2 and the bottom as point 1. This changes Equation 10-11 to Equation 10-12.

(Eq. 10-12) 
$$G_{m1} + L_{m2} = G_{m2} + L_{m1}$$

In this same manner, a material balance for the contaminant to be removed is obtained as expressed in Equation 10-13.

(Eq. 10-13) 
$$G_{m1}Y_1 + L_{m2}X_2 = G_{m2}Y_2 + L_{m1}X_3$$

Equation 10-13 can be simplified by assuming that as the gas and liquid streams flow through the absorber, their total mass does not change appreciably (i.e.,  $G_{m1} = G_{m2}$  and  $L_{m1} = L_{m2}$ ). This is justifiable for most air pollution control systems since the mass flow rate of pollutant is very small compared to the liquid and gas mass flow rates. For example, a 10,000-cfm exhaust stream containing 1000 ppm SO<sub>2</sub> would be only 0.1% SO<sub>2</sub> by volume, or 1.0 cfm. If

the scrubber were 100% efficient, the gas mass flow rate would change from 10,000 cfm at  $G_{m1}$  to 9999 cfm at  $G_{m2}$ . The transfer of a quantity this small is negligible in an overall material balance. Therefore, Equation 10-13 can be reduced to Equation 10-14.

(Eq. 10-14) 
$$G_m(Y_1 - Y_2) = L_m(X_1 - X_2)$$

By rearranging, Equation 10-14 becomes Equation 10-15.

(Eq. 10-15) 
$$Y_1 - Y_2 = \frac{L_m}{G_m} (X_1 - X_2)$$

Equation 10-15 is the equation of a straight line. When this line is plotted on an equilibrium diagram, it is referred to as an operating line. This line defines operating conditions within the absorber: what is going in and what is coming out. An equilibrium diagram with a typical operating line plotted on it is shown in Figure 10-7. The slope of the operating line is the liquid mass flow rate divided by the gas mass flow rate, which is the *liquid-to-gas ratio*, or  $L_m/G_m$ . The liquid-to-gas ratio is used extensively when describing or comparing absorption systems. Determining the liquid-to-gas ratio is discussed in the next section.

# Determining the Liquid Requirement

In the design of most absorption columns, the quantity of exhaust gas to be treated  $(G_m)$  and the inlet solute (pollutant) concentration  $(Y_1)$  are set by process conditions. Minimum acceptable standards specify the outlet pollutant concentration  $(Y_2)$ . The composition of the liquid flowing into the absorber  $(X_2)$  is also generally known or can be assumed to be zero if it is not recycled. By plotting this data on an equilibrium diagram, the minimum amount of liquid required to achieve the required outlet pollutant concentration  $(Y_2)$  can be determined.

Figure 10-8a is a typical equilibrium diagram with operating points plotted for a countercurrent-flow absorber. At the minimum liquid rate, the inlet gas concentration of solute  $(Y_1)$  is in equilibrium with the outlet liquid concentration of solute  $(X_{max})$ . The liquid leaving the absorber is saturated with solute and can no longer dissolve any more solute unless additional liquid is added. This condition is represented by point B on the equilibrium curve.

The slope of the line drawn between point A and point B represents the operating conditions at the minimum flow rate in Figure 10-8b. Note how the driving force decreases to zero at point B. The slope of line AB is  $(L_m/G_m)$ min, and may be determined graphically or from the equation for a straight line. By knowing the slope of the minimum operating line, the minimum liquid rate can easily be determined by substituting in the known gas flow rate. This procedure is illustrated in Example 10-2.

Determining the minimum liquid flow rate,  $(L_m/G_m)$  min, is important since absorber operation is usually specified as some factor of it. Generally, liquid flow rates are specified at 25 to 100% greater than the required minimum. Typical absorber operation would be 50% greater than the minimum liquid flow rate (i.e., 1.5 times the minimum liquid-to-gas ratio). Setting the liquid rate in this way assumes that the gas flow rate set by the process does not change appreciably. Line AC in Figure 10-8c is drawn at a slope of 1.5 times the minimum  $L_m/G_m$ . Line AC is referred to as the actual operating line since it describes absorber operating conditions.



Figure 10-8. Graphic determination of liquid flow rate.

The following example problem illustrates how to compute the minimum liquid rate required to achieve a desired removal efficiency.

# Example 10-2

Using the data and results from Example 10-1, compute the minimum liquid rate of pure water required to remove 90% of the SO<sub>2</sub> from a gas stream of 84.9 m<sup>3</sup>/min (3000 acfm) containing 3% SO<sub>2</sub> by volume. The temperature is 293 K and the pressure is 101.3 kPa.

# Solution



Figure 10-9. Material balance for Example 10-2.

2. At the minimum liquid flow rate, the gas mole fraction going into the absorber,  $Y_1$ , will be in equilibrium with the liquid mole fraction leaving the absorber (the liquid will be saturated with  $SO_2$ ). At equilibrium:

$\mathbf{Y}_1 = \boldsymbol{H}' \mathbf{X}_1$	$\mathbf{Y}_1 = \boldsymbol{H}' \mathbf{X}_1$
and Henry's law constant is	$\mathbf{X}_1 = \frac{\mathbf{Y}_1}{H'}$
H' = 42.7 mole fraction of SO <sub>2</sub> in air	0.03
$H = 42.7 \frac{1}{\text{mole fraction of SO}_2 \text{ in water}}$	$=\frac{1}{42.7}$
from Example 10-1.	= 0.000703

3. The minimum liquid-to-gas ratio is calculated by using Equation 10-15.

 Convert the exhaust stream flow rate, Q, to the exhaust gas molar flow rate, G<sub>m</sub> (from units of m<sup>3</sup>/min to units of g-mol/min). At 0°C and 101.3 kPa, there are 0.0224 m<sup>3</sup>/g-mol (for an ideal gas).

At 20°C:

0.0224 m<sup>3</sup>/g-mol 
$$\left(\frac{293}{273}\right) = 0.024$$
 m<sup>3</sup>/g-mol of air  $G_m = 89.4$  m<sup>3</sup>/min  $\left(\frac{1 \text{ g-mol}}{0.024 \text{ m}^3}\right)$ 

Therefore,

$$G_m = Q\left(\frac{1 \text{ g-mol of air}}{0.024 \text{ m}^3}\right)$$

5. Calculate the minimum liquid flow rate,  $L_m$ . The minimum liquid-to-gas ratio was calculated in step 3.

 $\frac{L_m}{G_m} = 38.4 \frac{\text{g-mol of water}}{\text{g-mol of air}}$ 

Therefore,

$$\mathbf{L}_{\mathbf{m}} = \mathbf{G}_{\mathbf{m}}(38.4)$$

$$L_{m} = \left(3538 \frac{\text{g-mol of air}}{\text{min}}\right) \left(38.4 \frac{\text{g-mol of water}}{\text{g-mol of air}}\right)$$
$$= 136,000 \frac{\text{g-mol of water}}{\text{min}}$$
$$= 136.0 \frac{\text{kg-mol of water}}{\text{min}}$$

Converting to mass units:

$$= \left(136.0 \ \frac{\text{kg-mol}}{\text{min}}\right) \left(\frac{18 \ \text{kg}}{\text{kg-mol}}\right)$$

= 3538 g-mol of air/min
6. Figure 10-10 illustrates the graphical solution for this problem. To obtain the actual operating line, multiply the slope of the minimum operating line by 1.5.



Figure 10-10. Graphical solution to Example 10-2.

Review Exercise	
<ol> <li>In absorption calculations, a(an) equates the gas and liquid concentrations coming into the absorber with the gas and liquid concentrations going out of the absorber.</li> <li>a. material balance</li> <li>b. energy balance</li> <li>c. transfer unit</li> </ol>	
2. In air pollution calculations, the mass of the pollutant is usually very <u>small/large</u> compared to the mass of exhaust gas being treated and the mass of the liquid used in the absorber.	l. a. material balance
<ul> <li>3. In the graph below, the line AB is the <ul> <li>a. equilibrium line.</li> <li>b. actual operating line.</li> <li>c. minimum operating line.</li> </ul> </li> <li>you be the set of the set</li></ul>	2. small
<ul> <li>4. The slope of the actual operating line is</li> <li>a. minimum liquid-to-gas ratio.</li> <li>b. G<sub>m</sub>/L<sub>m</sub> (actual).</li> <li>c. L<sub>m</sub>/G<sub>m</sub> (actual).</li> </ul>	3. c. minimum operating line.
	4. c. L <sub>m</sub> /G <sub>m</sub> (actual).

5. True or False? In the following figure, point B represents absorber conditions where the liquid leaving the absorber is saturated with the pollutant and can no longer absorb any additional pollutant, unless more liquid is added.



#### Sizing a Packed Tower

#### Packed Tower Diameter

The main parameter affecting the size of a packed column is the gas velocity at which liquid droplets become entrained in the exiting gas stream. Consider a packed column operating at set gas and liquid flow rates. By decreasing the diameter of the column, the gas flow rate (m/s or ft/sec) through the column will increase. If the gas flow rate through the column is gradually increased (by using smaller and smaller diameter columns), a point will be reached where the liquid flowing down over the packing begins to be held in the void spaces between the packing. This gas-to-liquid ratio is termed the *loading point*. The pressure drop of the column begins to increase and the degree of mixing between the phases decreases. A further increase in gas velocity will cause the liquid to completely fill the void spaces in the packing. The liquid forms a layer over the top of the packing and no more liquid can flow down through the tower. The pressure drop increases substantially, and mixing between the phases is minimal. This condition is referred to as *flooding*, and the gas velocity at which it occurs is the *flooding velocity*. Using an extremely large-diameter tower would eliminate this problem. However, as the diameter increases, the cost of the tower increases.

Normal practice is to size a packed column diameter to operate at a certain percent of the flooding velocity. A typical operating range for the gas velocity through the columns is 50 to 75% of the flooding velocity. It is assumed that, by operating in this range, the gas velocity will also be below the loading point.

A common and relatively simple procedure for estimating flooding velocity (thus, setting a minimum column diameter) is to use a generalized flooding and pressure drop correlation. One version of the flooding and pressure drop relationship in a packed tower is in the Sherwood correlation, shown in Figure 10-11 (Calvert et al. 1972). This correlation is based on the physical properties of the gas and liquid streams and tower packing characteristics. The procedure to determine the tower diameter is given below.





1. Calculate the value of the abscissa.

Where: L and G = mass flow rates: any consistent set of units may be used as long as the term is dimensionless

- $\varrho_s$  = density of the gas stream
- $\varrho_i$  = density of the absorbing liquid
- 2. From the point calculated in Equation 10-16, proceed up the graph to the flooding line and read the ordinate  $\epsilon$ .

3. Rearrange the equation of the ordinate and solve for G'.

(Eq. 10-17) 
$$G' = \left[\frac{(\epsilon)(\varrho_s)(\varrho_l)(g_c)}{F\phi\mu_l^{0.2}}\right]^{0.5}$$

Where: F = packing factor given in Table 10-5 for different types of packing (Bhatia 1977)

 $\phi$  = ratio of specific gravity of the scrubbing liquid to that of water  $\mu_t$  = viscosity of liquid

G' = mass flow rate of gas per unit cross-sectional area of column,g/s·m<sup>2</sup> (lb/sec·ft<sup>2</sup>)

 $\varrho_l$  = density of the absorbing liquid, kg/m<sup>3</sup> (lb/ft<sup>3</sup>)

- $\rho_{g}$  = density of the gas stream, kg/m<sup>3</sup> (lb/ft<sup>3</sup>)
- $g_c = \text{gravitational constant}, 9.82 \text{ m/s}^2 (32.2 \text{ ft/sec}^2)$
- 4. G' at operating conditions is a fraction of G' at flooding conditions.

(Eq. 10-18) 
$$G'_{operating} = (f)(G'_{flooding})$$

Where: f = the percent of flooding velocity, usually 50 to 75%

5. The cross-sectional area of column A is calculated from Equation 10-19.

(Eq. 10-19) 
$$A = \frac{G}{G'_{operating}}$$

6. The diameter of the column is obtained from Equation 10-20.

(Eq. 10-20) 
$$d_r = \left(\frac{4A}{\pi}\right)^{0.5} = 1.13 A^{0.5}$$

Table 10-5.	Packing	data.*
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Packing	Size (in.)	Weight (lb/ft <sup>2</sup> )	Surface area, a (ft <sup>2</sup> /ft <sup>2</sup> packing volume)	Void fraction (%)	Packing factor, F (ft²/ft³)	Price (\$/ft')
Raschig rings (ceramic and porcelain)	1/2 1 1 1/2 2 3	52 44 42 38 34	114 58 36 28 19	65 70 72 75 77	580 155 95 65 37	14.00°, 19.00° 7.00°, 9.30° 6.30°, 8.40° 6.20°, 8.30° 6.50°, 9.50°
Raschig rings (steel)	$\frac{1}{2} \times \frac{1}{32}$ 1 × 1/32 2 × 1/16	77 40 38	128 63 31	84 92 92	300 115 57	105.50 75.10 39.10
Berl saddles (ceramic and porcelain)	1/4 1/2 1 2	55 54 48 38	274 155 79 32	63 64 68 75	900 240 110 45	
Intalox saddles (ceramic)	1 1 2	54 45 44 42	300 190 78 36	75 78 77 79	725 200 98 40	28.35 10.85 —
Intalox saddl <del>es</del> (plastic)	1 2 3	6.00 3.75 3.25	63 33 27	91 93 94	30 20 15	- 7.65 -
Pall rings (plastic)	5/8 1 2	7.0 5.5 4.5	104 63 31	87 90 92	97 52 25	
Pall rings (metal)	5/8×0.018 thick 1½×0.03 thick	38 24	104 39	93 95	73 28	81.25° 33.23°
Tellerettes	1 2 3	7.5 3.9 5.0	55 38 30	87 93 92	40 20 15	12.50 7.30 5.25

\*Prices for ceramic packing. \*Prices for porcelain packing. \*Prices for 304 S.S. packing.

\*Note: Data for guide purposes only.

Source: Bhatia 1977.

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#### Example 10-3

This example illustrates the use of Figure 10-11 for computing the minimum allowable diameter for a packed tower. For the scrubber in Example 10-2, determine the column diameter if the operating liquid rate is 1.5 times the minimum. The gas velocity should be no greater than 75% of the flooding velocity, and the packing material is two-inch ceramic Intalox saddles.

#### Solution

1.	From Example 10-2, the gas molar flow rate in the absorber, $G_m$ , was 3538 g-mol/min and the minimum liquid flow rate, $L_m$ , was 2448 kg/min. The actual liquid flow rate in the absorber should be 1.5 times the minimum flow rate:	
	$\mathbf{L} = \mathbf{L}_m \times 1.5.$	$L = L_m \times 1.5$
	Assuming the molecular weight of the exhaust gas is 29 kg/mol, the gas molar flow rate in mass units would be:	=(2448 kg/min)(1.5) = 3672 kg/min
	$G = G_m \times (29 \text{ kg/kg-mol}).$	G=(3538 g-mol/min)(29 kg/kg-mol) =(3.538 kg-mol/min)(29 kg/kg-mol) = 102.6 kg/min
2.	Using Equation 10-16, calculate the abscissa for Figure 10-11.	
(	$\left(\frac{L}{G}\right)\left(\frac{\varrho_s}{\varrho_l}\right)^{0.5}$	Abscissa = $\left(\frac{3672}{102.6}\right) \left(\frac{1.17}{1000}\right)^{0.5}$
	The densities of air and water at 30 °C are: $ \varrho_g = 1.17 \text{ kg/m}^3 $ $ \varrho_i = 1000 \text{ kg/m}^3. $	= 1.22

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3. Using Figure 10-12, with the abscissa of 1.22, move up to the flooding line and read the value of  $\epsilon$  on the ordinate.  $\epsilon = 0.019$ 



Figure 10-12. Generalized flooding and pressure drop correlation for Example 10-3.

4. Use Equation 10-17 to calculate the superficial flooding velocity, G'. The superficial flooding velocity is the flow rate per unit of cross-sectional area of the tower.

$$G' = \left[\frac{(\epsilon)(\varrho_s)(\varrho_l)(g_c)}{F\phi\mu_l^{0.2}}\right]^{0.5}$$

$$G' = \left[\frac{(0.019)(1.17)(1000)(9.82)}{(131)(1)(0.0008)^{0.2}}\right]^{0.5}$$
For water:  $\phi = 1.0$   
 $\mu_l = 0.0008 \text{ Pa} \cdot \text{s}$ 
From Table 10-3, for two-inch Intalox saddles:  
 $F = 131 \text{ m}^2/\text{m}^3$   
 $g_c = 9.8 \text{ m/s}^2$ 

$$G' = \left[\frac{(0.019)(1.17)(1000)(9.82)}{(131)(1)(0.0008)^{0.2}}\right]^{0.5}$$

5. The superficial gas velocity at operating conditions is obtained by using Equation 10-18.

 $G'_{operating} = (f)(G'_{flooding})$ 

Use 75% of the flooding velocity for f.

6. Calculate the cross-sectional area of the packed tower by using Equation 10-19.

$$A = \frac{G}{G'_{operating}}$$

$$= 1.97 \text{ kg/m}^2 \cdot \text{s}$$

 $G'_{operating} = (0.75)(2.63)$ 

$$A = \frac{(102.6 \text{ kg/min})(1 \text{ min/60 sec})}{1.97 \text{ kg/m}^2 \cdot \text{s}}$$
$$= 0.87 \text{ m}^2$$

7. Calculate the tower diameter by using Equation 10-20.

$\mathbf{d}_{\mathrm{r}} = \left(\frac{4\mathrm{A}}{\pi}\right)^{0.5}$	$d_r = \left[\frac{4(0.87)}{3.14}\right]^{0.5}$
Where: $\pi = 3.14$	= 1.05 m
	≈1.1 m

8. Figure 10-11 may also be used to estimate the pressure drop across the absorber,  $\Delta p$ , once the superficial gas velocity for operating conditions has been set. First, plug G'operating back into Equation 10-17 and rearrange the equation to get the ordinate,  $\epsilon$ .

$$\epsilon = \frac{G'^2 \phi F \mu_i^{0.2}}{\varrho_s \varrho_i g_c}$$

The abscissa is equal to 1.22. Then, from Figure 10-11, read  $\Delta p$ .

$$\epsilon = \frac{(1.97)^2 (1) (131) (0.0008)^{0.2}}{(1.17) (1000) (9.82)}$$
  
= 0.0106

ordinate = 0.0106abscissa = 1.22

 $\Delta p = 0.416 \text{ m of water/m of packing}$ 

#### Packed Tower Height

The height of a packed column refers to the depth of packing material needed to accomplish the required removal efficiency. The more difficult the separation, the larger the packing height required. For example, a much larger packing height would be required to remove  $SO_2$ than to remove Cl from an exhaust stream using water as the absorbent. This is because Cl is more soluble in water than  $SO_2$ . Determining the proper height of packing is important since it affects both the rate and efficiency of absorption.

A number of theoretical equations are used to predict the required packing height. These equations are based on diffusion principles. Depending on which phase is controlling the absorption process, either Equation 10-5 or 10-6 is used as the starting point to derive an equation to predict column height. A material balance is then set up over a small differential section of the column.

The general form of the design equation for a gas-phase controlled resistance is given in Equation 10-21.

(Eq. 10-21) 
$$Z = \frac{G'}{K_{og} a P} \int_{Y_2}^{Y_1} \frac{dY}{(1-Y)(Y-Y^*)}$$

Where: Z = height of packing, m

G' = mass flow rate of gas per unit cross-sectional area of column,  $g/s \cdot m^2$   $K_{og} = overall mass-transfer coefficient based on the gas phase, <math>g \cdot mol/h \cdot m^2 \cdot Pa$   $a = interfacial contact area, m^2$ P = pressure of the system, kPa

In analyzing Equation 10-21, the term  $G'/K_{oG}aP$  has the dimension of meters and is defined as the *height of a transfer unit*. The term inside the integral is dimensionless and represents the *number of transfer units* needed to make up the total packing height. Using the concept of transfer units, Equation 10-21 can be simplified to:

 $(Eq. 10-22) Z = HTU \times NTU$ 

Where: HTU = height of a transfer unit, m NTU = number of transfer units.

The concept of a transfer unit comes from the assumptions used in deriving Equation 10-21. These assumptions are: (1) that the absorption process is carried out in a series of contacts, or stages, and (2) that the streams leaving these stages are in equilibrium with each other. These stages can be visualized as individual transfer units. The total tower height is equal to the number of transfer units times the height of each unit. Although a packed column operates as one continuous separation (differential contactor) process, in design terminology it is treated as discrete sections (transfer units). The number and the height of a transfer unit are based on either the gas or the liquid phase. Equation 10-22 now becomes:

(Eq. 10-23) 
$$Z = N_{oG} H_{oG} = N_{OL} H_{OL}$$

Where:  $N_{oG}$  = number of transfer units based on an overall gas-film coefficient  $N_{oL}$  = number of transfer units based on an overall liquid-film coefficient  $H_{oG}$  = height of a transfer unit based on an overall gas-film coefficient, m  $H_{oL}$  = height of a transfer unit based on an overall liquid-film coefficient, m. The number of transfer units, NTU, can be obtained experimentally or calculated from a variety of methods. For the case where the solute concentration is very low and the equilibrium line is straight, Equation 10-24 can be used to determine the number of transfer units  $(N_{oG})$  based on the gas-phase resistance. Equation 10-24 can be derived from the integral portion of Equation 10-21.

(Eq. 10-24) 
$$N_{og} = \frac{\ln\left[\left(\frac{Y_1 - mX_2}{Y_2 - mX_2}\right)\left(1 - \frac{mG_m}{L_m}\right) + \frac{mG_m}{L_m}\right]}{1 - \frac{mG_m}{L_m}}$$

Where: m = slope of equilibrium line  $G_m = molar flow rate of gas, kg-mol/h$   $L_m = molar flow rate of liquid, kg-mol/h$   $X_2 = mole fraction of solute entering the column$   $Y_1 = mole fraction of solute in entering gas$  $Y_2 = mole fraction of solute in exiting gas$ 

Equation 10-24 may be solved directly or graphically by using the Colburn diagram, which is presented in Figure 10-13. The Colburn diagram is a plot of the  $N_{0G}$  versus  $\ln[Y_1 - mX_2/Y_2 - mX_2]$  at various values of  $(mG_m/L_m)$ . The term  $(mG_m/L_m)$  is referred to as the *absorption factor*. Figure 10-13 is used by first computing the value of  $[Y_1 - mX_2/Y_2 - mX_2]$ , reading up the graph to the line corresponding to  $(mG_m/L_m)$ , and then reading across to obtain the  $N_{0G}$ .

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Equation 10-24 can be further simplified for situations where a chemical reaction occurs or if the solute is extremely soluble. In these cases, the solute exhibits almost no partial pressure; therefore, the slope of the equilibrium line approaches zero (m-0). For either of these cases, Equation 10-24 reduces to Equation 10-25.

(Eq. 10-25) 
$$N_{og} = \ln \frac{Y_1}{Y_2}$$

The number of transfer units depends only on the inlet and outlet concentration of the solute. For example, if the conditions of Equation 10-25 are met, achieving 90% removal of any pollutant requires 2.3 transfer units. Equation 10-25 applies only when the equilibrium line is straight and the slope approaches zero (for very soluble or reactive gases).



Figure 10-13. Colburn diagram.

Values for the height of a transfer unit used in designing absorption systems are usually obtained from experimental data. To ensure greatest accuracy, vendors of absorption equipment normally perform pilot plant studies to determine the HTU. For common absorption systems, such as NH<sub>3</sub> and water, manufacturers have developed graphs to use for estimating HTU. These graphs do not provide the accuracy of pilot plant data, but they are less expensive and easier to use. Figure 10-14 gives a typical example of these graphs for an ammonia and water system. In this figure, the superficial liquid flow rate is plotted versus the H<sub>oG</sub> with the superficial gas rate as a parameter. It is also common to plot gas rate versus the H<sub>oG</sub> and have the liquid rate as a parameter. Additional information on other gas-liquid systems can be found in *Chemical Engineers' Handbook* (Perry 1973). In applying these data, process conditions must be similar to conditions at which the HTU was measured.



Figure 10-14. Column packing comparison for ammonia and water system.

When no experimental data are available, or if only a preliminary estimate of absorber efficient is needed, generalized correlations are available to predict the height of a transfer unit. The correlations for predicting the  $H_{0G}$  or the  $H_{0L}$  are empirical in nature and are a function of:

- 1. type of packing,
- 2. liquid and gas flow rates,
- 3. concentration and solubility of the pollutant,
- 4. liquid properties, and
- 5. system temperature.

These correlations can be found in engineering texts such as *Chemical Engineers' Handbook* (Perry 1973), Wet Scrubber System Study, Volume I (Calvert et al. 1972), or Mass Transfer Operations (Treybal 1968). For most applications, the height of a transfer unit ranges between 0.3 and 1.2 m (1 to 4 ft) (Calvert 1977). As a rough estimate, 0.6 m (2.0 ft) can be used.

#### Example 10-4

From pilot plant studies of the absorption system in Example 10-2 it was determined that the  $H_{0G}$  for the SO<sub>2</sub>-water system is 0.829 m (2.72 ft). Calculate the total height of packing required to achieve 90% removal. The following data were taken from the previous examples.

$$m = 42.7 \frac{\text{kg-mol of water}}{\text{kg-mol of air}}$$
 Henry's law constant for the equilibrium diagram for SO<sub>2</sub>  
and water system (Example 10-1)

 $G_m = 3.5 \text{ kg-mol/min}$ 

$$L_{m} = 3672 \frac{\text{kg}}{\text{min}} \times \frac{\text{kg-mol}}{18 \text{ kg}}$$
$$= 204 \text{ kg-mol/min}$$
$$X_{z} = 0 \text{ (no recycle liquid)}$$
$$Y_{1} = 0.03$$
$$Y_{z} = 0.003$$

#### Solution

1. Calculate the number of transfer units,  $N_{og}$ , by using Equation 10-24.

$$N_{oG} = \frac{\ln\left[\left(\frac{Y_1 - mX_2}{Y_2 - mX_2}\right)\left(1 - \frac{mG_m}{L_m}\right) + \frac{mG_m}{L_m}\right]}{1 - \frac{mG_m}{L_m}} \qquad N_{oG} = \frac{\ln\left[\left(\frac{0.03}{0.003}\right)\left(1 - \frac{(42.7)(3.5)}{204}\right) + \frac{(42.7)(3.5)}{204}\right]}{1 - \frac{(42.7)(3.5)}{204}} = 5.04$$

2. The total packing height can be calculated using Equation 10-23.

$Z = H_{og} \times N_{og}$	
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Z = (0.829)(5.04)= 4.18 m of packing height

	Review Exercise	
1.	In designing a packed tower, the normal practice is to make the tower diameter so that the unit will operate at of the flooding velocity rate. a. 50 to 75% b. 100% c. 150%	
2.	True or False? The Sherwood correlation can be used to calculate the tower diameter of a packed tower, if the minimum liquid rate, $L_m$ , and the gas flow rate, G, through the absorber are known.	1. a. 50 to 75%
3.	In estimating packing height in a packed tower, the pack- ing sections are broken up into discrete sections called a. transfer units. b. gas-film coefficients. c. liquid-film coefficients.	2. True
4.	The packing height, Z, can be estimated from $Z = HTU \times NTU$ What are the terms HTU and NTU?	3. a. transfer units.
5.	True or False? The Colburn diagram can be used to estimate the number of transfer units based on an overall gas-film coefficient, $N_{OG}$ , if the absorption factor, $mG_m/L_m$ , the inlet and outlet pollutant concentrations, and the liquid recycle concentrations are known.	4. HTU = height of a transfer unit NTU = number of transfer units
6.	The height of a transfer unit is a function of a. type of packing. b. liquid and gas flow rates. c. pollutant concentration and solubility. d. liquid properties and system temperature. e. all of the above	5. True (by using Figure 10-13)
7.	For most packed tower applications, the height of a trans- fer unit can be estimated to be a. 3 to 4.6 m (10 to 15 ft). b. 0.3 to 1.2 m (1 to 4 ft). c. 1.82 to 3 m (6 to 10 ft).	6. e. all of the above
		7. b. 0.3 to 1.2 m (1 to 4 ft).

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#### Sizing a Plate Tower

Another scrubber used extensively for gas absorption is a plate tower. Here, absorption occurs on each plate, or stage. These are commonly referred to as discrete stages, or steps. The following discussion presents a simplified method for sizing or reviewing the design plans of a plate tower. The method for determining the liquid flow rate in the plate tower is the same as previously discussed. Methods for estimating the diameter of a plate tower and the theoretical number of plates follow.

#### Plate Tower Diameter

The minimum diameter of a single-pass plate tower is determined by using the gas velocity through the tower. If the gas velocity is too fast, liquid droplets are entrained, causing a condition known as *priming*. Priming occurs when the gas velocity through the tower is so fast that it causes liquid on one tray to foam and then rise to the tray above. Priming reduces absorber efficiency by inhibiting gas and liquid contact. For the purpose of determining tower diameter, priming in a plate tower is analogous to the flooding point in a packed tower. It determines the **minimum acceptable** diameter. The **actual** diameter should be larger.

The smallest allowable diameter for a plate tower is expressed in Equation 10-26.

(Eq. 10-26) 
$$d_r = \psi(Q\sqrt{\varrho_s})^{0.5}$$

Where:  $Q = volumetric gas flow, m^3/h$  $\psi = empirical correlation, m^{0.25} h^{0.5}/kg^{0.25}$  $\varrho_g = gas density, kg/m^3$ 

The term  $\psi$  is an empirical correlation and is a function of both the tray spacing and the densities of the gas and liquid streams. Values for  $\psi$  in Table 10-6 are for a tray spacing of 61 cm (24 in.) and a liquid specific gravity of 1.05 (Calvert et al. 1972). If the specific gravity of a liquid varies significantly from 1.05, the values for  $\psi$  in Table 10-6 cannot be used.

Tray	Metric $\psi^*$	English $\psi^{\flat}$
Bubble cap	0.0162	0.1386
Sieve	0.0140	0.1198
Valve	0.0125	0.1069

Table 10-6. Empirical constants for Equation 10-26.

"Metric  $\psi$  is expressed in m<sup>0.25</sup> h<sup>0.5</sup>/kg<sup>0.25</sup>, for use with Q expressed in m<sup>3</sup>/h, and  $Q_s$ expressed in kg/m<sup>3</sup>.

<sup>b</sup>English  $\psi$  is expressed in ft<sup>0.25</sup>min<sup>0.5</sup>/lb<sup>0.25</sup>, for use with Q in cfm, and  $\varrho_z$  expressed in lb/ft<sup>3</sup>.

Source: Calvert et al. 1972.

Depending on operating conditions, trays are spaced with a minimum distance between plates to allow the gas and liquid phases to separate before reaching the plate above. Trays should be spaced to allow for easy maintenance and cleaning. Trays are normally spaced 45 to 70 cm (18 to 28 in.) apart. In using Table 10-6 for a tray spacing different from 61 cm, a correction factor must be used. Figure 10-15 is used to determine the correction factor, which is multiplied by the estimated diameter. Example 10-5 illustrates how to estimate the minimum diameter of a plate tower.



Source: Calvert et al. 1972.

Figure 10-15. Tray spacing correction factor.

#### Example 10-5

For the conditions described in Example 10-2, determine the minimum acceptable diameter if the scrubber is a bubble-cap tray tower. The trays are spaced 0.53 m (21 in.) apart.

#### Solution

1. From Example 10-2 the following information is obtained:	
Gas flow rate, $Q = 84.9 \text{ m}^3/\text{min}$ Gas density, $\varrho_s = 1.17 \text{ kg/m}^3$ .	
Convert the gas flow rate, Q, to units of $m^3/h$ .	$Q = (84.9 \text{ m}^3/\text{min})(60 \text{ min/hr})$ = 5094 m <sup>3</sup> /h

2. From Table 10-6, the empirical constant  $\psi = 0.0162 \text{ m}^{0.25} \text{ h}^{0.5}/\text{kg}^{0.25}$ . The minimum diameter, d<sub>i</sub>, of the plate tower can be estimated by using Equation 10-26.

$$\mathbf{d}_r = \psi(\mathbf{Q}\sqrt{\varrho_s})^{\mathbf{0}\cdot\mathbf{1}}$$

- 3. The tray spacing for each tray is 0.53 m. Since Table 10-6 values are for a tray of 0.61 m, correct the diameter using Figure 10-16.
- $d_r = (0.0162) [5094(\sqrt{1.17})]^{0.5}$ = 1.2 m

Read a correction factor of 1.05.



Figure 10-16. Tray spacing correction factor for Example 10-5.

4. Adjust the minimum plate tower diameter value by using the correction factor.

Adjusted  $d_r = d_r$  (from step 2) × correction factor

 $d_r = 1.2 m (1.05)$ = 1.26 m

Note: The value of 1.26 m is the minimum estimated tower diameter based on priming conditions. In practice, a larger diameter based on economic conditions is usually chosen.

#### Number of Theoretical Plates

Several methods are used to determine the number of ideal plates, or trays, required for a given removal efficiency. These methods, however, can become quite complicated. One method used is a graphical technique. The number of ideal plates is obtained by drawing "steps" on an operating diagram. This procedure is illustrated in Figure 10-17. This method can be rather time consuming, and inaccuracies can result at both ends of the graph.

 $\mathcal{M}_{\mathcal{C}}$ 



Figure 10-17. Graphic determination of the number of theoretical plates.

Equation 10-27 is a simplified method used to estimate the number of plates. This equation can only be used if both the equilibrium and operating lines for the system are straight. This is a valid assumption for most air pollution control systems. This equation, taken from Sherwood and Pigford (1952), is derived in the same manner as Equation 10-24 for computing the  $N_{0G}$  of a packed tower. The difference is that Equation 10-27 is based on a stepwise solution instead of a continuous contactor, as is the packed tower. (Note: This derivation is referred to as the height equivalent to a theoretical plate, or HETP instead of HTU.)

(Eq. 10-27) 
$$N_{p} = \frac{\ln\left[\left(\frac{Y_{1} - mX_{2}}{Y_{2} - mX_{2}}\right)\left(1 - \frac{mG_{m}}{L_{m}}\right) + \frac{mG_{m}}{L_{m}}\right]}{\ln\left(\frac{L_{m}}{mG_{m}}\right)}$$

This equation is used to predict the number of *theoretical* plates required to achieve a given removal efficiency. The operating conditions for a theoretical plate assume that the gas and liquid streams leaving the plate are in equilibrium with each other. This ideal condition is never achieved in practice. A larger number of actual trays are required to compensate for this decreased tray efficiency.

Three types of efficiency are used to describe absorption efficiency for a plate tower:

- 1. an overall efficiency, which is concerned with the entire column,
- 2. Murphree efficiency, which is applicable with a single plate, and
- 3. local efficiency, which pertains to a specific location on a plate.

A number of methods are available to predict these plate efficiencies. These methods are complex, and values predicted by two different methods for a given system can vary by as much as 80% (Zenz 1972).

The simplest of tray efficiency concepts, the overall efficiency, is the ratio of the number of theoretical plates to the number of actual plates. Since overall tray efficiency is an oversimplification of the process, reliable values are difficult to obtain. For a rough estimate, overall tray efficiencies for absorbers operating with low-viscosity liquid normally fall in a 65 to 80% range (Zenz 1972).

#### Example 10-6

Calculate the number of theoretical plates required for the scrubber in Example 10-5 using the same conditions as those in Example 10-4. Estimate the total height of the column if the trays are spaced at 0.53-m intervals, and assume an overall tray efficiency of 70%.

#### Solution

- 1. From Example 10-5 and the previous examples, the following data are obtained:
  - m = 42.7  $Y_1 = 0.03$   $Y_2 = 0.003$   $X_2 = 0.0$   $L_m = 204 \text{ kg-mol/min}$  $G_m = 3.5 \text{ kg-mol/min}.$

The number of theoretical plates is estimated by using Equation 10-26.

$$N_{p} = \frac{\ln\left[\left(\frac{Y_{1} - mX_{2}}{Y_{2} - mX_{2}}\right)\left(1 - \frac{mG_{m}}{L_{m}}\right) + \frac{mG_{m}}{L_{m}}\right]}{\ln\left(\frac{L_{m}}{mG_{m}}\right)} \qquad N_{p} = \frac{\ln\left[\left(\frac{0.03 - 0}{0.003 - 0}\right)\left(1 - \frac{(42.7)(3.5)}{204}\right) + \frac{(42.7)(3.5)}{204}\right)}{\ln\left(\frac{204}{(42.7)(3.5)}\right)} = 3.94 \text{ theoretical plates}$$

2. Assuming that the overall efficiency of each plate is 70%, estimate the actual number of plates.

	Actual plates = $\frac{\text{estimated plates}}{70\%}$	Actual plates = $\frac{3.94}{0.70}$	
		= 5.6 or 6 plates (since you can't have a fraction of a plate)	
3.	Estimate the height of the tower by using $Z = N_p \times \text{tray spacing} + \text{top height of tower}$ . The top height of the tower is the distance that allows the gas-vapor mixture to separate. This distance is usually the same distance as the tray spacing.	Z = 6 plates $(0.53 m) + 0.53 m= 3.18 + 0.53= 3.71 m$	
	Note: This height is approximately the same as that predicted for the packed tower in Example 10-4. This seems logical since both packed and plate towers are efficient gas-absorption devices. However, due to the many assumptions, no concrete generalization can be made.		

# **Review Exercise**

1.	In a plate tower, if the gas velocity through the tower is too fast, liquid droplets become entrained in the gas stream, causing a condition called a. pumping. b. streaking. c. priming.	
2.	True or False? For the purpose of determining a plate- tower diameter, priming in a plate tower is the same as the flooding point in a packed tower.	1. c. priming.
		2. True

3. In a plate tower, the following equation	
$N_{p} = \frac{\ln\left[\left(\frac{Y_{1} - mX_{2}}{Y_{2} - mX_{2}}\right)\left(1 - \frac{mG_{m}}{L_{m}}\right) + \frac{mG_{m}}{L_{m}}\right]}{\ln\left(\frac{L_{m}}{mG_{m}}\right)}$	
<ul> <li>is used to calculate the</li> <li>a. number of transfer units based on an overall gas-film coefficient.</li> <li>b. number of transfer units based on Henry's law constant.</li> <li>c. number of theoretical plates.</li> </ul>	
<ul> <li>4. In plate towers, the efficiency of each plate, or tray, is usually</li> <li>a. 20 to 30%.</li> <li>b. 65 to 80%.</li> <li>c. 90 to 100%.</li> </ul>	3. c. number of theoretical plates.
	4. b. 65 to 80%.

## Review of Design Criteria for Permits

The principal design criteria are the exhaust flow to the absorber, measured in units of  $m^3/min$  (ft<sup>3</sup>/min, or acfm), and the gaseous pollutant concentration, measured in units of ppm. The exhaust volume and pollutant concentration are set by the process exhaust conditions. Once these criteria are known, the vendor can begin to design the absorber for the specific application. A thorough review of the design plans should consider the factors presented below.

Exhaust gas characteristics – average and maximum exhaust flow rates to the absorber, and chemical properties such as dew point, corrosiveness, pH, and solubility of the pollutant to be removed should be measured or accurately estimated.

Liquid flow—the type of scrubbing liquid and the rate at which the liquid is supplied to the absorber. If the scrubbing liquid is to be recirculated, the pH and amount of suspended solids (if any) should be monitored to ensure continuous reliability of the absorbing system. Pressure drop—the pressure drop (gas-side) at which the absorber will operate; the absorber design should also include a means for monitoring the pressure drop across the system, usually by manometers.

pH-the pH at which the absorber will operate; the pH of the absorber should be monitored so that the acidity or alkalinity of the absorbing liquor can be properly adjusted. **Removal of entrained liquid**-mists and liquid droplets that become entrained in the "scrubbed" exhaust stream should be removed before exiting the stack. Some type of entrainment separator, or mist eliminator, should be included in the design. Emission requirements—collection efficiency in terms of parts per million (ppm) to meet the air pollution regulations; collection efficiency can be high (90 to 99%) if the absorber is properly designed. The agency review engineer can use the equations listed in this lesson to estimate the absorber removal efficiency, liquid flow rate, tower diameter, and packing height. However, these equations can only estimate these values, and they should not be used as the basis to either accept or reject the design plans submitted for the permit process.

### Summary

For gas absorption, the two devices most often used are the packed tower and the plate tower. Both of these devices, if designed and operated properly, can achieve high collection efficiencies for a wide variety of gases. Other scrubbing systems can be used for absorption, but are limited to cases where the gases are highly soluble. For example, spray towers, venturis, and cyclonic scrubbers are designed assuming the performance is equivalent to one single equilibrium stage (i.e.,  $N_{oG} = 1$ ) (Perry 1973).

The equations and procedures used in designing packed and plate towers are very similar. Both are based on solubility, the mass-transfer model, and the geometry of the tower. The main difference is that the equations for a plate tower are based on a stepwise process, whereas those for a packed tower are based on a continuous-contacting process. Care must be taken when applying any of the equations presented in this lesson (or in other texts). Some of the equations are empirical and are applicable only under a similar set of conditions. Used correctly, these procedures can be a useful tool in checking absorber designs or in determining the effect of a process change on absorber operation.

When checking the design plans for the permit process, the agency engineer should check its files or another agency's files for similar applications for absorber installations. A review of these data will help determine if the absorber design specifications submitted by the industrial source's officials are adequate to achieve pollutant removal efficiency for compliance with the regulations. The agency engineer should require the source owner/operator to conduct stack tests (once the source is operating) to determine if the source is in compliance with local, State, and Federal regulations. The agency engineer should also require that the source owner/operator submit an operation and maintenance schedule that will help keep the scrubber system on line.

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a. DESCRIPTORS		ULDENTIFIERS/OPEN ENDED TERMS	COALL LIGATE LIGATOR	
Air Pollution Control Equipment Wet Scrubbers Particulate Emission Control Gaseous Emission Control Self-training Manual		Self-instructional Guidebook for Wet Scrubber Plan Review		
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