Lesson 6

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

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

At the end of this lesson, you will be able to do the following:

1. List four combination contacting scrubbers
2. Describe the operation of four combination contacting scrubbers
3. For each scrubber above, identify the range of operating values for pressure drop, liquid-to-gas ratio, as well as the collection efficiency for both particles and gaseous pollutants
4. Describe 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 four scrubbing systems that incorporate features of both liquid-phase and gas-phase contacting wet collectors:

- Cyclonic spray
- Mobile bed
- Baffle spray
- Mechanically aided scrubbers

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.

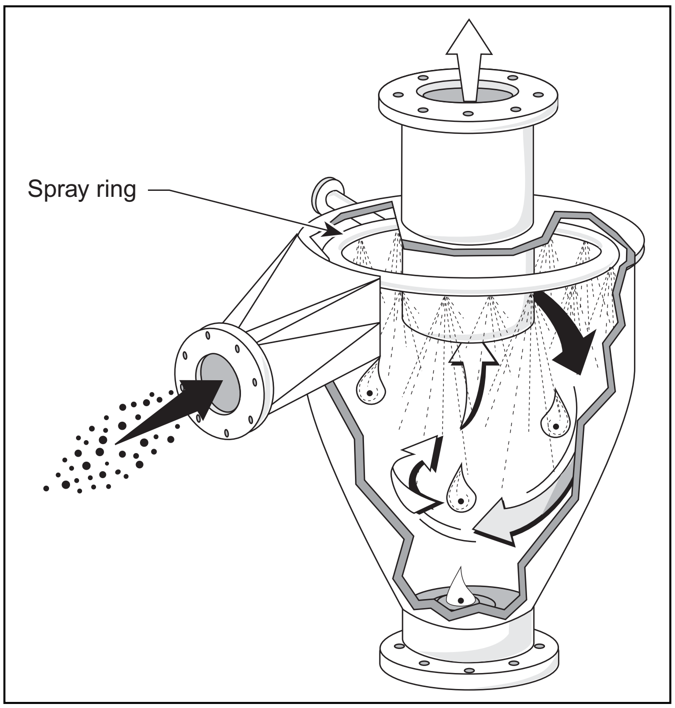

Figure 6-1. Irrigated cyclone scrubber

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.

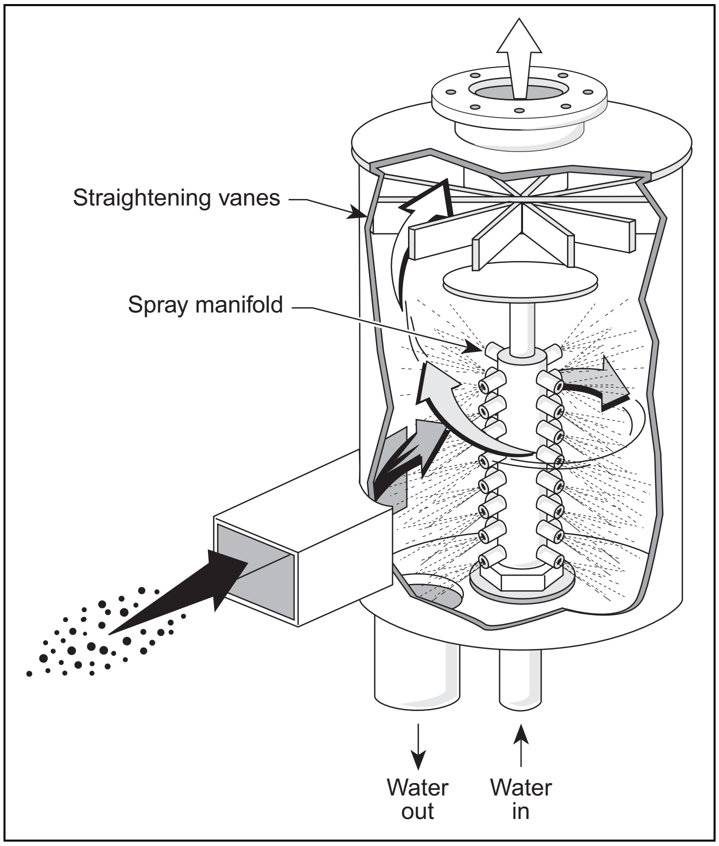

Figure 6-2. Cyclonic spray scrubber

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 μm are generally collected by impaction with 90% efficiency. 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, the cyclonic scrubber increases exhaust gas velocities (thus, particle velocities) 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 higher 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. Abrasion-resistant materials may be used to protect the cyclone body, especially at the inlet.

Summary

The pressure drops across cyclonic scrubbers are usually 4 to 25 cm (1.5 to 10 in.) of water; therefore, they are low- to medium-energy devices and are most often used to control large-sized 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. The liquid droplets are forced to the sides of the cyclone and removed prior to exiting the vessel. Their biggest disadvantages are that they are not capable of removing submicrometer particles and they do not efficiently absorb most pollutant gases. Table 6-1 lists typical operating characteristics of cyclonic scrubbers.

Table 6-1. Operating characteristics of cyclonic scrubbers

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

To test your knowledge of the preceding section, answer the questions in Part 1 of the Review Exercise.

Mobile-Bed Scrubbers

Mobile-bed, also called **moving-bed**, scrubbers use energy from both liquid sprays and the gas stream to provide contact. Mobile-bed scrubbers are similar to packed towers. However, 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.

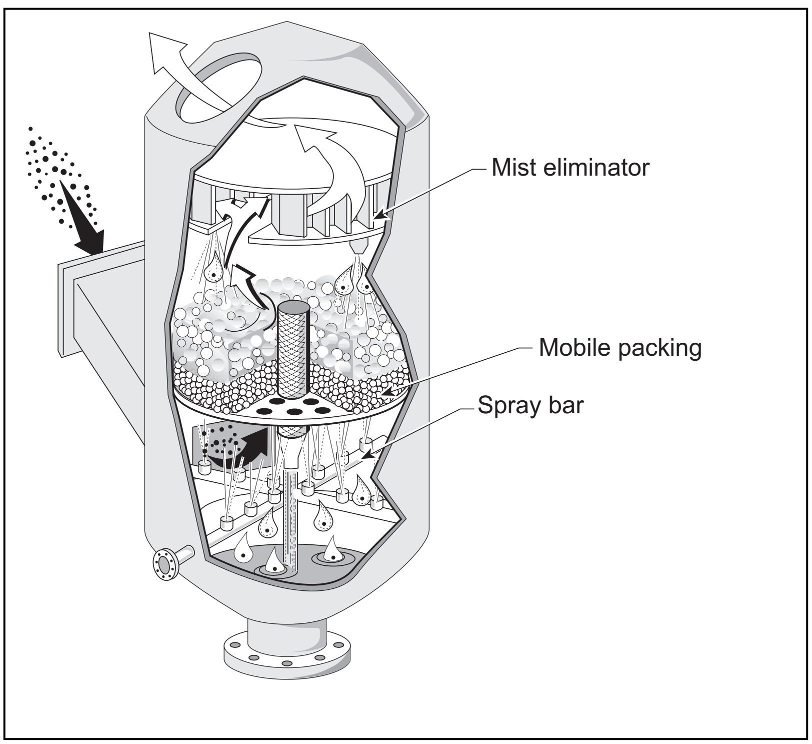

Figure 6-3. Flooded-bed scrubber

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, except for 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 high enough to keep 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)**.

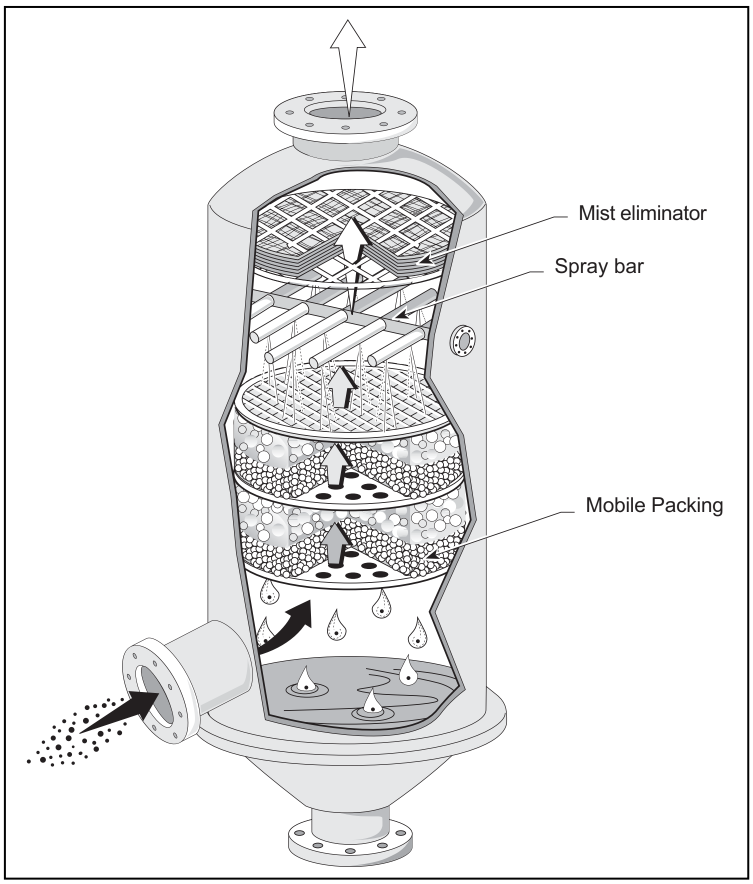

Figure 6-4. Fluidized-bed scrubber

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, layers above the bed. These devices will generally remove particles as small as 2 to 3 μm in diameter and have been used extensively when the exhaust stream does not contain a substantial amount of particles in the submicrometer 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-pollutant 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 packed and 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: 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 raises 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 a 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_2 from boiler flue gas exhausts. Using a lime or limestone slurry, the liquid-injection rates are approximately 8 L/m^3 (60 gal/1000 ft^3) of flue gas. This is compared to 0.4 L/m^3 (3.0 gal/1000 ft^3) 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 submicrometer 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.

Table 6-2. Operating characteristics of mobile-bed scrubbers

<table>
<tr><th>Pollutant</th><th>Pressure drop (Δp)</th><th>Liquid-to-gas ratio (L/G)</th><th>Liquid-inlet pressure (p_L)</th><th>Removal efficiency</th><th>Applications</th></tr>
<tr><td>Gases</td><td rowspan="2">5-15 cm of water per stage
(2-6 in. of water per stage)</td><td>2.7-8.0 L/m^3
(20-60 gal/1000 ft^3)</td><td rowspan="2">–</td><td>99$^+$% of theoretical</td><td rowspan="2">Mining operations
Pulp mills
Utility boilers
Food industry</td></tr>
<tr><td>Particles</td><td>0.4-0.7 L/m^3
(3-5 gal/1000 ft^3)</td><td>2-3 µm diameter</td></tr>
</table>

To test your knowledge of the preceding section, answer the questions in Part 2 of the Review Exercise.

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.

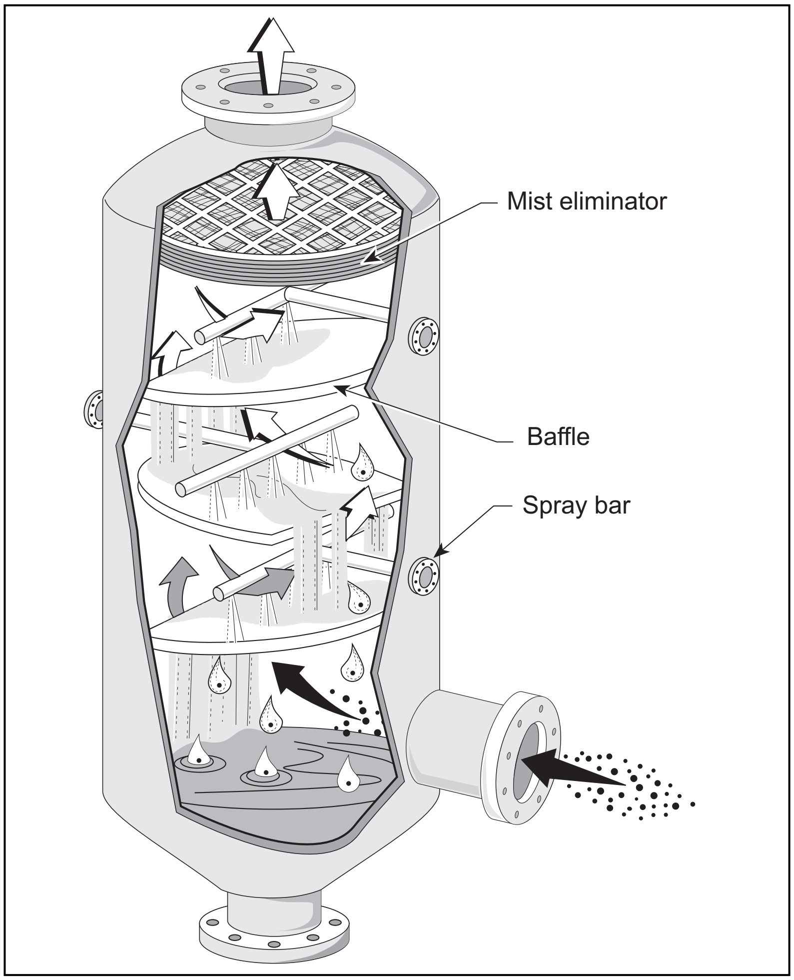

Figure 6-5. Baffle spray scrubber

Particle Collection

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

Gas Collection

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

Summary

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

Table 6-3. Operating characteristics of baffle spray scrubbers

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p_L)	Removal efficiency	Applications
Gases	2.5-7.5 cm of water (1-3 in. of water)	0.13 L/m^3 (1 gal/1000 ft^3)	< 100 kPa (< 15 psig)	Very low	Mining operations Incineration
Particles				10 μm diameter	Chemical process industries

Mechanically Aided Scrubbers

In addition to using liquid sprays or the exhaust stream, scrubbing systems can use motors to supply energy. The motor drives a rotor or paddles which, in turn, generate water droplets for gas and particle collection. Systems designed in this manner have the advantage of requiring less space than other scrubbers, but their overall power requirements tend to be higher than other scrubbers of equivalent efficiency. Significant power losses occur in driving the rotor. Therefore, not all the power used is expended for gas-liquid contact.

There are fewer mechanically aided scrubber designs available than 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 collected particles off the blades. The liquid droplets separate from the gas stream because of their centrifugal motion.

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

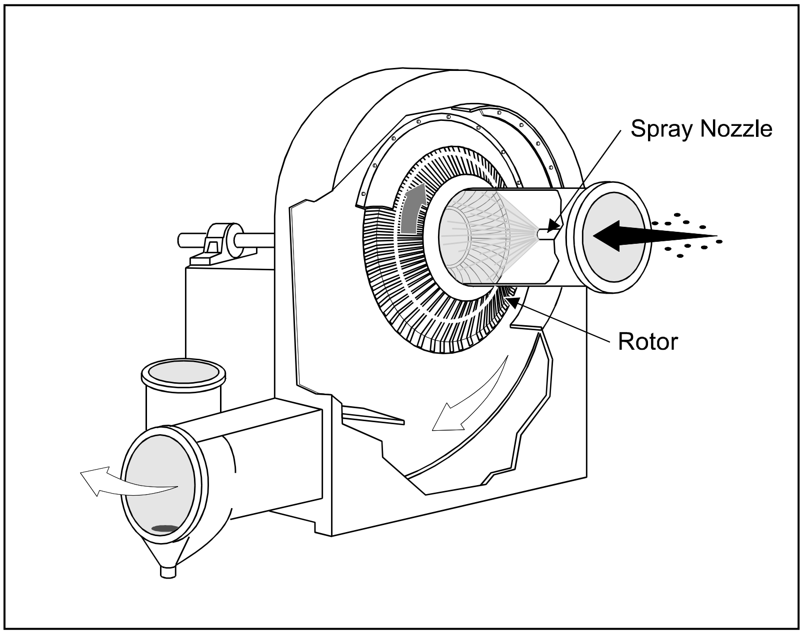

Figure 6-6. Centrifugal-fan scrubber

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.

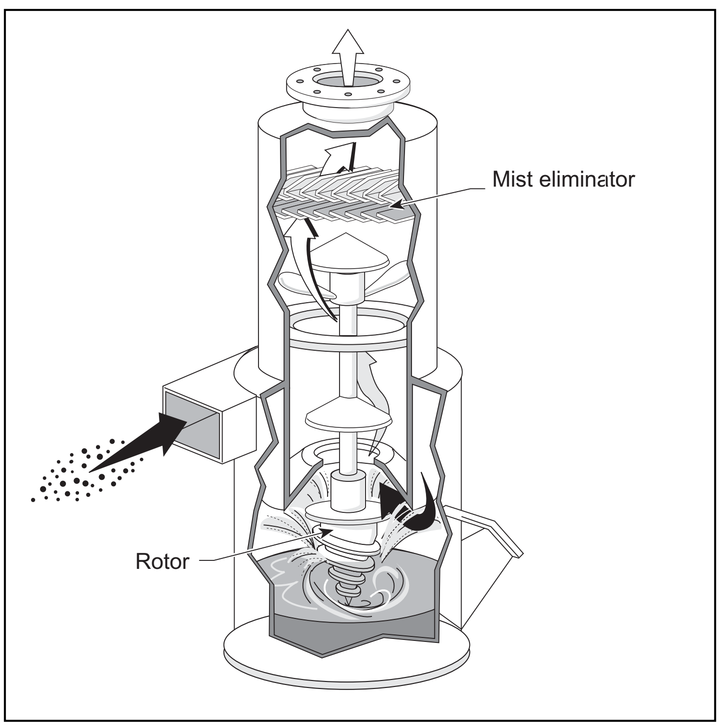

Figure 6-7. Mechanically induced spray scrubber

Particle Collection

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

Gas Collection

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

Maintenance Problems

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

Summary

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

Table 6-4. Operating characteristics of mechanically aided scrubbers

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

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

To test your knowledge of the preceding section, answer the questions in Part 3 of the Review Exercise.

Review Exercise

Part 1

1. Cyclonic scrubbers are ____________________ energy devices.
   a. High
   b. Low- to medium-
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
3. Cyclonic spray scrubbers are more efficient than ____________________, but not as efficient as ____________________, in removing particles.
   a. Spray towers, venturi scrubbers
   b. Venturi scrubbers, spray towers
4. True or False? Cyclonic scrubbers are not often used to control gaseous emissions.
5. List two main maintenance problems associated with cyclonic scrubbers.
   ____
   ____
6. What are cyclonic scrubbers used most often to control?
   a. Micrometer-sized particles
   b. Large-sized particles
   c. Gaseous emissions
   d. Particles and gases simultaneously

Part 2

7. Mobile-bed, or moving-bed, scrubbers were developed to provide the effective mass-transfer characteristics of ____________________ or ____________________ towers without the plugging problems.
   a. Spray (or) venturi
   b. Packed (or) plate
   c. Cyclonic (or) orifice
   d. Ejector (or) spray
8. In mobile-bed scrubbers, the moving packing is made of:
   a. Glass
   b. Plastic
   c. Marble
   d. Any of the above

9. In mobile-bed scrubbers, particles are collected:

   a. By using inlet sprays
   b. As they impinge on the wetted surface of the spheres
   c. In a froth, or foam, layer above the bed
   d. All of the above

10. True or False? In mobile-bed scrubbers, adding stages or more packing will usually increase particle collection efficiency.

11. In mobile-bed scrubbers, gas velocities are much ____________________ than in packed towers or plate towers; therefore, mobile-bed scrubbers can be much ____________________ in size.

   a. Lower, smaller
   b. Lower, larger
   c. Higher, smaller
   d. Higher, larger

12. Mobile-bed scrubbers provide the gas absorption efficiency of packed or plate towers; however, they consume ____________________ energy for the same unit operation.

   a. More
   b. Less
   c. The same

13. Gas absorption in mobile-bed scrubbers can be enhanced by:

   a. Increasing the L/G ratio
   b. Adding more packing height
   c. Adding stages
   d. All of the above

14. When used for gas absorption, mobile-bed scrubbers operate at ____________________ L/G ratios than when used for particle collection.

   a. Much higher
   b. Much lower
   c. The same

15. 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

16. The biggest maintenance problem with mobile-bed scrubbers is ball deterioration due to:
    a. Abrasive wear
    b. High temperatures
    c. Both high temperatures and abrasive wear
    d. None of the above

17. True or False? A major limitation of mobile-bed scrubbers is that they are not effective in removing submicrometer-sized particles.

Part 3

18. 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

19. Spray towers and baffle spray towers are generally not effective in removing particles smaller than:
    a. 10 µm
    b. 50 µm
    c. 100 µm
    d. Any of the above

20. Mechanically aided scrubbers use a rotor to generate water droplets. These devices usually require less ____________________ than other scrubbers, but have ____________________ that tend to be higher.
    a. Liquid, gas flows
    b. Space, power requirements
    c. Power, liquid requirements

21. True or False? Mechanically aided scrubbers can serve as both an air mover and a collection device.

22. In mechanically aided scrubbers, the majority of particle collection occurs:
    a. In liquid droplets formed by the rotating blades
    b. On the wetted blades
    c. At the inlet sprays

23. True or False? Mechanically aided scrubbers are generally not used for gas absorption, since several other designs provide better removal.

24. True or False? Mechanically aided scrubbers operate at lower liquid-to-gas ratios than most other scrubbers.

Review Exercise Answers

Part 1

1. **b. Low- to medium-**
Cyclonic scrubbers are low- to medium-energy devices with pressure drops ranging from 2 to 10 inches of water.

2. **b. As they impact the liquid droplets**
In a cyclonic spray scrubber, particles are primarily collected as they impact the liquid droplets.

3. **a. Spray towers, venturi scrubbers**
Cyclonic spray scrubbers are more efficient than spray towers but not as efficient as venturi scrubbers in removing particles.

4. **True**
Cyclonic scrubbers are not often used to control gaseous emissions due to limited liquid-to-gas contact.

5. **Nozzle plugging**
Corrosion or erosion of the side walls in the chamber
Two main maintenance problems associated with cyclonic scrubbers are nozzle plugging and corrosion or erosion of the side walls in the chamber.

6. **b. Large-sized particles**
Cyclonic scrubbers are used most often to control large-sized particles.

Part 2

7. **b. Packed (or) plate**
Mobile-bed, or moving-bed, scrubbers were developed to provide the effective mass-transfer characteristics of packed or plate towers without the plugging problems.

8. **d. Any of the above**
In mobile-bed scrubbers, the moving packing can be made of:
    - Glass
    - Plastic
    - Marble

9. **d. All of the above**
In mobile-bed scrubbers, particles are collected:
    - By using inlet sprays
    - As they impinge on the wetted surface of the spheres
    - In a froth, or foam, layer above the bed

10. **False**
In mobile-bed scrubbers, adding stages or more packing will usually NOT increase particle collection efficiency. Particle collection is based on particle size. Once a given size range is removed, you need to change the mechanism, not just do more of the same.

11. **c. Higher, smaller**
In mobile-bed scrubbers, gas velocities are much higher than in packed towers or plate towers; therefore, mobile-bed scrubbers can be much smaller in size.

12. **a. More**
Mobile-bed scrubbers provide the gas absorption efficiency of packed or plate towers; however, they consume more energy for the same unit operation.

13. **d. All of the above**
Gas absorption in mobile-bed scrubbers can be enhanced by the following:

- Increasing the L/G ratio
- Adding more packing height
- Adding stages

14. **a. Much higher**
When used for gas absorption, mobile-bed scrubbers operate at much higher L/G ratios than when used for particle collection. The added liquid increases the potential solubility of the gases.

15. **b. Uneven gas flow distribution through the bed**
Scale buildup or plugging at the mobile-bed scrubber inlet can cause uneven gas flow distribution through the bed that leads to a decrease in efficiency.

16. **c. Both high temperatures and abrasive wear**
The biggest maintenance problem with mobile-bed scrubbers is ball deterioration due to both high temperatures and abrasive wear.

17. **True**
A major limitation of mobile-bed scrubbers is that they are not effective in removing submicrometer-sized particles.

Part 3

18. **b. Pressure drop**
Adding baffles in a spray tower will generally help increase the particle removal efficiency, but also increases the pressure drop.

19. **a. 10 μm**
Spray towers and baffle spray towers are generally not effective in removing particles smaller than 10 μm.

20. **b. Space, power requirements**
Mechanically aided scrubbers use a rotor to generate water droplets. These devices usually require less space than other scrubbers, but have power requirements that tend to be higher.

21. **True**
Mechanically aided scrubbers can serve as both an air mover and a collection device.

22. **a. In liquid droplets formed by the rotating blades**
In mechanically aided scrubbers, the majority of particle collection occurs in liquid droplets formed by the rotating blades.

23. **True**
    Mechanically aided scrubbers are generally not used for gas absorption, since several other designs provide better removal.

24. **True**
    Mechanically aided scrubbers operate at lower liquid-to-gas ratios than most other scrubbers.

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