

## Wet Scrubbers for Mechanically Ventilated Animal Facilities

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This publication provides an overview of wet scrubbers and their use to treat exhaust air from mechanically ventilated livestock and poultry facilities.

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**A**nimal feeding operations (AFO) emit gases and particulate matter (PM). The gases and PM emissions can negatively impact the environment and human and animal health locally, regionally, and globally. Some gases are odorous; some, including ammonia (NH<sub>3</sub>) and hydrogen sulfide (H<sub>2</sub>S), can be hazardous; others like carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) are greenhouse gases. Some gases react with other chemicals in the atmosphere to produce fine particulates that contribute to respiratory distress, haze, and impaired visibility.

Many AFOs use mechanically ventilated buildings to house animals safely, comfortably, and economically. Many mechanically ventilated AFO buildings have exhaust fans that create a negative pressure in the building, which draws fresh outdoor air in through planned inlets to replace the exhausted air. The air being exhausted contains gases and PM.

Wet scrubbers can be used to reduce gas and PM emissions from exhaust air of mechanically ventilated animal facilities and manure storage units. Scrubbers can be installed directly to the exhaust fan outlet so that air leaving the building flows through the scrubber, where gases and PM are trapped by the scrubber.

Wet scrubbers use a liquid, usually water-based, to remove gases and PM by absorbing them onto wet surfaces or into liquid droplets or films. The liquid with the captured gases and PM needs to be handled properly to avoid polluting water, soil, and air. Well-designed and managed wet scrubbers can be very effective. Scrubbers can remove 50-99 percent of volatile organic compounds (VOC) and PM in air, and 90-99 percent of oxides of nitrogen (NO<sub>x</sub>), sulfur oxides (SO<sub>x</sub>), H<sub>2</sub>S, and other inorganic gases and vapors. Wet scrubbers can remove both PM and gases, but suitable operational conditions are needed.

### Wet Scrubber Working Principles

Wet scrubbers clean air by physically trapping PM on wet surfaces and absorbing gases into the liquid. In some cases, the gases react with chemicals in the liquid, too. Small liquid droplets are more effective per unit volume of scrubber liquid because they have more surface area than fewer, larger droplets. Very small liquid droplets, however, are difficult to remove from the airstream after they absorb or react with the gases.

**PM** is collected by physically impacting the PM into droplets or onto wet surfaces. PM is impacted on droplets or wet surfaces in different ways, depending on the scrubber type used.

*Spray scrubbers* use liquid droplets to capture PM when it "sticks" to the liquid. Droplets and PM are removed from the airstream as wastewater that needs to be treated.

In *packed column scrubbers*, the moist packing material captures PM when it adheres to the wet packing surfaces. Periodically packed column scrubbers are flushed with water to remove PM collected on the surface of packing material. The flush water is treated as a wastewater, which must be collected and handled properly. PM removal efficiency of a wet scrubber depends on the PM-laden air volume, scrubbing liquid

**Animal feeding operations emit gases and particulate matter, which can have a negative impact on the environment and human and animal health locally, regionally, and globally.**

flow rates, PM and liquid droplet velocities, and the retention time of the PM-laden air in the scrubber.

**Gases** are removed by absorbing the gases into the liquid, typically water. Gas solubility, which describes how easily a gas is absorbed in the scrubbing liquid, depends on gas concentration gradients, chemical compatibility, reactivity between gas and liquid phases, liquid temperature, pH, and contact time. Gases such as  $\text{CO}_2$ ,  $\text{CH}_4$ , and other VOCs are not readily captured by water alone due to their low solubility at ambient conditions.  $\text{NH}_3$  is absorbed in water at low (acidic) pH, while  $\text{H}_2\text{S}$  is absorbed in water at high (basic) pH. If both  $\text{NH}_3$  and  $\text{H}_2\text{S}$  or similar gases need to be removed from the air, two separate wet scrubbing stages are needed to absorb the respective gases. The main drawbacks to adding either an acid or base to the scrubbing water include additional chemical costs, increased corrosion potential, and difficulties with handling chemicals safely. Plain water and a very long contact time is an option, but it requires a larger scrubber. Gas absorption depends on the air and liquid flow rates, air retention time, and droplet size and distribution.

## Wet Scrubber Design Factors

Wet scrubber type and size depend on the gas and PM concentrations and the amount of exhaust air to be treated, which depends on species, number, and size of animals housed. Scrubbers need to be sized to handle the maximum exhaust airflow rate. Scrubbers need to effectively remove air pollutants and efficiently use water, space, and power. Standard wet scrubber design tools are still being developed.

Four main characteristics affect scrubber effectiveness: flow configuration, scrubbing liquid composition, liquid-to-air ratio, and retention time.

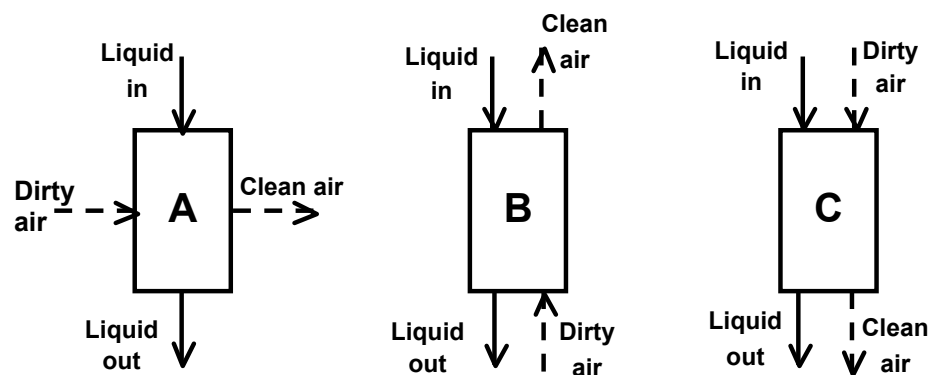
### Flow Configurations

Flow configuration influences retention time and the likelihood of scrubber plugging. Three flow configurations (*Figure 1*) are commonly used in wet scrubbers: cross-flow, counter-current-flow, and concurrent flow. The configurations determine how the liquid and air flow interact with each other.

In *cross-flow* scrubbers (*Figure 1a*), the exhaust air flows at right angles to the scrubber liquid flow. The retention time in cross-flow wet scrubbers is shorter than the other configurations. Cross-flow is quite acceptable in most scrubber types.

In *counter-current-flow* scrubbers (*Figure 1b*), the scrubbing liquid flows in the opposite direction of the airflow.

The cleanest scrubbing liquid enters across from the cleanest air leaving the scrubber. The dirtiest scrubbing liquid leaves the scrubber across from the dirtiest air entering the scrubber. While counter-current flow is theoretically the best configuration



*Figure 1. Flow configurations for operating scrubbers: (A) cross, (B) counter-current, and (C) concurrent.*

for gas absorption, counter-current is usually only recommended for packed bed operation because of plugging concerns.

In *concurrent-flow* scrubbers (Figure 1c), the exhaust ventilation air and the scrubbing fluid travel in the same direction. The cleanest scrubbing liquid enters across from the dirtiest air leaving the building. The dirtiest scrubbing liquid leaves the scrubber across from the cleanest air leaving the scrubber. The gas absorption diminishes with scrubber length, so concurrent flow requires the longest contact time of the three flow configurations. Because concurrent flow minimizes plugging, it is recommended for most PM applications in spite of the long contact time.

## ***Scrubbing Liquid Composition***

Scrubbing liquid choice is influenced by its concentration and the pollutants to be removed from the air. The scrubbing liquid can be water, water with either an acid added to enhance  $\text{NH}_3$  absorption, or a base added to enhance  $\text{H}_2\text{S}$  absorption. Gas solubility and reactivity in the scrubbing liquid impact gas absorption and are dependent on ambient temperature. Water can remove many gases emitted from livestock facilities.

An acidic solution (pH lower than 7) can be used to capture and retain  $\text{NH}_3$ . Sulfuric acid is commonly used because of its relatively low cost, and the ammonium sulfate byproduct has fertilizer value.

A basic solution (pH higher than 7) can be used to capture  $\text{H}_2\text{S}$ . Hypochlorite is a common base. A two-stage scrubber, one to capture  $\text{NH}_3$  and one to capture  $\text{H}_2\text{S}$ , may be used to scrub both  $\text{NH}_3$  and  $\text{H}_2\text{S}$  from the ventilation air. Scrubber liquid pH does not affect PM removal.

## ***Liquid-to-Air Ratio***

Wet scrubber effectiveness depends on the ratio of scrubber liquid flow rate to the exhaust air flow rate through the scrubber. Liquid-to-air ratios for prototype scrubbers suggest that ratios from  $4 \times 10^{-4}$  to  $2 \times 10^{-6}$  can be used. These ratios mean that from 2,500 to 500,000 times more air than scrubbing liquid is flowing through the wet scrubber. Research on liquid-to-gas ratios is ongoing. The particular liquid-to-air ratio needed depends on how much gas (i.e.,  $\text{NH}_3$ ,  $\text{H}_2\text{S}$ , or other gases) removal is needed and the operating temperature.

## ***Retention Time***

Retention time describes how much time the air is in contact with the scrubbing liquid. Factors affecting the retention time include liquid velocity, air velocity, flow configuration, and scrubber size. Retention time can range from 0.4 to 8 seconds (s). With a spray-type wet scrubber using a liquid with 1 percent weight/volume sulfuric acid, 90 percent of the ammonia in an airstream can be removed in 0.4 s. Using plain water, it takes 8 s to remove 84 percent of the ammonia in an airstream.

## ***Air Velocity***

The air velocity through wet scrubbers is recommended to be less than 4.3 m/s (850 ft/min). Agricultural fan air exhausts can be slowed before entering the scrubber by increasing the cross-sectional size of the scrubber. Increasing scrubber size usually increases initial costs.

## ***Pressure drop***

Pressure drop describes the flow resistance caused by the scrubber. The exhaust fans must overcome the pressure drop. When selecting a wet scrubber, the capability of the ventilation fans to overcome the scrubber pressure drop must be considered. Most animal facilities use axial fans, which are capable of delivering large amounts of airflow, but are very sensitive to increases in pressure drop.

**Wet scrubbers clean air by physically trapping particulate matter on wet surfaces and absorbing gases into the liquid.**

## Wet Scrubber Types

Wet scrubbers can be used to collect both PM and gas. Scrubbers have been developed specifically for particulate removal or gas removal (Figure 2). PM collection is improved by disturbing the airflow to “shake out” particles, i.e., by enhancing impaction with droplets.

Gas absorption requires a large surface area, which can be created by droplet breakup or wet sheet formation. Several scrubber types are used in industry for gas absorption. To overcome the high pressure drop of industrial-type scrubbers, low pressure drop scrubbers, such as loosely packed bed and spray scrubbers, are commonly used in AFOs.

**Loosely packed bed scrubbers** use a packing material, such as ceramic saddles or rings, to maximize the wetted surface area for PM and gas collection. They operate well in cross-flow, concurrent-flow, and counter-current-flow arrangements.

Loosely packed, randomly positioned packing materials in packed bed scrubbers can have a small pressure drop. Packed bed scrubbers are prone to plugging if the PM concentration is too high. Concurrent-flow operation can reduce the potential for early plugging.

**Fiber bed scrubbers** are a subset of packed bed scrubbers. They use fibers, such as fiberglass or steel fibers, for the wetted packing media. Fiber beds best operate using a cross-flow arrangement, which prevents pore plugging. Fiber bed scrubbers are also useful in bio-scrubber applications because they allow microbial growth on fibers, which can improve VOC breakdown.

**Spray scrubbers** use nozzles to spray very fine droplets into a chamber where the liquid and air come into contact. Finer droplets increase the contact area between the air and liquid, but they can be more difficult to remove from the air stream before the air leaves the scrubber. Spray scrubbers are effective in all three flow configurations, cross, concurrent, and counter-current. Spray scrubbers have the lowest airflow pressure drop among scrubbers. Spray scrubbers operating in concurrent-flow and cross-flow operations are least prone to plugging.

## Wet Scrubber Costs

Wet-scrubber system costs include initial capital and installation, energy, liquid and chemical, maintenance, and scrubber effluent storage and disposal costs. Table 1 gives typical capital and operating and maintenance (O&M) costs for different wet scrubbers

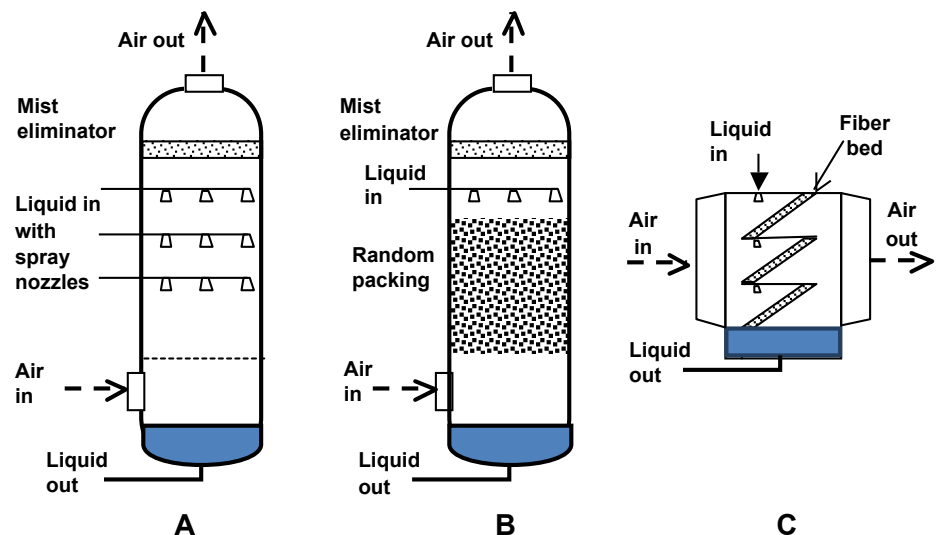


Figure 2. Schematic diagrams of spray scrubber (A) packed bed, (B) and fiber-bed, (C) scrubbers.

**Table 1. Common industrial wet scrubber capture efficiencies and costs (Sources: USEPA, 2008, Schnelle and Brown, 2002 ).**

Scrubber type	Material removed	Capture Efficiency (%)			Costs (based on 2002 \$ value)		
		PM	Volatile organic compounds	Inorganic gases	Capital cost (\$/ft <sup>3</sup> )	O&M cost (\$/ft <sup>3</sup> )	Total cost (\$/ton)
Spray	PM / Gas	70 – 90	50 – 95	95 – 99	\$2 – \$6	\$1.5 – \$30	\$45 – \$860
Packed bed	Gas		70 – 99	95 – 99	\$11 – \$55	\$15 – \$49	\$100 – \$500
Fiber bed	PM / Gas	70 – 90	70 – 99		\$1 – \$3	\$1.6 – \$ 36	\$36 – \$344
Impingement	PM / Gas	50 – 99		90 – 99	\$4 – \$11	\$3.1 – \$44	\$94 – \$1,300
Mechanical	PM	80 – 99			\$2.6 – \$ 17	\$3 – \$79	\$60 – \$1,400
Venturi	PM	70 – 99			\$2.5 – \$21	\$4.4 – \$120	\$70 – \$2,400

O&M = operation and maintenance

in industrial applications. Capital costs range from \$1 to \$55 per standard cubic foot per minute (scfm) of air treated, based on 2002 dollar value. Spray scrubbers and fiber-bed scrubbers were least expensive; mechanically aided and venturi scrubbers were most expensive at that time.

O&M costs include energy costs for pumping the liquid and blowing the air through a wet scrubber and any chemicals used. Capital costs include initial equipment, installation, and construction costs.

Pilot-scale scrubber studies have reported capital and operating costs. Marsh et al. (2003) spent \$1,632 per exhaust fan on capital costs and \$75 per year for operating costs for scrubbers on a swine nursery. The total cost was \$0.13 per pig space. The low scrubber costs were due to the low PM, NH<sub>3</sub>, and H<sub>2</sub>S concentrations of the exhaust air, which required a smaller scrubber and less scrubbing liquid. Melse and Ogink (2005) used scrubbers with higher pollutant loads and average removal efficiencies greater than 90 percent. They reported an investment cost of \$42 per pig or \$1.30 per broiler. The operating cost was \$14.82 per pig and \$0.27 per broiler. Chemical costs were 14 percent and 37 percent of operating costs. The operating costs included fan power, pump power, and scrubbing liquid consumption. Fan power depended on the pressure drop through the scrubber. Pump power depended on the liquid flow rate.

## Wet Scrubber Limitations

While wet scrubbers can effectively remove some gases and PM, their use is limited in animal facilities because of their high pressure drop and relatively high initial and operating costs. Scrubbers also require a system to handle the scrubber liquid effluent. Development of low cost and high efficiency wet scrubbers that do not significantly affect axial fan operation needs further study. Some of the challenges are:

*Clogging.* Wet scrubbers can become clogged with accumulated PM if the air being treated has high PM concentrations (especially fibrous particles or feathers). Particulate matter can accumulate in the packing material and restrict or block the airflow. The risk of wet scrubber clogging can be reduced by increasing the liquid flow or using either a cross- or concurrent-flow configuration.

*Water Use.* Wet scrubbers need to have sufficient and economical water supplies. Wet scrubbers can consume substantial quantities of water. The wastewater handling is an important consideration. Even if chemicals are not used, the gases dissolved in the water make the scrubber liquid effluent unsuitable for discharge to public waters (i.e., streams, lakes, or wetlands). Scrubber effluent can be applied to cropland or added to a manure storage unit or treatment system in compliance with local, state, and federal regulations. Recycling scrubber effluent reduces wastewater generation.

**Four main characteristics affect scrubber effectiveness: flow configuration, scrubbing liquid composition, liquid-to-air ratio, and retention time.**

**Wet scrubber costs include initial capital and installation, energy, chemicals, maintenance, and effluent storage and disposal costs.**

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