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PARTICULATE EMISSIONS:

EVALUATING REMOVAL METHODS

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PARTICULATE EMISSIONS: EVALUATING REMOVAL METHODS

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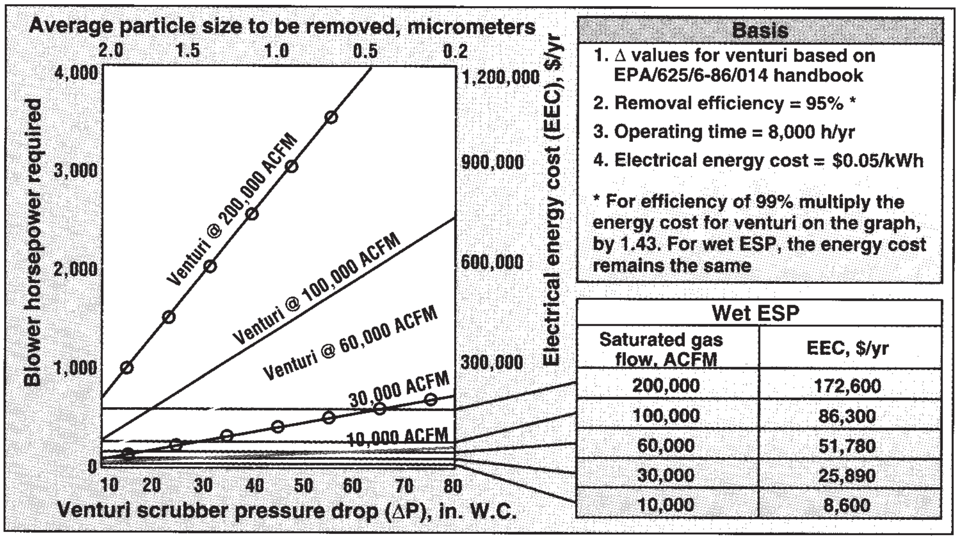
Clean Air Technologies

As particle size shrinks, the field of equipment options narrows



Basis

1. Δ values for venturi based on EPA/625/6-86/014 handbook
2. Removal efficiency = 95% *
3. Operating time = 8,000 h/yr
4. Electrical energy cost = $0.05/kWh

* For efficiency of 99% multiply the energy cost for venturi on the graph, by 1.43. For wet ESP, the energy cost remains the same

Wet ESP

Saturated gas flow, ACFM	EEC, $/yr
200,000	172,600
100,000	86,300
60,000	51,780
30,000	25,890
10,000	8,600

FIGURE 1. This comparison of operating costs for venturi scrubbers and wet electrostatic precipitators shows that for tiny particles and high gas flows, venturi scrubbers can become prohibitively expensive

Next month, the U.S., the Environmental Protection Agency (EPA; Washington, D.C.) expects to finalize a new set of regulations for the removal of airborne particulate matter. The so-called PM-2.5 Standard would set thresholds for the removal of particles under 1 micrometer (μm) in diameter (*CE*, January 1997, pp. 42–47). Current EPA rules regulate airborne particles that are 2.5–10 μm dia. The impetus behind the controversial PM-2.5 Standard comes from recent studies that suggest that the finest airborne particles cause considerable health damage to humans [*1, 2*].

This article examines a variety of air pollution control devices, and discusses how each performs in the removal of submicrometer-sized particles. Such particles are ubiquitous in exhaust streams from combustion and other high-temperature operations, such as boilers and smelters. Since toxic vapors and volatilized heavy metals created during high-temperature operations condense on the surface of particles, submicrometer-sized particles can be deadly carriers of toxic substances.

Once coated with heavy metals, tiny particles pose a greater toxicity threat than larger particles, due to their increased surface area. For example, one gram of 0.1-μm particles has 10 times the surface area as a gram of 1.0-μm particles (60 m^2 vs. 6 m^2).

In recent years, scientists have discovered that small particles drawn deeply into the lungs are to blame for much of the death and illness associated with air pollution. Thus, the threat posed by minute particulates raises concerns about worker safety and public health, and calls for an effective control strategy for submicrometer airborne particles.

Many of today's air pollution control devices are not suited for the efficient removal of submicrometer particles. While settling chambers, cyclonic separators, venturi scrubbers, packed towers and conventional electrostatic precipitators remove a variety of gaseous and particulate pollutants, some perform better than others in the removal of submicrometer-sized particles.

The laws of physics rule

When selecting a pollution-control system, one must begin with a thorough analysis of the gas stream. Efficiency and cost effectiveness are often compromised when system specifications are not matched with the parameters of a given gas stream [*3*].

Key variables that will impact equipment selection and performance are:

- Volumetric flowrate
- Temperature of the exhaust gas
- Moisture content
- Particulate concentration
- Particle size distribution

Particle size is the most important factor. Each process relies on the laws of physics that govern the separation of particles from a gas flow. In general, gas-solid separation requires:

- A differential force that acts on the particle
- A differential force that crosses the gas streamline perpendicular to the motion of the gas
- A retention zone to collect the separated particles

Today's devices for gas-solid separa-

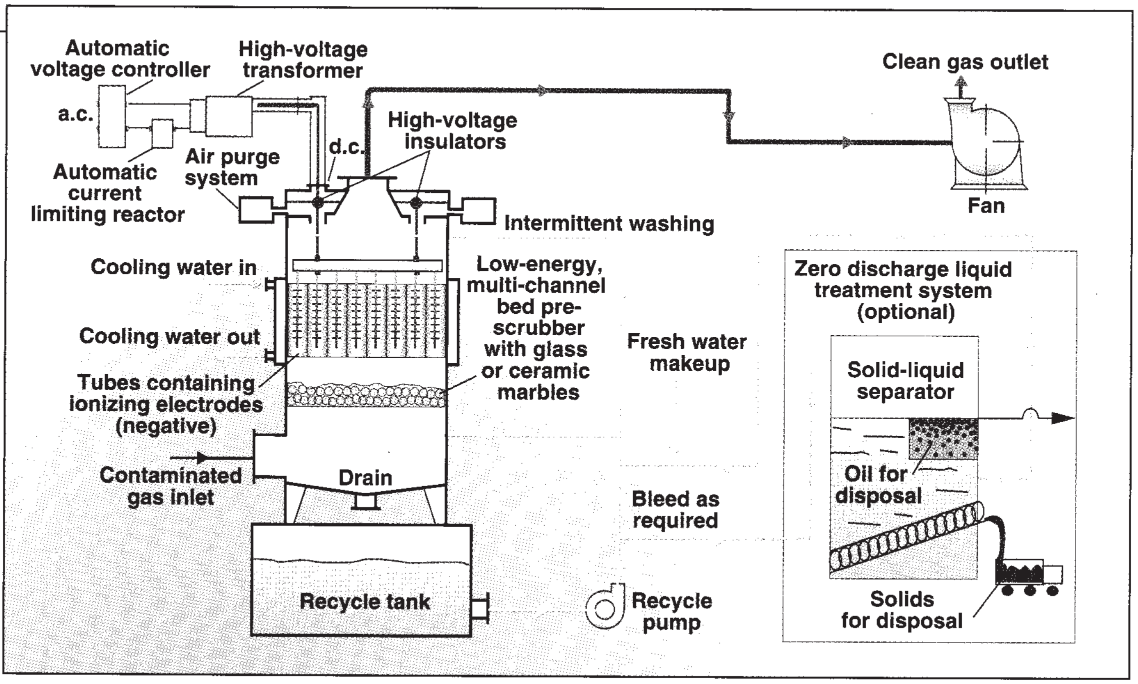


FIGURE 2. The condensing, vertical-tube WESP combines a heat exchanger to cool the gas stream and an upflow WESP. The system integrates the influences of gas velocity, particle size and temperature to optimize particle removal

tion rely on a variety of forces, depending on particle size: gravity, centrifugal force, electrical impulse, and Brownian motion [*3*]. Particles of varying size are displaced as a result of each of these forces (Table 1). For instance, since particles measuring 10 μm or less generally do not respond well to gravitational force, settling chambers (which are based on gravitational force) are not typically effective for the removal of particles less than 50 μm.

In contrast, cyclonic separators rely on centrifugal force, which increases as radius decreases. This makes cyclonic separators more effective than gravity chambers at separating small-diameter particles from a gas stream. As particles follow a circular path in a cyclonic separator, centrifugal force is directly proportional to both particle mass and tangential velocity to the second power, but is inversely proportional to the radius of the turn. However, the inlet velocity required for separating small particles (i.e., less than 5 μm) may result in excessive energy consumption and wear on the equipment. This makes centrifugal separators impractical for the removal of tiny particles.

Since small particles typically respond well to electrical forces, electrostatic precipitators (ESP) are particularly effective in removing particles less than 1 μm in size. For instance, the electrical forces exerted on an electrically charged particle of 0.1 μm can be more than a million times the force of gravity [*5*]. Particles smaller than 0.1 μm are also responsive to the substantial force of Brownian motion, which causes random movement and collision with other gas molecules.

In 1905, Albert Einstein developed an equation based on elementary kinetic theory. This equation allowed one to calculate the velocity of particles subject to Brownian motion and showed that particle velocity is a function of particle size, gas temperature and viscosity. Equipment based on the relationship between gas temperature and particle velocity can yield impressive results, especially when applied with electrostatic forces.

TABLE 1. PARTICLE DISPLACEMENT IN STANDARD AIR DUE TO VARIED FORCE FIELDS

Particle diameter		Displacement in one second[1]				
Micrometer	Ft	Cc	Gravity	Centrifugal	Electrostatic	Brownian
10.0	3.28×10^{-5}	1.02	2.4×10^{-2}	2.1×10	0.98	5.70×10^{-6}
1.0	3.28×10^{-6}	1.17	2.7×10^{-4}	2.4×10^{-1}	0.11	1.94×10^{-5}
0.1	3.28×10^{-7}	2.93	6.9×10^{-6}	5.9×10^{-3}	0.27	9.72×10^{-5}
0.01	3.28×10^{-8}	22.60	5.3×10^{-7}	4.6×10^{-4}	2.12	8.54×10^{-4}

[1] Stokes Cunningham slip - correction factor (dimensionless).
Gravitational force field — downward linear displacement based on 32.2 ft/s^2 acceleration.
Centrifugal force field — outward radial displacement based on 862 G acceleration.
Electrostatic force field — normal linear displacement based on 7,500 volts/in. field strength and a saturation charge on the particles.
Brownian movement — random linear displacement based on average values.

Several devices are available to capture minute airborne particles. Users must understand the limitations of each type in a given situation.

Fabric filters. These devices, especially pulse-jet filters, provide effective removal of fine particles. However, their use is limited by the chemical and physical nature of the particles. For instance, fabric filters cannot be used to capture hydroscopic particles, or particles that can stick to the filter bags.

Similarly, since fabric filters typically operate at temperatures of 350–400°F, they are suitable for the removal of solids, flyash and particulates. But, such systems cannot remove gaseous pollutants and uncondensed vapors unless combined with a dry scrubber, which would further complicate temperature control and waste disposal, and add to system cost.

Venturi scrubbers work best when treating moist gas or liquids with particles larger than 1 μm. They are most effective for gas pre-treatment as part of a complete system. However, the use of a venturi scrubber for submicrometer particle control can be costly, since the removal of smaller particles requires an increase in horsepower (HP) to draw the gas through the scrubber throat:

$$HP = PQ/6{,}356E \qquad (1)$$

where:

P = The pressure drop in the scrubber,

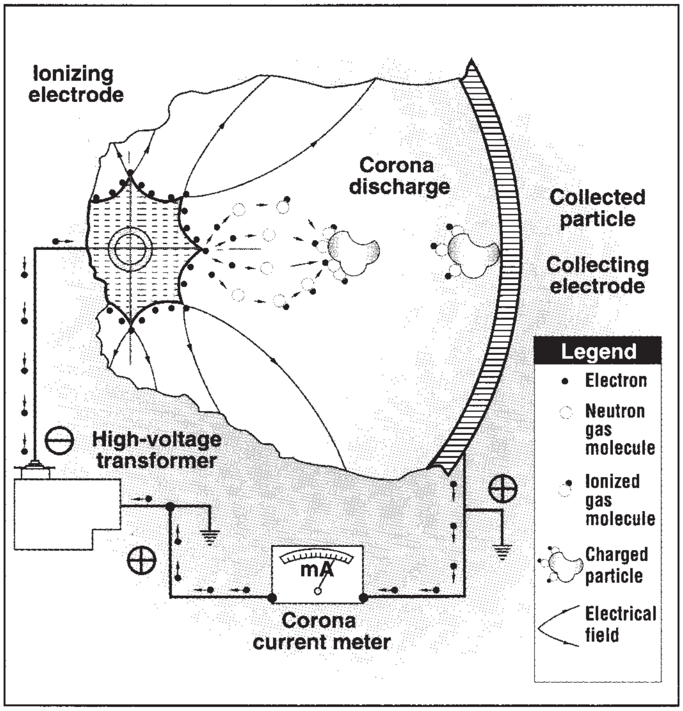


FIGURE 3. Shown here in cross-section, the ionizing electrodes in a condensing WESP have a series of sharp points. These points give off a corona that charges suspended particles, causing them to migrate toward the walls of the collection tube

in. w.c
Q = Gas flow, ft^3/min
E = Total mechanical efficiency of the system (0.65)

The increased horsepower requirements consequently increase energy use and operating cost. In addition, in a venturi scrubber, energy is required to move the entire body of gas through the restricted venturi throat (Figure 1). Using a venturi scrubber to clean 100,000 ft^3/min of gas containing submicrometer particles can cost $500,000/yr or more, based on a rate of $0.05/kWh at 8,000 h/yr. This makes it an expensive option for submicrometer particulate control.

Electrostatic precipitators (ESP) offer high capture efficiency for submicrometer particulates by using electrical forces to remove suspended particles from a gas stream. Because an ESP uses electricity only to charge particles in a passive air stream (not to move the entire gas stream through a venturi throat), ESP energy use is much lower than a venturi scrubber (Figure 1).

Typically, three steps are involved: charging, collection and removal. A corona discharge electrically charges the suspended particles, which are collected on electrodes. In a dry ESP, the electrodes are periodically shaken to remove accumulated particles for disposal. Despite that periodic shaking, dry ESPs are prone to buildup on the walls of the collection chamber; such buildup acts as an insulator, reducing the overall efficiency of the equipment. While dry ESPs (also operating at 350–400°F) are commonly used for particulate removal, they must be used in concert with scrubbers or other equipment used to capture VOCs and acid gases that are also typically contained in industrial exhaust streams.

Wet ESP (WESP). In a WESP, a liquid, usually water, is used to continuously wash away particulate buildup from the collection surface. The WESP is widely used for applications where the gas to be treated is hot, has a high moisture content, contains sticky particles, and has been pretreated in a scrubber but requires additional removal of particulate and acid droplets, or contains submicrometer particles not able to be treated through other methods (Table 2).

In a conventional, "upflow" WESP, the gas stream flows co-current to the water. This requires frequent cleaning because many droplets in the bottom water sprays do not reach the top of the chamber where submicrometer particles accumulate, and sprayers are susceptible to plugging. As such, the equipment must be periodically shut down for cleaning, leading to interruption of operations. In a "downflow" WESP, the inlet gas and water sprays move concurrently downward, so these limitations can be partially overcome.

One variation on the WESP design is well-suited for the removal of submicrometer-sized particles. The condensing, vertical-tube WESP (Figure 2) increases removal efficiency and reduces operating costs and maintenance by harnessing temperature to affect particle movement perpendicular to the gas flow direction [*6, 7*]. This design combines a heat exchanger that cools the gas stream with an upflow, vertical-tube WESP. It integrates variables of velocity, particle size and temperature to maximize the removal of submicrometer particles.

For an incineration system, for example, the hot, contaminated inlet stream is cooled from roughly 1,800°F to 140–170°F in a quencher, and is then precleaned of particles larger than 2 μm in a low-energy scrubber. This pre-treated gas stream then passes into a series of tubes containing ionizing electrodes in the center. Each electrode has a number of sharp points, which give off the corona discharge that mobilizes the particles (Figure 3). Once particles are charged to the point of saturation, they migrate toward the walls of the collection tube.

In a condensing WESP, the double-walled collection chamber internally circulates cold water in a closed-loop system. When a gas temperature profile exists on either side of a particle, the gas molecules on the warmer side will have a higher kinetic energy than the molecules on the cooler side. The hot, active gas molecules will strike the surface of the particle with more force — in essence propelling the particle toward the cooler temperature zone (a process known as *thermophoresis*).

Particle velocity depends on the temperature gradient, the relative thermal conductivities of the gas and the particle, and the density and viscosity of the gas. Thermal forces for particles 0.1 μm can be 100 times greater than those for particles of 1 μm.

In addition to thermophoresis, a process known as *diffusiophoresis* occurs when the partial vapor pressure of water in a carrier gas is greater than the water vapor pressure at the surface of the water droplets in a scrubbing liquid. In this case, water vapor will condense onto the water droplets, creating a bulk motion of gas (and entrained particles) toward the droplets. Because the droplets are larger than the particles — and are thus more easily removed by either electrical or mechanical means — diffusiophoresis can have a significant effect upon the collection efficiency of fine particles [*8*].

In a condensing WESP, electrically charged particles (both liquid droplets and solids) are subject to electrical forces, as well as thermophoresis and diffusiophoresis, so they migrate toward the positive (grounded) wall of the collection tubes. These tubes are cooled by circulating water. Similarly, water vapor condenses and leaves a wet film on the wall, which flushes particulates down the wall and out of the system.

By condensing water vapor from the contaminated gas, this WESP design can cut external water needs by 30% compared with conventional WESPs. The continuous presence of condensate also reduces corrosion and the need for system shutdown for cleaning.

The basic design consideration of a condensing WESP is:

$$\eta = 1 - \exp(-AW_C/V) \quad (2)$$

where:

η = Collection efficiency, represented by a decimal fraction

A = Collection area of a WESP or surface area of all collection tubes, ft^2

V = Inlet gas flowrate, ft^3/s

W_C = Combined migration velocity of particles under the influence of electrical and thermal forces, ft/s

The combined migration velocity is derived from lab, pilot tests in the field, and tests of a full-scale WESP. Since migration velocity is the variable in this equation, electrostatic and thermophoretic forces (which dictate migration velocity) become a key consideration. When the electrostatic field intensity and temperature differential increases, the migration velocity also increases in proportion to a given particle size and flow condition.

TABLE 2. COMPARISON OF CONTROL METHODS

Process conditions and requirements	Wet ESP	Scrubber	Dry ESP	Baghouse
Captures particles < 1 micrometer in size	Yes	Yes	Yes	Yes
Handles moist gas	Yes	Yes	No	No
High efficiency for submicrometer particles with low energy consumption	Yes	No	Yes	No
Particles collected in liquid	Yes	Yes	No	No
Recommended for fire-sensitive processes	Yes	Yes	No	No

The product of the operating voltage and the operating corona current is defined as *corona power*. WESP efficiency is directly proportional to corona power.

During operation, corona power is limited by internal sparks between ionizing and collecting electrodes. Since WESP efficiency is directly proportional to the electrical power conveyed to the moving gas, each time an ESP sparks, the voltage — and consequently the particulate collection efficiency — is reduced.

For a given WESP, gas flow conditions and fine particle concentration, sparking rate is a function of:

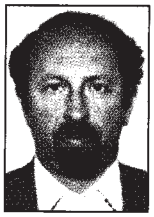
- Gas-to-liquid ratio for entrained liquids
- Quality of the WESP components
- Selection of high-voltage power supply components to match both WESP geometry and the physical and chemical nature of suspended particles

One can dramatically increase the power level and efficiency of a WESP by properly designing the automatic voltage control (AVC) system. While the industry average seldom goes beyond 40% conduction (i.e., the ability to deliver 40% of the available power to the gas), with the proper selection of the transformer-rectifier, AVC and automatic current-limiting reactor (ACLR), systems can be designed to deliver 86% conduction (the maximum theoretically possible) to a corona discharge.

The powerful combination of liquid scrubbing, thermophoretic and diffusiophoretic effects, and high-voltage electrostatic precipitation in a condensing WESP is an effective way to remove submicrometer particles. And, the condensing WESP captures certain hard-to-handle heavy metals, such as arsenic, cadmium, nickel, cobalt and lead. Thus, a condensing WESP can produce stack exhaust with zero opacity, satisfying state and federal regulations.

Air pollution control devices — particularly those for the removal of submicrometer particles — should be able to operate as part of an integrated system. For example, by combining a WESP with a relatively inexpensive, low-energy scrubbing section (which acts as the air distribution device), large and small particles (down to 0.01 μm) can be easily removed from exhaust with minimum maintenance. ■

Author



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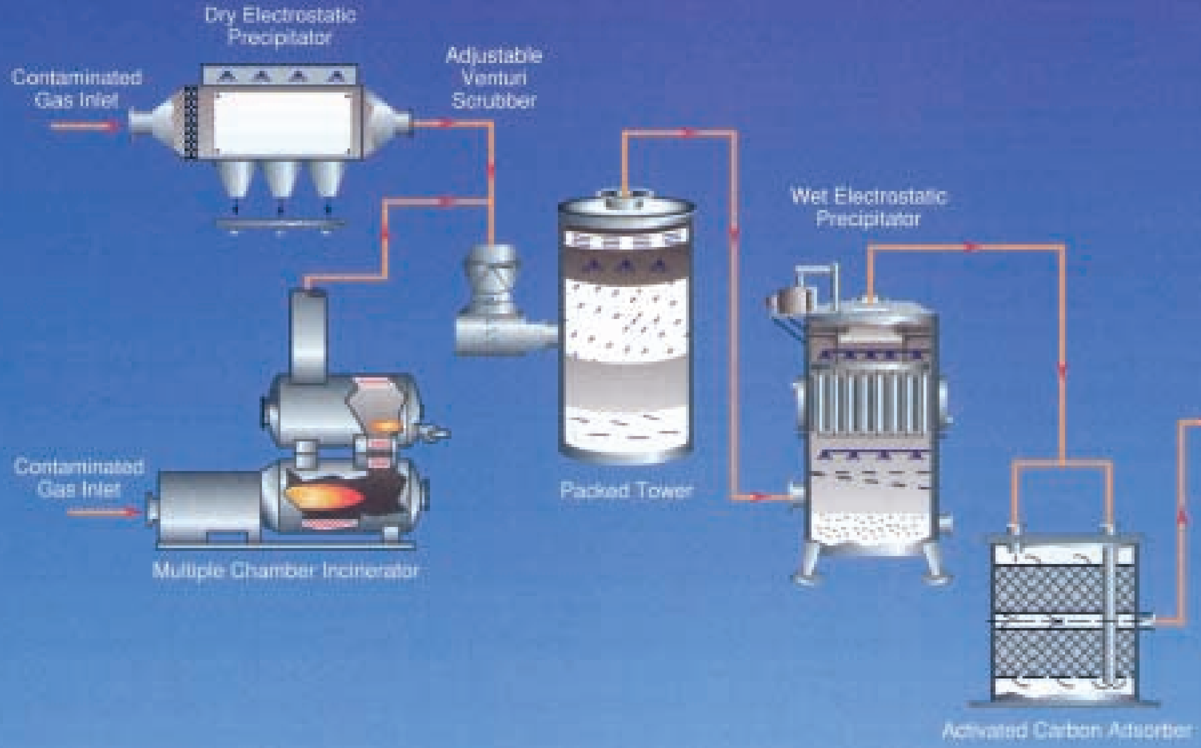

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