COMPARISON OF WET AND DRY ELECTROSTATIC PRECIPITATOR (ESP) TECHNOLOGIES

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Abstract: With the recent surge in Electrostatic Precipitator (ESP) installations and future predictions of continued growth, ESP technology has been and will continue to be utilized for many applications. Wet and dry ESP technologies are in many ways similar but many questions arise as to the applicability of each technology as well as the advantages and limitations of each technology.

Siemens Environmental Systems & Services provides both wet and dry ESP technology for the utility power, cement and refinery industries as well as other applications. While wet and dry ESPs retain similar high voltage and collection systems and share similar physical characteristics, many differences exist; attributable mainly to the inherent design of the technology to address various size particles. Dry ESPs are used to capture coarse, filterable particulate matter (PM_{10}) such as flyash. PM_{10} is defined by the U.S. Environmental Protection Agency (EPA) as particles smaller than 10 microns (a micron is one millionth of a meter). Wet ESPs capture sub-micron particulate matter, condensables and water mist commonly referred to as $PM_{2.5}$ (defined by the EPA as particles less than 2.5 microns). Whereas dust or flyash characteristics play a large role in the sizing of dry ESPs, this is not the case with wet ESPs as they are not dependent upon particulate resistivity.

This paper compares the two technologies and Siemens’ experience with the technologies. To gain a better understanding of each technology a discussion of particle size is first required.

1. Particle Size and Surface Area

As seen in Figure 1 below, there is a significant difference between a 1 micron particle and a 10 micron particle.

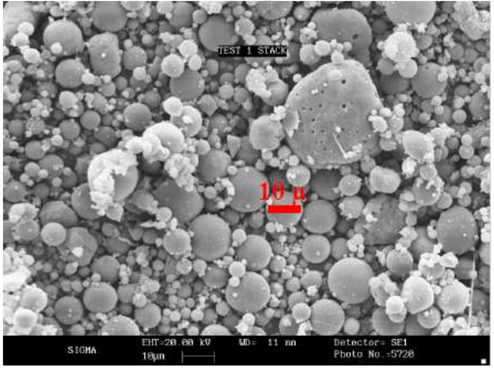
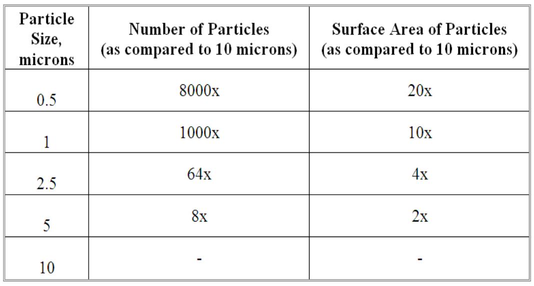


Fig. 1 Varying Flyash Particle Sizes (source CleanAir)

As expected, not only are smaller particles harder to capture because of their small size but there are significantly more particles to capture when dealing with fine particulate. The table in Figure 2 compares the relative number of particles that can fit within a volume of one cubic meter of flue gas. For the same cubic meter of flue gas there can be 1000 times more 1 micron particles than 10 micron particles with 10 times more total surface area!



Particle Size, microns	Number of Particles (as compared to 10 microns)	Surface Area of Particles (as compared to 10 microns)
0.5	8000x	20x
1	1000x	10x
2.5	64x	4x
5	8x	2x
10	-	-

Fig. 2 Particle Size: Relative Numbers and Surface Area in 1 m^3 of Gas

To support the theoretical analysis in Figure 2 above, the charts in Figure 3 show the particle size distribution from a coal-fired utility wet scrubber on a mass basis and quantity basis (broken down by dry vs. wet for comparison). While the relative mass of “wet” particles is similar for particles sized 5 micron to 100 microns as for particles sized 0.1 to 1 micron, on a quantity basis the overwhelming number of particles are those less than 0.1 micron.

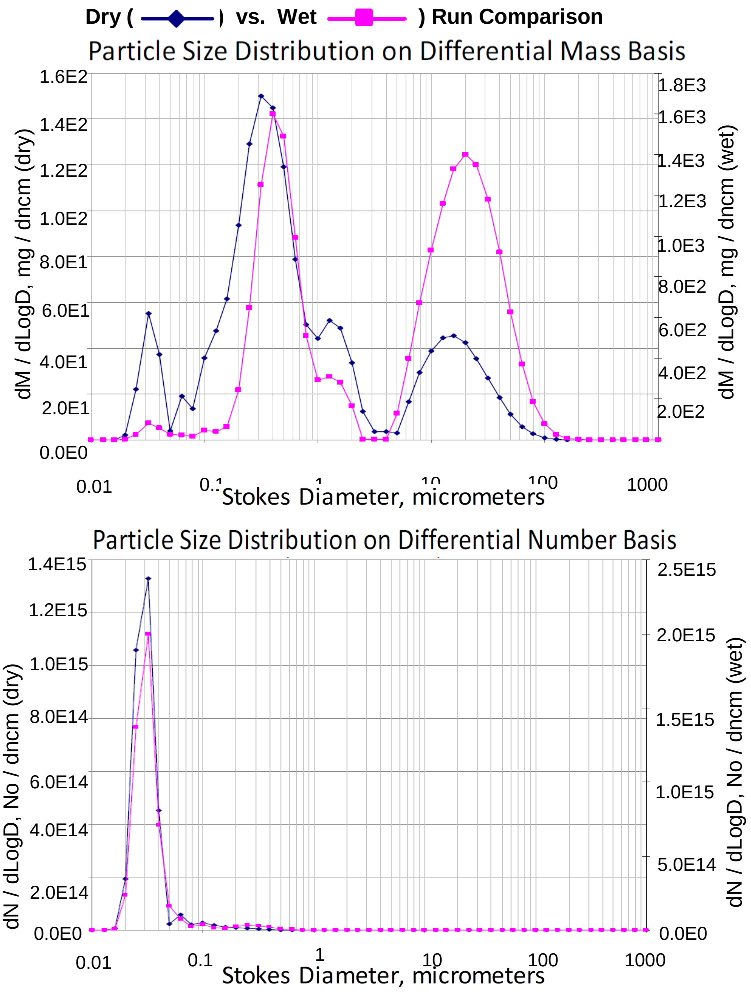


Fig. 3 Dry & Wet Particle Size Distribution[1]

When condensable vapors cool they tend to condense on the smallest sub-micron particles because there are a greater number of small particles. The reason there has been increasingly more focus on capturing fine particles is that these size particles are more toxic than large particles and lodge deeper in the lungs therefore posing higher health risks. Particle toxicity increases as particle size decreases as shown in Figure 4.

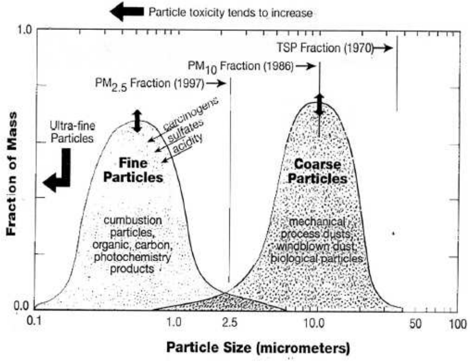


Fig. 4 Particle Size vs. Toxicity (source U.S.EPA)

2. Opacity

The most visible particles are approximately a half-micron in size due to their light extinction properties. The picture in Figure 5 shows a coal-fired power plant plume that has both a dry ESP and wet scrubber installed with high visible opacity.

Fig. 5 Opacity Plume

Though both air pollution control devices capture coarse particulate neither is very efficient at capturing fine particulate. The visible plume seen is from light refracting off of particles 0.1 to 1 micron in size that have passed through the dry ESP and wet scrubber; with 0.5 micron particles being the most visible[2]. The greatest contributor to this sub-micron particulate is sulfuric acid mist (H_2SO_4). As shown in Figure 6, opacity is directly proportional to concentration of sulfuric acid.

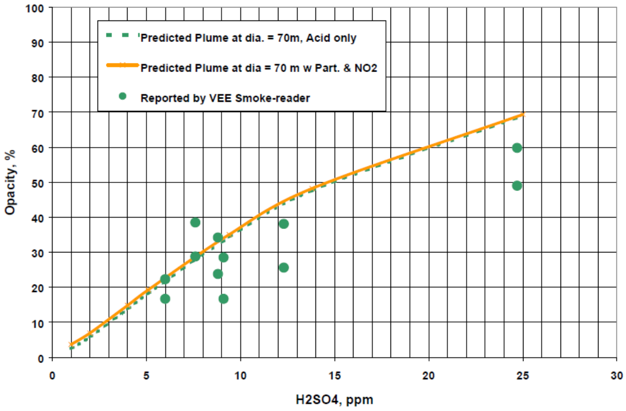


Fig. 6 Opacity vs. H_2SO_4 for Large Unit with Dry ESP & Wet Scrubber[3]

Note that the above graph is independent of the sulfur level in the coal. With typical low-sulfur coals, H_2SO_4 concentration may be 5ppm or less, however H_2SO_4 will still represent a significant portion of the measured opacity.

3. History

The first reported ESP in commercial service was a wet ESP installed in 1907 for acid mist control. The first dry ESPs followed in the 1910's in the non-ferrous metals and cement industry. Dry ESPs in the coal-fired boiler industry went into service in 1923 at one of Detroit Edison's power plants in the U.S. While dry ESPs have been in use in many industries for decades as a primary particulate control device, wet ESPs have found their use primarily in the sulfuric acid industry as a piece of process equipment to collect sulfuric acid. Not until regulatory authorities established emission limits on fine particulate matter has there been a wider need for wet ESP emission technology.

4. Theory of Operation

Dry and wet ESPs are similar in their main purpose which is to collect non-gaseous particulate from a flue gas stream. Both technologies include a multi-stage process for removal of the particulate from the gas stream by creation of an electric field (refer to Figure 7). First, a high voltage corona discharge is emitted from the discharge electrodes, ionizing the flue gas molecules between the discharge and collecting electrodes. The particulate entering this electric field are then charged by the ionized flue gas molecules and naturally attracted to the collecting electrode of opposite polarity. And finally, the collected particulate is removed from the collecting electrode.

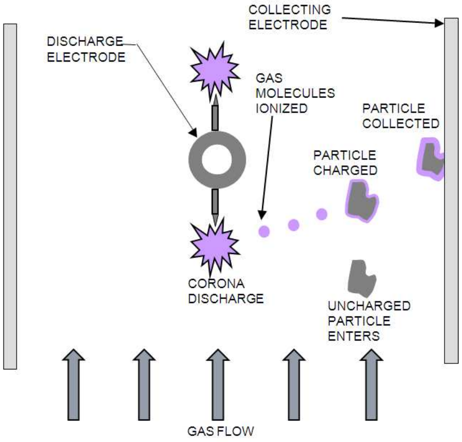


Fig. 7 ESP Collection Schematic

All ESPs use this method of particulate charging and collection; the differences between dry and wet ESPs are in the process of removing the particulate from the electrodes. Dry ESPs allow the collected particulate to build-up in a layer on the collection surface, which is then removed via mechanical rapping or vibration. Many different rapping variations exist including tumbling hammer, gravity impact, vibrators, pneumatic and drop-rod rapping. The collected particulate falls into a collection hopper where it is removed from the dry ESP with an ash handling system. Similar rapping systems are used on the discharge electrodes to minimize potential build-up that could inhibit corona generation.

In a wet ESP, the collecting electrodes are cleaned via use of intermittent water sprays or a continuous irrigation system preventing any build-up of particulate on the collecting electrode surface. If sprays are used, the affected electrical bus section must be de-energized to protect the transformer/rectifier sets whereas in an irrigation system the transformer/rectifiers may stay on as there is no interference with the electrical system. The water washes away the collected particulate on the collection surface. The difference in cleaning has a significant impact on function, location, operating temperature, materials of construction and performance**.**

5. Configuration

Dry ESP design configuration consists of a horizontal flow of flue gas between two vertical plates with discharge electrodes in the middle, commonly referred to as a "plate-type" ESP. Due to the large volume of gas and the heavy inlet loading of particulate that typically needs to be removed from a bottom hopper, the plate design has become the most common configuration.

Wet ESPs can come in a variety of configurations. They can be either plate or tubular; down-flow, up-flow or horizontal flow. Plate wet ESPs are very similar to dry ESPs with two vertical plates facing each other and discharge electrodes located between the plates. However, flue gas flow can be either horizontal or vertical. Alternatively "tubular" wet ESPs (tubular collecting surfaces with electrodes in the middle) are always vertical but the flow can be either up-flow or down-flow. Additionally, tube configuration can be round, square or hexagonal. Tubular designs, with all four sides containing the flue gas offer higher efficiency per square foot of gas treated and smaller size. However, when multiple electrical bus sections are required to achieve high removal, cleaning of the collecting surface is more of a challenge in a tubular design to minimize impact on the lower bus sections with inter-stage drains. Consideration of available real estate, flue gas volume, inlet loading, required removal, sectionalization, water usage, cost and maintenance access are all factors that come into play when selecting the most appropriate wet ESP configuration.

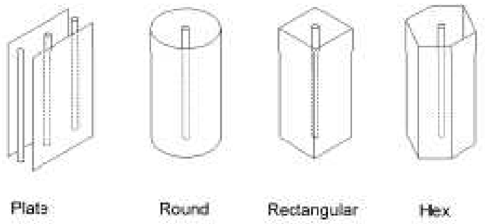


Fig. 8 Wet ESP Electrode Arrangements[4]

6. Process Comparison

Dry and wet ESPs are utilized on coal-fired boilers as well as many similar industrial applications. The differences between ESPs become evident when looking at where the ESPs are installed in the process. Dry ESPs are typically the first control device to remove the heaviest load of particulate while wet ESPs are the last control device prior to the stack and act as a final polishing device.

Dry ESPs are most often installed in high ash and high temperature environments. The flue gas at this stage is most often above the adiabatic saturation temperature and the acid dew point temperature. In some older utility installations, dry ESPs were installed upstream of the air heater in a “hot-side” arrangement (temperatures of 750°F / 400°C); however this arrangement has fallen out of favor due to detrimental issues such as performance degradation over time and structural problems in many installations. Modern day utility dry ESPs are installed on the “cold-side” of the air heater at temperatures of approximately 250-350°F (120-175°C) as shown in Figure 9. Some industrial applications such as rock product kilns and catalytic cracking units still successfully use dry ESPs on temperatures of 600-800°F (315-425°C).

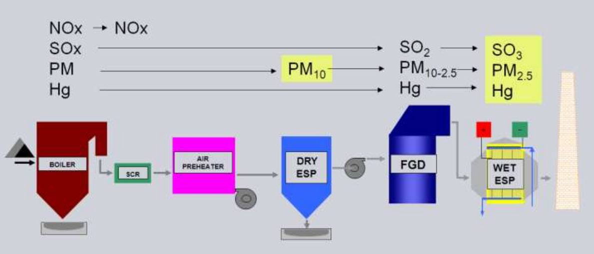


Fig. 9 AQCS Schematic

Particulate loading to a dry ESP varies greatly depending upon the flyash/process; for a coal-fired boiler ranges are typically 1-10 gr/acf (2-23 g/m3) while ranges for an oil-fired boiler are typically much lighter at <0.1 gr/acf (0.2 g/m3). Flue gas temperature as well as particulate loading and dust (ash) composition will play a role in to how the ESP is sized.

Wet ESPs are installed in saturated flue gas streams with considerably less particulate loading than dry ESPs. Typically, a wet ESP follows a scrubber where the flue gas is saturated to the moisture dew point (typically 130°F / 55°C) and the wet ESP is used to collect $PM_{2.5}$, H_2SO_4 and liquid droplets that remain in the flue gas after the scrubber.

In a typical utility boiler, sulfur trioxide exists in the gaseous form until the air heater where the decrease in temperature converts SO_3 to H_2SO_4 (Figure 10). While the sulfuric acid remains in vapor form through the dry ESP (approx 300°F), in the saturated flue gas stream, all sulfuric acid previously existing as a vapor condenses into an aerosol (Figure 11).

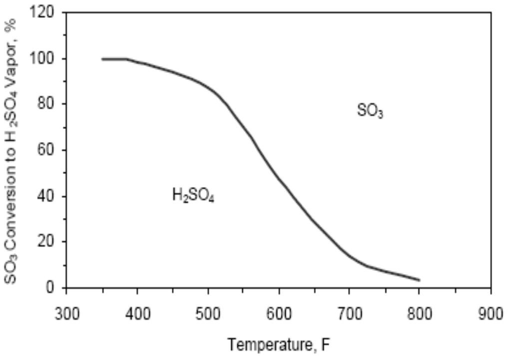


Fig. 10 SO_3 Conversion to Sulfuric Acid Vapor @ 8% Moisture[5]

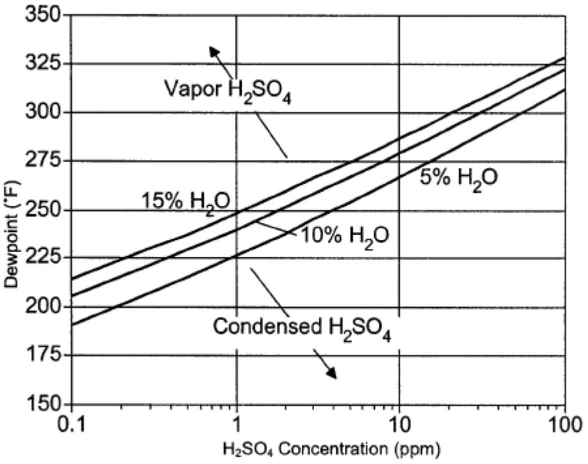


Fig. 11 Formation of Condensed Sulfuric Acid[6]

The particulate loading to a wet ESP is typically much less than a dry ESP with PM of less than 2.5 microns and H_2SO_4 droplets of 0.1 – 0.3 microns. This creates an ultra-fine aerosol droplet and as the droplet sizes get smaller, the number of droplets generated for a given mass concentration increases dramatically as previously shown in Figures 2&3.

Particulate Resistivity

One of the differences between dry and wet ESPs is how the particulate resistivity affects the ESPs. In a wet ESP, as particulate is minimal and collecting electrodes are continually cleaned, particulate is immediately captured and washed from the collecting electrodes. With no particulate buildup on the collecting electrodes, potential problems with back corona are eliminated. Particulate resistivity is temperature dependent and as the temperature decreases, so does the resistivity. This makes the particulate easier to collect than with a dry ESP without the problems of particulate re-entrainment as the particulate is immediately removed when it is collected. In other words, resistivity of the particulate does not play a significant factor into the sizing of the wet ESP. Because of this, wet ESPs can be sized to higher precipitator velocities and lower specific collecting areas (SCA) than dry ESPs.

However, a high volume of sub-micron particulate entering the wet ESP can lead to corona or current suppression. Current suppression reduces wet ESP efficiency and can occur at particulate loadings of just 0.1 gr/acf (0.2 g/m3). Most suppliers of wet ESPs utilize a high intensity discharge electrode to combat current suppression.

Resistivity of the particulate plays a significant role in the sizing and performance of dry ESPs. Resistivity can be broadly divided into three grades; low ($<10^9$ ohm-cm), moderate (10^9 – 10^{11} ohm-cm) and high ($>10^{11}$ ohm-cm). Ideally dry ESPs prefer and operate best with particulate in the moderate range. This allows the ash layer to form on the plates and mostly shear off into the hoppers when rapped. High resistivity particulate leads to back corona where the flow of positive ions from the ash layer on the collecting plate effectively hampers the precipitator process. Low resistivity particulate, though less harmful than high resistivity, results in the ash layer quickly losing its charge and having a higher propensity to re-entrain into the gas stream during rapping.

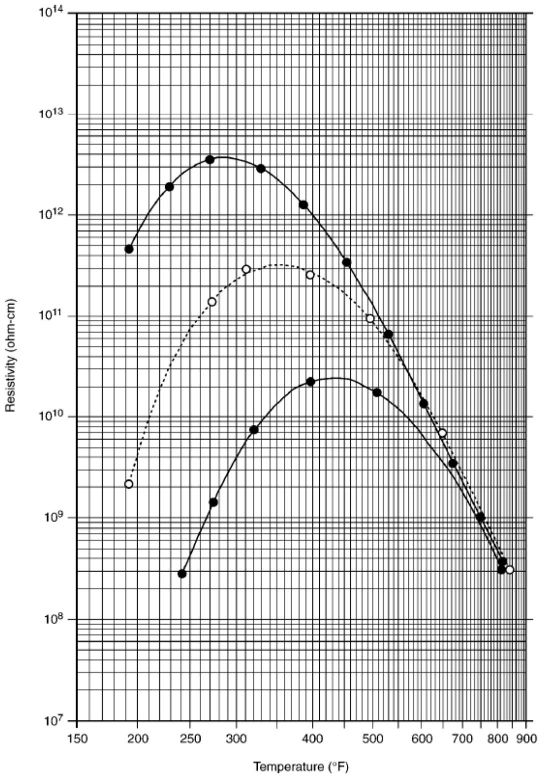


Fig. 12 Resistivity Curves for Low, Moderate and High Resistive Particulate[7]

Water Usage

Another major difference between dry and wet ESPs is the collection and disposal of particulate. Collected flyash from dry ESPs is collected as solid waste and is typically able to be land-filled, reused in the process or sold. As wet ESPs use wash water to collect the particulate on the collecting electrodes, the water demands and effluent needs to be addressed. The wet ESP can use once-through water or a recycle system with bleed incorporated. With a scrubber, the wet ESP effluent can be pumped back into the scrubber for mist eliminator wash water and with first use of the water meant for the wet scrubber; there is no additional water burden from the wet ESP. If no scrubber is present, water treatment facilities or other modifications may be required to handle the effluent.

7. Installations

Dry ESPs have been installed on just about every utility and industrial process that requires removing particulate from a gas stream.

Because of the conditions that they operate under (high temperature, typically above acid dew point), dry ESPs can be fabricated from mild carbon steel making them relatively inexpensive. Internal collecting electrodes are typically gauge thickness carbon steel, and recent designs utilize unbreakable, rigid frame or rigid discharge electrodes.

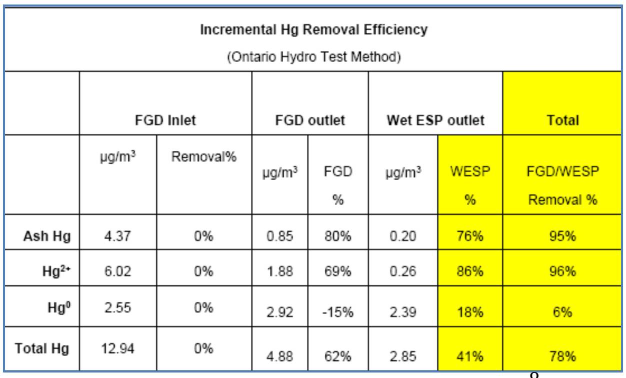
Wet ESP technology has become a standard component in the sulfuric acid industry to capture sub-micron H_2SO_4 aerosol. Wet ESPs have been employed in many different industrial applications for plume reduction associated with $PM_{2.5}$ and H_2SO_4 mist, as well as abatement of toxic metals.

Due to the saturated and high-corrosive environment in which they operate, wet ESPs are typically constructed of corrosion resistant materials such as alloy steel, FRP or plastics. The material chosen will have to withstand the concentration of acid gases and sulfur oxides in the flue gas stream as well as temperature surges. While physically smaller than a dry ESP, the materials of construction make the wet ESP more expensive.

8. Mercury Control

In recent years in the U.S., mercury emissions regulations have gone into effect throughout utility and industrial sectors. In flue gas, mercury exists as either a vapor or particulate. Vapor phase mercury is further broken down into elemental mercury (Hg^o) and oxidized mercury (Hg^{2+}), which is water soluble. Particulate mercury (Hg^P) exists as a solid. In dry ESPs, particulate mercury may be captured but any elemental or oxidized mercury will pass through. However, vapor phase mercury can be captured in a dry ESP with the use of an activated carbon injection system. These systems inject activated carbon into the ductwork upstream of the dry ESP which allows the activated carbon to adsorb the vapor phase mercury into its pores. These systems can achieve mercury removal efficiencies of 90%+.

There has been very limited testing of mercury removal through a wet ESP. However, the testing that has been performed has shown that a wet ESP will capture any particulate bound Hg as $PM_{2.5}$ with high efficiency as well as some oxidized mercury. Interestingly, a small fraction of elemental mercury was found to oxidize within the wet ESP, which most likely occurs from the reaction with ozone generated within the wet ESP. Therefore, a wet ESP can enhance mercury capture as a secondary free co-benefit.



Incremental Hg Removal Efficiency

(Ontario Hydro Test Method)

	FGD Inlet		FGD outlet		Wet ESP outlet		Total
	μg/m^3	Removal%	μg/m^3	FGD %	μg/m^3	WESP %	FGD/WESP Removal %
Ash Hg	4.37	0%	0.85	80%	0.20	76%	95%
Hg^{2+}	6.02	0%	1.88	69%	0.26	86%	96%
Hg^0	2.55	0%	2.92	-15%	2.39	18%	6%
Total Hg	12.94	0%	4.88	62%	2.85	41%	78%

Fig. 13 FGD/Wet ESP Hg Removal[8]

9. Performance

Both wet and dry ESPs are cable of high efficiency removal. Dry ESPs have consistently demonstrated 99%+ removal efficiencies for filterable PM_{10} and certainly in the 90+% range for filterable $PM_{2.5}$. However, $PM_{2.5}$ generated also contains condensables that the dry ESP cannot remove as they exist as vapor at the high temperatures that dry ESPs operate within. Wet ESPs have demonstrated 99%+ removal of total $PM_{2.5}$ (filterable and condensable), droplets and H_2SO_4 as well as having some mercury removal as indicated in the previous section. Current-day state of the art power plants have recognized the advantages of installing both dry and wet ESPs in the air quality control system where there is a wet scrubber installed.

Siemens has provided dry ESPs and wet ESPs in series on three (3) large utility coal-fired boilers and one (1) coal-fired utility with a fabric filter and wet ESP in series. Performance results are provided below in Figure 14. Site "A" air pollution control consists of hydrated lime injection, activated carbon injection, fabric filter, wet scrubber, wet ESP. Site "B" APC consists of dry ESP, hydrated lime injection, activated carbon injection, fabric filter, wet scrubber, wet ESP. Sites "C" and "D" APC consist of hydrated lime injection, activated carbon injection, dry ESP, wet scrubber, wet ESP.

	Site A	Site B	Site C	Site D
FPM*	0.0019	0.0007	0.007	0.006
TPM**	0.013	0.005	0.020	0.011
H_2SO_4	0.0047	0.0004	0.0001	0.0033
Hg	6.4E-7	4.9E-7	6.7E-7	3.9E-7

*Filterable particulate

**Total particulate (filterable and condensable)

Fig. 14 Stack Emissions Results in lb/MMBtu

As can be seen in the table above, the wet ESP acts as a final polishing device providing near-zero emissions. Also note that with the future possibilities of carbon dioxide regulation, sites with a wet ESP installed are "CO_2 ready" as CO_2 scrubbing requires very low inlet pollutant levels of particulate matter, sulfuric acid SO_2, etc.

10. Summary

Dry and wet ESPs can be utilized effectively for high efficiency removal. In order to maximize their effectiveness, it is important to understand the advantages and limitations of the technologies. The following table provides a summary of the discussion points presented above.

Parameter	Dry ESP	Wet ESP
Purpose	Primary PM Control Device	Polishing Device
Location	First APC Device	Last APC Device
Configuration	Horizontal Plate	Vertical Tubular or Horizontal / Vertical Plate
Humidity	5-20%	100%
Temperature	250-800°F (120-425°C)	<150°F (65°C)
High PM Loading	Yes	No
FPM_{10} Removal	High	Limited
$FPM_{2.5}$ Removal	Moderate	High
PM Condensables Removal	No	High
H_2SO_4 Removal	No*	High
Mercury Removal	No*	Moderate
SCA	300-800	50-200
Gas Velocity	3-5 ft/sec 0.9-1.5 m/sec	6-10 ft/sec 1.8-3.0 m/sec
Pressure Drop	< 2 in.w.c. (0.5 kPa)	< 2 in.w.c. (0.5 kPa)
Water Usage	No	Yes
Waste Water Treatment	No	Yes
Resistivity Issue	Yes	No
Back Corona	Possible	No
Re-Entrainment	Possible	No
Mat'ls of Constr	Carbon Steel	Stainless Steel, minimum
Cost	Low / Moderate	Moderate / High

*Unless treated with sorbent injection

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