APPLICATION OF WET ELECTROSTATIC PRECIPITATION TECHNOLOGY (WESP) IN THE UTILITY INDUSTRY FOR MULTIPLE POLLUTANT CONTROL INCLUDING MERCURY

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Abstract
Wet electrostatic precipitation technology can be used to control acid mists, sub-micron particulate, mercury, metals and dioxins/furans as the final polishing device within a multi-pollutant air pollution control system. Test results from coal –fired installations demonstrate >90% removal efficiencies on PM2.5, SO3, and near zero opacity. Additionally, wet ESP technology (WESP) can be used for mercury removal. How wet ESPs work, what configurations they come in and some of the design considerations are described. New developments to wet ESP technology to reduce cost, make higher performance efficiency removal in less space (single pass dual field, US Patent 6,508,861) and enhance mercury control will also be discussed.

Introduction

Power utilities are coming under increased scrutiny from regulators, the public and environmental groups. The ready availability of information about power plant emissions, along with recognition of the effects of acid gases, fine particulate and toxic chemicals on the environment and human respiratory systems, are forcing utilities to control their emissions to a much greater degree than ever before. The U.S. Environmental Protection Agency (EPA) has issued regulations to control PM10, NOx and SO2. New regulations to control mercury, PM2.5 and other hazardous air pollutants are being proposed. The trend is clear: EPA is seeking to control a multitude of pollutants that are comprised of smaller and harder-to-capture sub-micron particles, mists and metals.

The first ESP developed was actually a wet ESP to remove a sulfuric acid mist plume from a copper smelter designed by Dr. Cottrell in 1907. The technology has become a standard piece of process equipment for the sulfuric acid industry for over 50 years to abate SO_3 mist, a sub-micron aerosol.
In the past twenty years, wet ESP technology has been employed in numerous industrial applications for plume reduction associated with PM2.5 and SO_3 mist, as well as for removal of toxic metals. Unfortunately, wet electrostatic precipitation is a relatively unknown technology to most industries and utilities because air regulations up to recently have not required high levels of control of sub-micron particulate.

Most utility facilities already have some sort of dry technology installed to control particulate emissions, such as a cyclone, fabric filter or dry ESP. Where acid gases or condensable particulate may be present in a gas stream, a scrubber or gas absorber is typically in place. However, as regulations emerge requiring stringent control of sub-micron particulate—which includes acid mists, low and semi-volatile metals, mercury, and dioxins/furans—wet ESP technology is increasingly attractive due to its low pressure drop, low maintenance requirements, high removal performance and reliability as a final polishing device.

ESP Operation

Electrostatic precipitation consists of three steps: (1) charging the particles to be collected via a high-voltage electric discharge, (2) collecting the particles on the surface of an oppositely charged collection electrode surface, and (3) cleaning the surface of the collecting electrode.

As particles become smaller, gravitational and centrifugal forces become less powerful, while electrical and, to a lesser degree, Brownian forces become greater, especially for 0.1 to 0.5-micron particles. Consequently, electrical collection is an effective method for separating those sub-micron particles from the gas stream.

TABLE 3

PARTICLE DISPLACEMENTS IN STANDARD AIR DUE TO VARIOUS FORCE FIELDS

PARTICLE DIAMETER *Displacements in 1 sec. for force field listed*

Size in Microns	Feet	Cc*	Grav. **	Cent***	Elect. ****	Brown. ** ***
10.0	3.28 x 10 (-5)	01.016	.024	20.5	0.98	.0000057
1.0	3.28 x 10 (-6)	01.165	.00027	00.235	0.11	.0000194
0.1	3.28 x 10 (-7)	02.93	.0000069	00.0059	0.27	.0000972
0.01	3.28 x 10 (-8)	22.6	.00000053	00.00046	2.12	.0008540

* Stokes Cunningham slip-correction factor-dimensionless

** Gravitational force field-downward linear displacements based on 32.2 ft./s2 acceleration

*** Centrifugal force field-outward radial displacements based on 862 g's acceleration

**** Electrostatic force field-normal linear displacements based on 7500 volts/in. Field strength and a saturation charge on the particles.

***** Brownian movement-random linear displacements based on average values

Most importantly, whereas mechanical collectors exert their force upon the entire gas, ESPs exert their force only upon the particles to be collected. ESPs typically operate at around 0.5-1.0 inch pressure drop, regardless of air volume or particle size. Alternatively, a mechanical collector such as a venturi scrubber would have to operate at around 60 inches of water column to achieve 95 percent collection efficiency on 0.5-micron particles. This is a major reason why dry ESPs are predominantly used in the utility industry. Every inch of pressure drop translates into dramatically higher energy requirements for operating the ID fan. To achieve 95 percent removal efficiency on 0.5-micron particles in a 1,000,000 cfm air flow, 12,000 kW of energy is required using a venturi scrubber, while an ESP needs only 100-200 kW of energy for I.D. fan operation.

Dry ESPs

Dry ESPs consist of a series of parallel vertical plates, which act as the collecting electrodes, with a series of discharge electrodes in between the plates spaced some distance apart. As the contaminated flue gas passes through the ESP, negatively charged ions form near the tips of the sharp points of the ionizing electrode (corona discharge). These negatively charged ions move toward the positively charged collecting electrode surface and charge the contaminated particles passing through the ESP. These charged particles become attracted to the positively charged collection plate, where they accumulate on the surface. The collected particulate builds up on the dry collection surface and forms a layer of particles or "cake" that has insulating properties.

Dry ESPs perform best when particle deposits on the collecting plates have a resistivity greater than approximately 10^7 ohm-cm, but less than 2×10^{10} ohm-cm. If resistivity is less than 10^7, the electrostatic force holding the dust particles on to the dust layer is too low and re-entrainment of particles in the flue gas can become a serious problem, reducing efficiency. If resistivity exceeds 2×10^{10} ohm-cm, the voltage drop through the particle layer to the grounded electrode becomes significant, lowering field strength in the space between the ionizing electrode and the top of the dust layer. This can cause a breakdown in the electrical field and "back corona" can take place, again lowering efficiency. Resistivity becomes a limiting factor to the amount of electrical power that can be achieved within a dry ESP.

To dislodge the dust from the collecting electrode surface and into the bottom hopper, mechanical rappers or sonic horns are employed. However, portions of the particles remain suspended in air and get re-entrained in the gas stream. This secondary re-entrainment requires the use of another dry ESP field to collect the re-entrained particulate plus those particles not captured in the first field.

Dry ESPs have been used successfully for many years in industrial and utility applications for coarse particulate removal. Dry ESPs can achieve 99+ percent efficiency for particles 1 micron to 10 micron in size. However, they have several limitations that prevent their use in all applications:

- Dry ESPs are not capable of removing toxic gases and vapors that are in a vapor state at 400°F.
- Due to their low corona power levels because of resistivity of the particulate cake, dry ESPs cannot efficiently collect the very small fly ash particles.
- Dry ESPs cannot handle moist or sticky particulate that would stick to the collection surface.
- Dry ESPs cannot remove oxidized or elemental mercury
- Dry ESPs require a lot of real estate for multiple fields due to re-entrainment of particulate.
- Dry ESPs rely on mechanical collection methods to clean the plates, which require maintenance and periodic shutdowns.

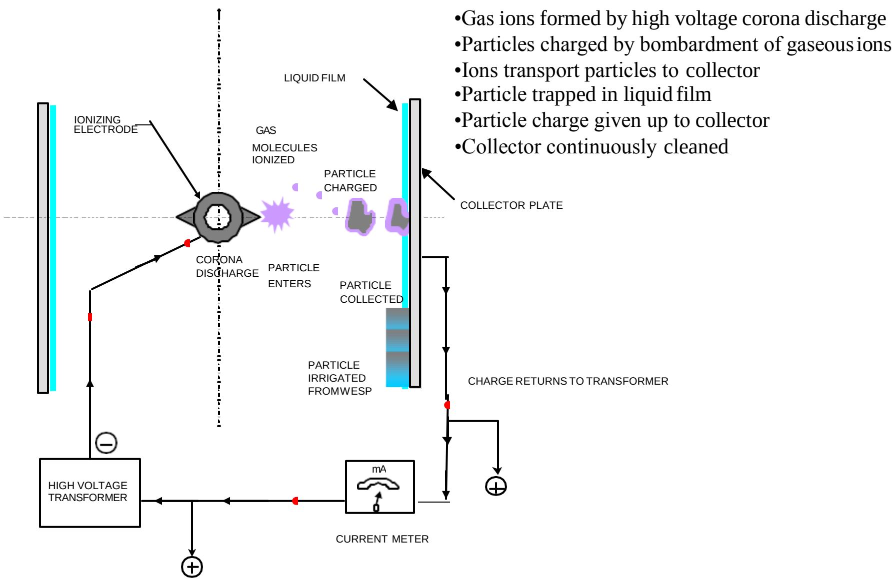
Therefore, dry ESPs may not be the best practicable control device to meet the proposed PM2.5 standard, or as a final mist eliminator for acid gas mist on FGD systems in order to reduce opacity levels to near zero.

Wet ESPs

Wet ESPs operate in the same three-step process as dry ESPs—charging, collecting and finally cleaning of the particles. However, cleaning of the collecting electrode is performed by washing the collection surface with liquid, rather than mechanically rapping the collection plates

(Figure 1).

Wet Precipitation Process



While the cleaning mechanism would not be thought to have any impact upon performance, it significantly affects the nature of the particles that can be captured, the performance efficiencies that can be achieved and the design parameters and operating maintenance of the equipment. Simply stated, wet ESP technology is significantly different than dry ESP technology.

Because wet ESPs operate in a wet environment in order to wash the collection surface, they can handle a wider variety of pollutants and gas conditions than dry ESPs. Wet ESPs find their greatest use in applications where gas streams fall into one or more of the following categories:

- The gas in question has a high moisture content;
- The gas stream includes sticky particulate;
- The collection of sub-micron particulate is required;
- The gas stream has acid droplets or H2SO4
- The temperature of the gas stream is below the dew point.

Because wet ESPs continually wet the collection surface area and create slurry that flows down the collecting wall to a recycle tank, the collecting walls never build up a layer of particulate cake.

Consequently, there is no deterioration of the electrical field due to resistivity, and power levels within a wet ESP can be dramatically higher than in a dry ESP. The ability to inject much greater electrical power within the wet ESP and elimination of secondary re -entrainment are the main reasons a wet ESP can collect sub-micron particulate more efficiently.

The captured particulate flows down the collection wall in suspension to a recycle tank for treatment and never gets re-entrained into the flue gas. This reduces the need for multiple fields, as in a dry ESP where additional fields must be added to capture re- entrained particles from the previous field.

Wet ESPs are most effective for submicron particulate control. Smoke plume from a stack is the sign of the presence of sub-micron particles in a gas stream. Due to refraction of sunlight, 0.5- micron particles are the most visible. Additionally, the surface area of the smallest particles in a flue gas is greater than the surface area of larger particles. One gram of 0.1-micron particles has 10 times the surface area as a gram of 1.0-micron particles (60 m^2 vs. 6.0 m^2). Toxic vapors however, condense uniformly on the surface area of all particles. That is why the capture of a gram of 0.1-micron ash particles is 10 times more effective at removing toxic pollutants than the capture of a gram of 1.0-micron ash particles.

In wet ESPs, the delivery mechanism for the irrigating liquid is critical to maintain thorough wetting of the collecting electrode surface to avoid corrosion issues without degrading the electrical system.

Collection Efficiency

For a given particulate or droplet size and concentration, ESP efficiency can be calculated by using the exponential Deutsch-Anderson equation. Field experience has shown that, with some modification, the same equation can also be applied to wet ESPs. The Deutsche-Anderson equation is:

$$\text{Eff} = 1 - \text{Exp}(-Aw/V) \qquad [1]$$

Where the collecting electrode surface area, *A*, and volumetric flow rate, V, are calculated from the known geometry of the ESP and the process design data. The drift, or migration velocity, *w*, is determined by the operating power (watts/1000ACFM) and particle size distribution.

There are two types of charging processes at work in an ESP. For particles greater than 1 micron, “field-charging” is primary and refers to particles being charged through the collision of negative ions as they follow the electric field lines to the surface of the particles. The peak operating voltage is the most important factor in field charging. For particles smaller than 0.5 micron, “diffusion-charging” is primary and occurs because of the random motion of the sub-micron particles and their collision with negative ions. The current density injected into the ESP is the most important factor in diffusion charging.

Wet ESPs are capable of removing sub-micron particles, droplets, and mists as small as 0.01 micron in size up to 99.9+ percent efficiency depending upon the number of fields employed and can achieve near zero opacity levels.

Tubular vs. Plate
Wet ESPs can be configured either as tubular precipitators with vertical gas flow or as plate precipitators with horizontal gas flow (Figure 1). For a utility application, tubular wet ESPs would be appropriate as a mist eliminator above a FGD scrubber, while the plate type could be employed at the back end of a dry ESP train for final polishing of the gas in a hybrid ESP. In general, tubular precipitators are more efficient than the plate type and take up less space due to simple geometry. A tubular wet ESP is just a horizontal ESP turned vertical with all four sides enclosed to act as collection surface. Other differences between the two types are:

- **For a given efficiency, a tubular precipitator may be operated at twice the gas velocity of a plate precipitator of equal electrode length**
- **For a given efficiency, a tubular precipitator has a smaller footprint than a plate type precipitator.**

Tubular precipitators can be designed as either up-flow or down-flow. In up-flow tubular ESPs, flue gas enters at the bottom of the ESP and flows upwards. The wash nozzles are located at the bottom spraying up into the ESP, co-current with the gas. In some cases, nozzles that spray down into the field are added above the field. In down-flow designs, the flue gas enters the top of the wet ESP and flows downwards. Similarly, the sprays are mounted on top, spraying down co- current with the gas.

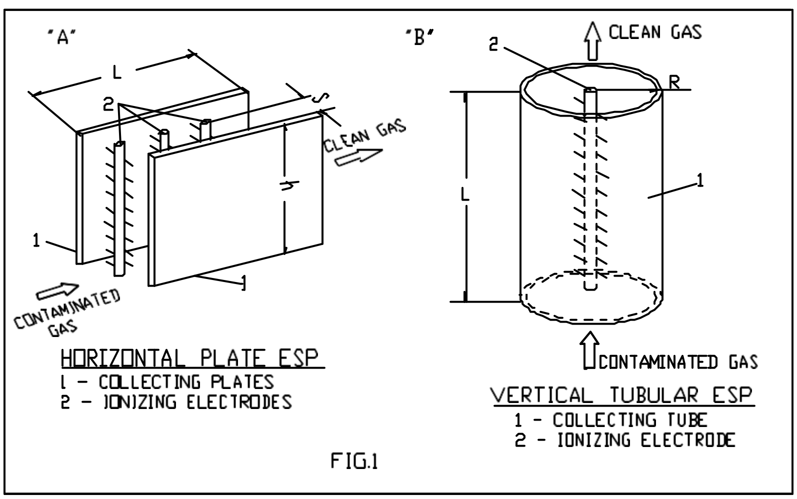


Figure1: The comparison of a tubular WESP vs. a plate type WESP shows that, for a given efficiency, a tubular WESP can operate at twice the velocity of a plate type WESP, resulting in a smaller footprint (Applicable mostly for new construction).

While in some installations a down-flow design may minimize inter-connecting ductwork, it will require a mechanical mist eliminator to capture the water mist that has been carried along with the flue gas before entering the stack. Conversely, an up-flow, tubular wet ESP is an excellent mist eliminator due to its ability to capture sub-micron droplets and requires no mechanical mist eliminator.

Air Distribution
Distribution of the flue gas throughout the wet ESP is a critical design function. Overloading a section of

the wet ESP will negatively impact collection efficiency. While perforated plates below the electrical section will aid in proper air flow distribution, an alternative is using some sort of scrubber in front of the wet ESP. This accomplishes multiple purposes:

- Removal of any acid gas present, which reduces corrosion in the wet ESP and allows for less expensive materials of construction to be used (i.e., FGD application)
- Removal of particulate larger than 2 microns, which reduces the particulate loading on the wet ESP and allows for smaller size of the wet ESP
- Cooling of the gas, which reduces the gas volume and cuts down on the size of the wet ESP
- Saturation of the gas, which enhances condensation within the wet ESP
- Enhanced airflow distribution throughout the wet ESP due to limited pressure drop.

Sparking

Since wet ESP efficiency is directly proportional to the electrical power conveyed to the moving gas, each time a spark occurs, the voltage, and consequently the particulate collection efficiency, is reduced. Sparking rate for a given inter-electrode spacing is a function of the inlet loading (mist, droplet, or particulate) and alignment of the discharge electrodes. Additionally, the power level and efficiency of a wet ESP can be dramatically increased by properly designing the automatic voltage control system. While the industry average seldom goes beyond 50 percent conduction (i.e., the ability to deliver 50 percent of the available power to the gas), the proper selection of the transformer-rectifier (T/R), automatic voltage controller (AVC) and current limiting reactor (CLR) can deliver much greater conduction.

Corona Current Suppression

If there is a high loading of charged particles, corona current is diminished due to the low mobility of charged particles in the inter-electrode space. This phenomenon is called current suppression or space charge effect. A high concentration of fine particles, a typical scenario for space charge effect, can reduce the corona current by a factor of 10 (typical for power plant Applications) or more.

Certain criteria should be met in order to prevent the deterioration of removal efficiency in the presence of a space charge effect. The level of current suppression that will be experienced in a particular application is related to the total surface area of the suspended particles and the designed corona current density within the given volume of the wet ESP collection section. For example, particles of 0.6- micron diameter have 100,000 cm^2/gram of surface, whereas particles of 0.3-micron diameter have more than 10 times the surface area per unit weight (1,100,000 cm^2/gram). For a given grain loading, the finer the particle, the more potential there is for current suppression to occur.

In the case of multiple fields in a wet ESP, collection efficiency can be maintained even in the presence of current suppression. The first pass will operate in “suppressed” conditions at a somewhat reduced efficiency level, but will condition the gas for the second pass, which will operate at its full design potential.

Materials of Construction

A wet ESP's collection section can be made out of any conductive material. However, the material chosen must be corrosion resistant to any acid mist contained in the flue gas. Wet ESPs have been made out of conductive fiberglass, carbon steel, various stainless steels and various high-end alloys depending upon the duty intended. Most multi-pollutant applications for wet ESPs typically employ some sort of scrubber in front of the wet ESP to remove corrosive acid gases. Material selection should be based upon a "worst-case" scenario analysis in order to protect the equipment against upset conditions. Alternatively, the water sprayed into the ESP can be treated to neutralize acids collected within the WESP. Proper pH control is essential to maintain integrity of the equipment.

Modular

Like dry ESPs, wet ESPs can be modular. Each field is limited in size to the power of the available transformer. The largest transformers available today are 70,000 V @ 2500 mA of installed electrical power. Depending on the specific application (large air flow or heavy inlet loading), multiple sections can be arranged together, either in series or in parallel, to achieve the required efficiencies.

Utility Application

Coal fired plants are starting to recognize the need for wet ESP technology to reduce opacity related to PM2.5 and SO3 concentrations in the flue gas as States start to mandate more stringent opacity limits.

Northern State Power's Shirco Station with two 750 MW boilers installed the first full-scale wet ESP in the country to reduce opacity. Eleven modules/unit of tubular, up flow wet ESP technology were installed after a FGD system and opacity was reduced to less than 10% with 22 Wet ESP modules in

Sherco 1 & 2 opacity over time

service.

In several instances where plants have installed SCR technology with ammonia injection on high sulfur coal and FGD systems are installed, increased plume resulted from higher levels of SO_3 and fine ammonia salt concentration in the flue gas. These plants are considering installing a wet ESP after the FGD system to capture the additional SO_3 and ammonia salts, which cannot be captured in the FGD system due to their sub-micron nature. Therefore, for the 25% of coal fired plants that burn high sulfur bituminous coal that have FGD systems installed, installing a wet ESP is the next logical step to meet opacity, PM2.5 SO_3 and mercury standards.

Tubular Pilot Wet ESP at First Energy's Bruce Mansfield Station

Under Dr. Ray's supervision was installed and tested a pilot wet ESP at a major coal-fired plant in 2001. This plant burns 3% bituminous coal and has a FGD system installed for PM10 and SO_2 control. A 5,000 acfm slipstream, tubular pilot wet ESP was installed for PM2.5 and SO_3 control, the two primary contributors to stack plume. Speciated mercury testing was also performed to measure collateral benefits of installing wet ESP technology.

Summary of Pilot Wet ESP Test Results- Bruce Mansfield Plant –2001-2002

					Mercury		
	PM2.5		SO_3 Mist Tests		Particulate	Oxidized	Elemental
Average of all Tests							
Test Series	Sep-01	Nov-01	Sep-01	Nov-01	Sept –01	Sept -01	Sept –01
Airflow-acfm	8394	8235	8394	8235	8000	8000	8000
Velocity – ft./sec.	10	10	10	10			
# of fields	1	2	1	2	1	1	1
Power Levels	100%	100%	100%	100%	100%	100%	100%
					ug/dscm	ug/dscm	ug/dscm
Inlet	0.0292	0.0506	11.475	10.01	0.011	0.689	6.245
Outlet	0.0063	0.002	2.7	0.85	0.004	0.158	3.474
Removal %	**79%**	**96%**	**76%**	**92%**	**64%**	**77%**	**44%**

An initial series of tests completed during Sept. of 2001 were performed in a single electrical field at approximately 8,000-cfm. Removal achieved at this higher than designed for airflow was 79% for PM2.5 and 76% for SO_3. Mercury testing during this time period showed 64% for particulate, 77% for oxidized and 44% for elemental. Removal levels for particulate and oxidized mercury were similar to that for PM2.5 and SO_3. Most importantly, 44% removal of elemental mercury was measured at the highest inlet concentration. Mercury levels were extremely low because most of the particulate and water soluble HgCl was already removed in the upstream FGD system. It is estimated that at higher inlet levels, higher removal efficiencies would be expected.

In order to improve removal efficiency within the wet ESP pilot, the electrical system was subsequently retrofitted from a single to a two-field configuration. New test results on PM2.5 and SO3 improved to 96% and 91% respectively.

Observation Tube

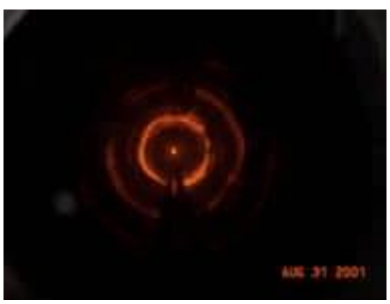
In order to estimate opacity on this slipstream application, we suggested supplying a 19' long observation tube to that is the same diameter as the top of the stack. A light source provided at one end

With an observation port at the other allows for direct visual observation. The pictures below show the results at varying power levels.

10,000 cfm wet ESP unit at Bruce Mansfield plant

Observation tube – 19' long to simulate diameter of top of stack.

<u>Pictures looking down the observation tube</u>



Looking down observation tube with minimal power.

Looking down observation tube with some power on in the WESP.

Looking down observation tube with maximum power on in the WESP.

Mercury Control –Plasma Enhanced ESP Technology

Mercury adsorbed onto particulate and oxidized forms of mercury are readily removed from the flue gas using a wet scrubber or flue gas desulfurization system. However, the remaining elemental mercury vapor passes through the air pollution control devices unabated. Most mercury research has focused on sorbent injection followed by a bag house for those plants without an FGD system, typically where low sulfur coal is used.

Tests of wet ESP technology at the Bruce Mansfield pilot plant indicate that a wet ESP can remove both oxidized and particulate forms of mercury at similar levels to that for PM2.5 and SO_3. Mercury testing showed 64% for particulate, 77% for oxidized in the single electrical field configuration. Most importantly, 44% removal of elemental mercury was measured at the highest inlet concentration. Mercury levels were extremely low because most of the particulate and water soluble HgCl was already removed in the upstream FGD system. It is estimated that at higher inlet levels and /or a dual electrical field configuration, higher removal efficiencies would be expected.

In 2012 EnviroEnergy Solutions, Inc has developed, Patented and tested revolutionary new process of Mercury removal based on the molecular interaction with molecules of free radicals that are present in the gas that is exposed to the strong high voltage field. **(See our Patent US 9,533,311 of Jan.3, 2017).** According to the Invention the Mercury separated from the moving gas does not enter the recycling loop of the liquid but being segregated and thus eliminated from the environment recycling loop.

Conclusion

Wet ESP technology is a proven, well-known technology that can achieve very high removal of mists, particles and aerosols with low pressure drop and minimum maintenance, if properly designed and built. Whereas it has traditionally been installed after a FGD system in a saturated flue gas as a final wet electrostatic mist eliminator, it can be installed in the up-flow multi-pass configuration or down –flow as a self supported unit next to the FGD tower, to increase collection of PM2.5, SO3 and mercury and reduce opacity.

In order to minimize the cross section , material and eventually the cost of the unit the WESP's collector section should be of square tubular type that allows 2 times higher velocity for the same collection efficiency according to equation [1]

Successful demonstration of these various developments will offer coal-fired plants using either bituminous, sub-bituminous or lignite coal a reliable control technology that has multi-pollutant capability for reducing PM2.5, SO_3 mist, mercury with the co-benefits for some SO_2 and HCL trim control.

Key Words
Wet electrostatic precipitation
Wet ESP