A REPORT

ON

STUDY OF ELECTROSTATIC PRECIPITATORS

BY

NAME OF STUDENTS	ID NUMBER
DIVYANSH GUPTA	2014B3A8606G
DEEPAK PATEL	2014B2A3708P
PRIYANJAL JOY	2014A4PS357P

AT

VINDHYACHAL SUPER THERMAL POWER STATION (VSTPS), SINGRAULI

A PRACTICE SCHOOL I STATION OF

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCES, PILANI

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Key Words: Electrostatic Precipitator, Corona Quenching and Back-Corona discharge.

Abstract: This report thoroughly discuss about industries one of the most important component, Electrostatic Precipitator. It has very high collection efficiency and is also very energy efficient. Various principles of electrostatic precipitation like conditioning of particles, collection efficiency, and dust layer resistivity are described. The report also includes phenomenon of back corona of high resistivity dust and corona quenching for fine dust particles which affects the performance of an ESP. The report also discusses the new research which being conducted in this field. Also the report provide some alternate solution to the existing problems which can enhance the performance of an ESP.

Signature of PS Instructor **Signature of Supervisor** **Signature of Students**

Date: - **Date: -** **Date: -**

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ABSTRACT

Electrostatic Precipitators are one of the most important industrial component and are widely used in industries and they also play an important role in controlling the environmental pollution. Electrostatic Precipitators are very efficient as it can operate with high collection efficiency with a low pressure drop. They are also energy efficient and wastage of energy in the working of an Electrostatic Precipitator is also minimum.

In this report, principles of an Electrostatic Precipitation, such as conditioning of particles, collection efficiency, dust layer resistivity, particle size distribution, are described. Performance of an Electrostatic Precipitator deteriorates by abnormal phenomenon, including back corona of high resistivity dust and corona quenching for fine dust, are also described.

To cope up with these above phenomenon, new technologies and recent changes which had been developed are also described. The report also tries to find out solutions to the existing problems which can enhance the performance of an Electrostatic Precipitator. The report also provide some other guidelines which can enhance the performance too.

There is also the brief discussion on various types of Electrostatic Precipitators, which are used in various types of industries.

INTRODUCTION

Coal-fired power generation is the main source of power production in India. According to the reports from the Ministry of Power nearly 54.5% of the energy requirement of India is fulfilled by coal combusting.

From burning this much amount of coal in power plants, tons of ash is produced daily. This ash which is produced is of two type, one the bottom ash and the other fly ash. Bottom ash is collected in a chamber below the boiler unit, but the fly ash is taken away from the boiler with the flue gases, which are emitted from the chimneys untreated. As to the knowledge fly ash constitute nearly 80% of the total ash produced. Thus releasing this much amount of ash in the environment untreated is very hazardous for the health of the living being as there are many toxic gases also present in this mixture, like sulphur dioxide, nitrogen dioxide, ozone and many others.

As the environmental guidelines become stricter, releasing of untreated fly ash become prohibited. So then devices which can collect fly ash are being developed.

One of the device developed is the Electrostatic Precipitator (ESP). It is very much more efficient than the other devices. It uses the principle of Electrostatic precipitation for collecting the dust particles from flue gases. It is very effective as its efficiency is very high which nearly tends to 100% and is also energy efficient.

It is now being transformed in various types, according to its use in different types of industries and factories. It is now-a-days is also uses as the air-cleaner for domestic purposes in many of the metro cities as the surrounding air is so much polluted to inhale.

Current researches on Electrostatic Precipitators are normally focuses on to their working with dust of different resistivity and increasing the life-time of them. Now-a-days Electrostatic precipitators are also coming up with denitrification and desulphuring units, so that nitrogen and sulphur oxides do not directly emitted in the environment.

1. Smoke, Flue Gas and Fly Ash

1.1 Smoke

Smoke is the volatile matter or the vapour which escapes from a burning substance during the combustion process, especially the visible vapour produced by the burning of wood, coal etc. [a].Mostly smoke looks like a gas but it is actually an aerosol. Mostly aerosols are made up of liquid particles dispersed in gaseous medium but smoke is an aerosol of solid particles dispersed in liquid droplets.

1.2 Flue Gas

This is the combustion exhaust gas which is produced by burning of the combustible materials in a power plant. It is known as flue gas because it exits from the flue which is a pipe or channel. Its composition depends on the substance which is been burnt, like the grade of coal which is used in power plants, but it mainly consists of fly ash, Nitrogen and some amount of Carbon Dioxide, water vapour and unused oxygen. It also consists of small amount of number of pollutants like Soot, Carbon Monoxide, Nitrogen Dioxide, and Sulphur Dioxide as primary pollutants and H_2SO_4, SO_3, ozone and Nitrogen Oxides as secondary pollutants.

1.3 Fly Ash

Fly ash is one of the major coal combustion product which is composed of fine particles, which are driven out from the boiler with the flue gases. The components of fly ash also vary considerably, depending upon the grade of coal used for burning, but all fly ash includes substantial amounts of aluminium oxide (Al2O3), calcium oxide (CaO) and silicon dioxide (SiO2) (both amorphous and crystalline).

Constituent of coal used may differ from coal bed to another but it may include one or more of the following elements or substances which are found in the traces like Arsenic, Beryllium, Cadmium, Cobalt, Boron, Lead, Manganese, Molybdenum, Thallium, Strontium and Vanadium.

In the past, this fly ash was released directly in the atmosphere releasing all the harmful constituent directly in the surrounding environment.

Some of the constituent like Lead (Pb) reacts with Oxygen and form Lead Oxide which can cause cancer, also Nitrogen dioxide and Sulfur Dioxide are very harmful and causes acid rain. As the air pollution control standard become stricter, it become necessary not to release fly ash directly in the atmosphere.

There are many type of dust collecting methods which can be used to collect the fly ash without releasing it in the atmosphere.

Table 1 *Types of Dust Collection Equipment*

S. No.	Types of dust collector	Pressure drop (mmWc)	Collection Efficiency (%)	Remarks
1	Gravity Settling unit	25-30	30-40 %	Less efficiency, More space required and not suitable for use in power plant.
2	Inertial Collectors • Impact • Centrifugal	 30-40 60-80	 30-40 % 70-80 %	 Not use for power plant. Were used in Power plants earlier, but cannot satisfies the present day pollution control norms.

3	Scrubbers (Wet)	50-60	80-90 %	Can be used in process industries but still can't satisfy pollution control norms.
4	Electrostatic Precipitator	15-25	99.99 %	Can meet any efficiency and can be use in Power plants.
5	Fabric Filters	125-150	99.99 %	Can be used in power plant and can meet any efficiency.

Source: - NTPC Vindhyachal

From the above table we saw many types of dust collecting methods, in which the use of Electrostatic Precipitator is looking the best as it has the best dust collecting efficiency and also with very low pressure drop.

2. Electrostatic Precipitator

2.1 Definition

An Electrostatic precipitator is a filtration device that uses electric charge to remove certain impurities i.e. either solid or liquid and fine particles like dust and smoke from flowing gases while minimally impending the flow of gases through the units. An Electrostatic Precipitator applies energy only to particulate matter being collected and thus very efficient in energy consumption. It was originally designed for recovery of various important industrial material, Electrostatic Precipitator is now mainly use for removing fly ash particles from the flue gases in power plants and industries. It is also used as Air Purifier usually in urban places.

2.2 History of Electrostatic Precipitator

The first use of the principle of corona discharge was done by Hohlfeld in 1824 for removing particles from aerosol but cannot commercialize it that time.

In 1878, R. Nahrwold conducted an experiment with an electrified sewing needle and a tin jar. He noted that collection of atmospheric dust increases as the discharge current increases.

In 1907, Frederick Gardner Cottrell, a professor of chemistry in University of California, invented a device for charging the particles and then collecting it through electrostatic attraction which he used for collecting sulfuric acid mist and Lead Oxide fumes emitting from various acid making and smelting activities.

The first large-scale precipitator was a dust-busting device built by Western Precipitation for the Riverside Cement Company in 1911

In 1912, Cottrell with the help of German researchers understands the operational theory and incorporated more reliable rectifier transformer circuits of Electrostatic Precipitator which can sustain higher voltage.

2.3 Advantage of Using Electrostatic Precipitator

The main advantage of using Electros tic Precipitator is that it can collect dust particles from size varying from 0.01 µm to 100 µm with an efficiency more than 99 %. The other advantages are that it can operate at high temperature 1200°F (650°C) as well as in high pressure (up to 150 psi (10 atm)). It can also withstand high flow rates of fluids, up to 3,000,000 cfm (1500 cubic meter). Another advantage is that, it is very cost efficient as well as energy efficient, 200-1000 Watts. It has also high particle loading factor, 500 gram per cubic meter. It has also low pressure drop factor (as given in Table. 1).

2.4 Types of Electrostatic Precipitators

There are various types of industrials Electrostatic Precipitator according to their applications. They are classified as Vertical gas-flow and Horizontal gas-flow (Tubular Precipitator), Plate type (Plate-Wire and Flat Plate), One stage and Two stage (electrodes geometry), and dry and wet type (with and without water).

2.4.1 Plate-Wire Type: - In these types of Electrostatic Precipitators, gas flows between the parallel sheets of metal with high voltage electrodes. These electrodes are long weighed wires and are hanging between the plates or either supported by rigid frame from the top. Gas must flow through the path which have these wire in the unit. These types of Precipitator allows many flow lanes to operate in parallel, and each lane can be quiet tall. Thus these types of Precipitator can handle large volume of gas at any particular time.

These types of Precipitators are divided into many sections to dislodge the dust which is collected by rapping process. These types of Precipitator works on DC current, so the industrial AC current is converted into DC current. This applied voltage causes the gas between the electrodes to break down electrically which is known as 'corona discharge'.

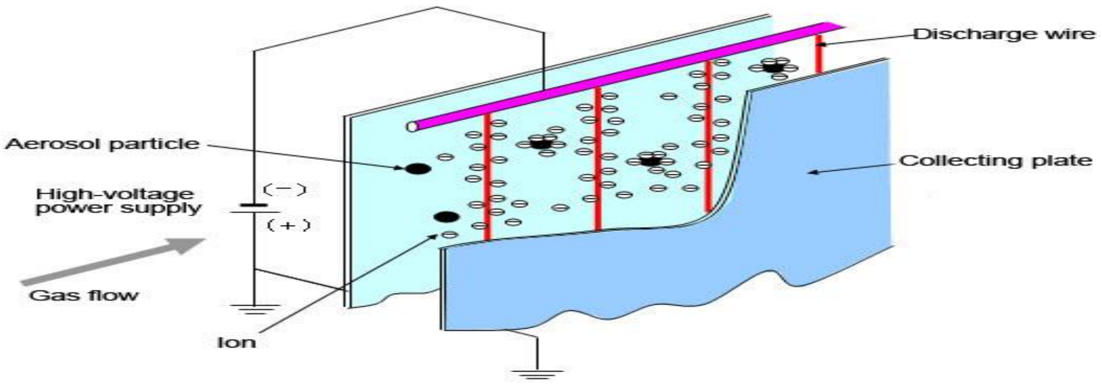

Figure 1 Wire-plate type Electrostatic Precipitator

Source: -hitachi-infra.com.sg

2.4.2 Flat-Plate Precipitator: - These types of Precipitator are used in small scale industries (100,000-200,000 acfm). These Precipitators uses flat plate instead of wires for high voltage

electrodes. The flat plate used provide an increased surface area for collection of particles due to increase in average electric field created.

Corona-Discharge cannot take place by itself in these Precipitators, so the Corona generating electrodes are installed ahead of or sometimes behind the flat plate electrodes. Unlike plate-type and Tubular-type Precipitator, these electrodes works well with either positive or negative polarity. These type of Precipitator have wide application use for high particle resistivity with small mass median diameter.

2.4.3 Tubular Precipitator: - The initially designed ESPs were all tubular, with high voltage electrode running along the axis of the tube. These types of Precipitators are widely used in iron and steel sinter plant, sulfuric acid plants and coke oven by-product gas clearing plants. Such tubular units are still in use, with many tubes operating in parallel to handle the increase gas flow. The tubes may be formed as square, circular or either hexagonal honeycombed structure with gas flowing downwards and upwards. A tubular ESP is tightly sealed so that hazardous material cannot leak from it. All the gas passes through the one gas electrode region and the current varies across the length with high voltage electrode operates at one single voltage. These ESPs are used where the particulars are wet or sticky and are cleaned with water. Tubular ESPs make only a small portion of ESP population.

2.4.4 Wet-Type Precipitator: - these types of Electrostatic Precipitators are used where dry ESPs cannot be used like when the material collected is wet, flammable, and sticky or either explosive. As we require more collection efficiency, wet ESPs are used more in comparison to Tubular ESPs. Wet-type ESPs are used commonly in textile industries and pulp and paper industries, coke including industries, the metallurgical industries, and sulphuric acid producing industries. Now-a-days many types of Wet ESPs are available, like the shape of collector, whether gas coming in is water sprayed, whether the treated gas is flowing horizontal or vertical and either ESP is operating in wet conditions.

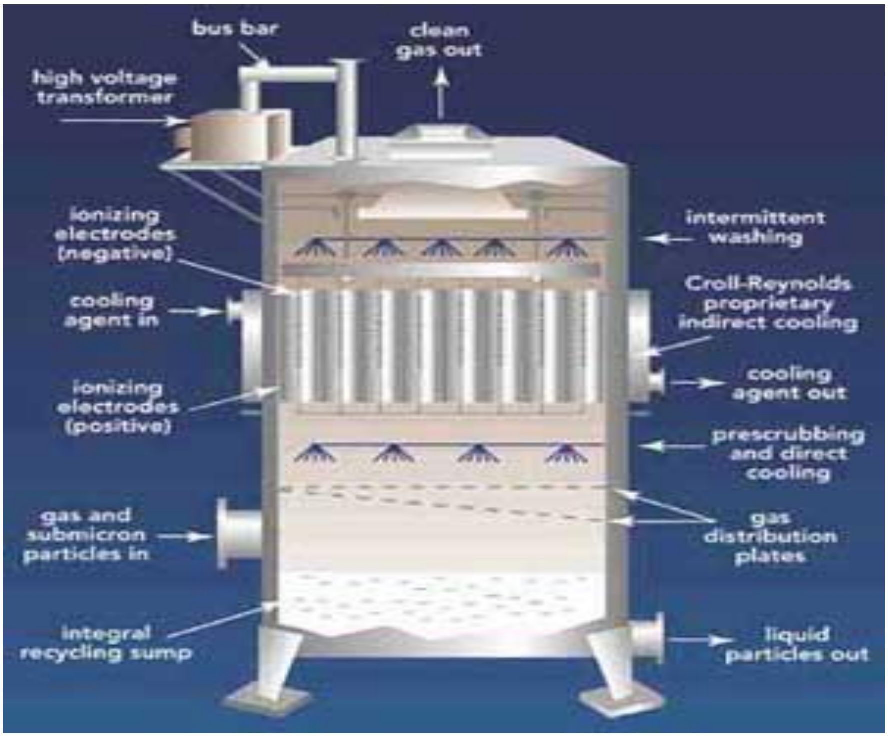

Figure 2 Wet Electrostatic Precipitator

Source:- poweronline.com

3. Components Used in an Electrostatic Precipitator

3.1 Mechanical Components:

3.1.1 Precipitator Casing: The precipitator casing is the outermost covering of the precipitator. It is the part visible to us from the outside. It is an all-welded construction and consists of pre-fabricated walls and roof panels. There are inspection doors provided for entry into the chamber during overhauling and maintenance. The doors are of heavy construction with machined surfaces to ensure a gas tight seal.

The roof carries the precipitator internals, insulator housings, transformers etc. while the bottom of the casing houses the hoppers, rapping mechanism, etc. The supports on which the ESP rests allows free thermal expansion of the casing during operation.

3.1.2 Hoppers: The hoppers are in the shape of an inverted pyramid, and are built to hold required levels of ash. Baffle plates are provided in each hopper to avoid gas leakage. An inspection door is provided on each hopper. Thermostatically controlled heating elements are arranged at the bottom portion of the hopper to ensure free flow of ash. This helps in allowing just the right amount of ash to the ash slurry pumps.

3.1.3 Agitating (chain) system: This has been a recent addition to agitate the chains. It consists of four chains, connected to a focal point from where one handle has been extended outside the hopper and moved adequately in shifts to prevent any ash accumulation inside hoppers. Agitating system has been provided for first three fields hoppers in all Units of Stage-I (exceptionally the system has been provided for all hoppers for Unit III).

3.1.4 Flushing apparatus: The flushing apparatus is one of the most important parts of an ESP and needs regular attention for LP water and Air ingress (if any). LP water is given through the nozzles, which create a vortex motion inside the flushing apparatus. By this, ash gets completely mixed with the water and goes towards the ash channel and ultimately to ASPH (ash slurry pump house). Hence, LP water provided should be adequate and no air must enter through the entrance doors.

3.1.5 Gas Distribution System: The good performance of the precipitator depends on even distribution of gas over the entire cross section of the field. GD screens are provided at inlet of each pass and these direct flue gas evenly over entire cross section of the ESP.

3.1.6 Collecting Electrode (CE) System: CEs are made of 1.6mm cold rolled mild steel plate and shaped in one piece by roll forming. These CEs are provided with hooks at their top edge for suspension. All the Collecting plates in a row are held in position by a shock bar at the bottom. The shock bars are spaced by guides. There are 9 No of CE per row x 31 row /field x 7 fields / pass = 1953 no. per Pass.

3.1.7 Emitting Electrode (EE) System: The most essential part of precipitator is Emitting Electrode (EE) system. This is supported by four Support Insulators to prevent excessive

increase in the emitted voltage. The frames for holding electrodes are located centrally between Collecting Electrodes' curtains. In NTPC Vindhyachal, there are 54 no. of EE per row (i.e. 6 no per CE) x 30 row / field x 7 fields / pass = 11340 per Pass.

3.1.8 Rapping Motors: These operate as per sequence set. Normally more rapping is required for early fields. Rapping Motors are run in 'intermittent mode'; but there is provision to run these in 'continuous' mode also. Continuous mode running should be under strict monitoring only and should not be more than 15 min at a time.

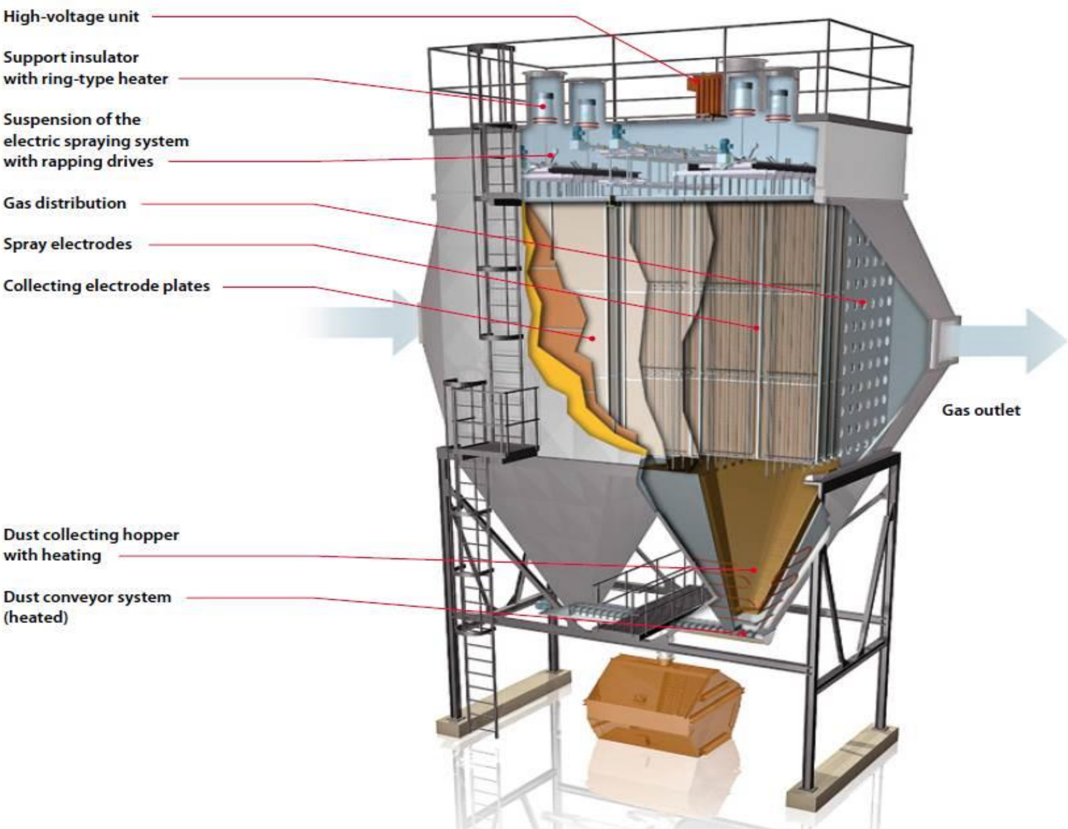

Figure 3 Components of an ESP – 1

Source: - tapc.com.au

3.1.9 Weather Enclosure: A part of the precipitator casing with the specific purpose of shielding the ESP from environmental hazards. It consists of 2 parts.

3.1.10 Upper Weather Enclosure – A non-gas-tight enclosure on the roof of the precipitator to shelter equipment (TR sets, rappers, purge air fans, etc.) and maintenance personnel.

3.1.11 Lower Weather Enclosure – A non-gas-tight enclosure at base of precipitators to protect hoppers from wind and/or detrimental weather condition.

3.1.12 Scrubber: Scrubber are devices used to shoot a liquid spray onto the flue gas channel to remove aerosols and gaseous pollutants from the air stream before it gets ionized. If the ionized gas particles contain aerosols, it would stick to the collection plates, rendering the rapping mechanism unreliable.

3.1.13 Penthouse: A weatherproof gas-tight enclosure over the precipitator to contain the high voltage insulators.

3.2 Electrical Components:

3.2.1 Rectifiers: There is Rectifier at Roof Top for each Field which comprises of two sections and each section can be isolated by isolator (handle) provided at Roof top. Each section consists of no of CEs and EEs in matrix form.

3.2.2 Supply System: The supply system along with the rectifiers is also known as the TR set .There are two ESP transformers (BU-4 and BU-5) for each unit. It consists of bus coupler in LT side (415 V), 70 KV (max) DC Rectifier-Transformer, LT panel and ACP Breaker. Field supply is given through LT panel breaker. ESP Control Room isolator (each panel) are constructed through Electronic panel in Control Room Isolators at Roof Top.

3.2.3 ACP (Auxiliary Control Panel): There are four panels for one unit namely ACP for A-pass, B-pass, C-pass, D-pass. ACP provides supply to all Heaters and Rapping Motors. Heaters can be made ON only from ESP control room. Rapping Motors can be run from ACP (‘intermittent’ as well as ‘continuous ‘mode)

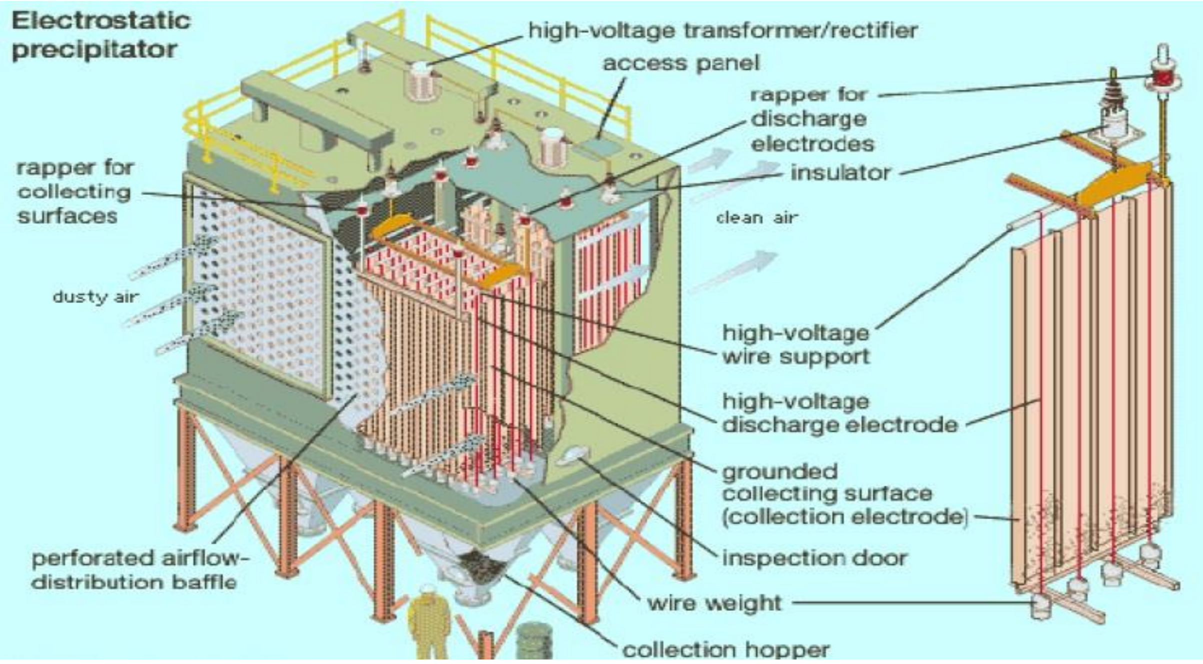

Figure 4 Components of an ESP – 2

Source: - slideshare.net

3.3 Instrumentation (C&I) Components:

3.3.1 Opacity Monitor:

There are three Opacity Monitors for every unit located at ID (Induced Draft) fan inlet. Emission data are available at UCB (Universal Control Board). As per State Pollution Control Board, Max SPM (Suspended Particulate Meter) value allowable is 150 mg/Nm^3 (as evident from Opacity Monitors value).

3.3.2 Hopper Ash Level Indicator:

Ash level indicator has been provided in each hopper. If level is very high as sensed by Indicator (for any hopper), that particular field gets tripped on “ash level high” protection, and the amount of flue gas flowing through that field reduces drastically. Ash level indication is available at local (Hopper area) and ACP.

4. Construction of an Electrostatic Precipitator

An Electrostatic Precipitator generally consists of discharge electrodes and collecting electrodes. Discharge electrodes are usually frame fixed. Mechanical strength of discharge electrodes are also required in order not to vibrate. Sometimes these are pulled down using weights. Erosion of electrodes should also be avoided by selecting proper materials. Insulating bushes are also used for the supporting of discharge electrodes. These bushing are usually placed in air tightened, dust-free chambers to keep their surface clean.

Generally plate-type collecting electrodes are commonly used for larger Electrostatic Precipitator. For small scale industrial useable electrostatic Precipitator, Cylindrical collecting electrodes are sometimes used. The cross section area of the collecting electrodes are designed to give enough mechanical strength and to minimize particles re-entertainment. In general separation between the collecting electrodes is in between 20-25 cm.

Usually an Electrostatic Precipitator is divided into several sections. Upstream and Downstream of gas flow also has different electrical characteristics. In Downstream, the particle density is low, and more corona current can be supplied whereas in upstream flow, the dust particle density is larger and the corona current is often suppressed by the space charge created by small charged particles.

Mechanical rapping is done continuously to the discharge electrodes for optimum operation of an Electrostatic Precipitator. The particles which are collected on discharge and collecting electrodes are moved into hoppers with the help of mechanical shocks.

To achieve better performance, a plate is inserted in the hoppers for prevention of air bypass, so that by passing air gets minimized.

Inside a hopper, thermal insulation should be there as circulation of hot gas is not enough because the temperature inside there often decreases, thus resulting in sticking of dust particles due to the condensing of the moisture present there.

The electrical characteristics of an industrial Electrostatic Precipitator varies in accordance to the operating conditions, like the layer thickness of dust collected on the plate, density of the dust particles, dust resistivity, pressure and temperature of the gas.

Sparking also takes place very frequently, thus establishing an arc channel. Thus a high voltage power source should be installed to deal with the variable load property. This high voltage is controlled to achieve maximum collection efficiency. A protection is also given to the Electrostatic Precipitator power source.

5. Process involving in Precipitation

The precipitation process involves 3 main functions:

- **Charging of dust particles due to corona-discharge**
- **Collection of particles**
- **Removal of particles through rapping**

5.1 Charging of particles

The dust particles in ESP are charged on account of taking over the electric charge of gaseous ions. The cause of gas ionization is a negative corona discharge initiating at the discharge electrodes (DE). A **corona discharge** is an electrical discharge caused due to the ionization of a fluid surrounding a conductor which is electrically charged. Spontaneous corona discharges take place naturally in high-voltage systems if care is not taken to limit the electric field strength (potential gradient). The corona discharge will occur when the strength of the electric field around a conductor is high enough to create a conductive region, but not that high to cause electrical breakdown and/ or arcing of nearby objects.

In the ESPs the corona discharge takes place due to strong electric field in the vicinity of appropriately formed discharge electrode (DE) surface, for instance, in the form of thin wire or else a similar element with spikes mounted on it. The magnitude of applied voltage at which the process of corona discharge begins on the discharge electrode surface is known as the corona onset voltage. Above this level, electron avalanches are developed from the discharge electrode towards the collection plate. The electrons emitted from the spikes accelerate in the strong electric field and gain sufficient energy for ionization of atoms and gaseous molecules. The avalanches originating from discharge electrode develop in the direction of collection plates. Electrons from the avalanche head quickly attach to the neutral gas molecules that becomes negative gas ions. Dust particles acquire electric charge due to non-elastic collisions with these negatively charged ions. In a typical industrial ESP, the strength of electric field is usually above 1kv/m.

5.2 Collection of particles:

Migration velocity: it is the velocity with which dust particles move toward the collection plate. For characterizing the movement of the charged particle in an ESP it is essential to assume the forces acting on the particle are balanced. After some simplifications it can be assumed that the following forces act on a dust particle in an ESP: the electric force and viscous (drag) force of the medium, where the electric force acting on a charged particle in an electric field is

$$F = qE$$

Where F is the Coulomb force (N), q the particle charge(C) and E is the electric field (V/m). Now the viscous (drag) force on the moving particle is given by stokes law i.e.

$$F_s = - 3\pi\mu d_p\omega$$

Where ω is the migration velocity (m/s), d_p is the diameter of the particle (m), μ is the viscosity (Pa s). Now since we have assumed forces on the particle are balanced, therefore

$$F + F_S = 0$$

$$\text{I.e. } qE + (-\ 3\pi\mu d_p\omega) = 0$$

$$\text{I.e. } \omega = qE/3\pi\mu d_p$$

The minimum range of the size of the particles to which the Stokes's equation may be applied is the case when the particle's diameter is of the order of magnitude of the mean free path of gas molecules. For particles smaller than 1 µm it is essential to take into account the Cunningham slip correction factor

$$\omega = qEC/3\pi\mu d_p$$

$$\text{Where} \quad C = 1 + 1.72\lambda/d$$

The formulas used for the estimation of theoretical migration velocity do not consider many factors affecting the motion of dust particle in an electric field such as inertia, gas velocity, in homogeneity of electric field strength distribution. Therefore there is a considerable difference between the theoretical and the experimental values. Typically observed migration velocity of a 5µm particle is about 30cm/s at 350^0c and about 48 cm/s at 20^0c.

6. Collection efficiency:

The collection efficiency of an ESP (η) is given by the Deutsch and Anderson formula as:

$$\boldsymbol{\eta = 1\text{-}\exp(-\omega A/Q)}$$

Where ω is the migration velocity (m/s), A the area of the collecting electrode (m^2) and Q is the gas flow rate (m^3/s). In reality many factors contribute to the collection efficiency like characteristics of dust particles, the geometry of the electrodes etc. the Deutsch formula has a reasonable theoretical basis but it fails to give the actual collection efficiency with the desired level of accuracy because of dust re entrainment, dust characteristics, flow irregularities, sparking and a few other factors. The collection efficiency is markedly affected by two particulate properties:

6.1 Dust layer resistivity:

Resistivity is the electrical resistance of a dust sample 1.0 cm^2 in cross-sectional area, 1.0 cm thick, and is recorded in units of ohm-cm. The table below, gives value ranges for low, normal, and high resistivity.

Table 2 Resistivity of Dust layer in an ESP

Resistivity	**Range of Measurement**
Low	between 10^4 and 10^7 ohm-cm
Normal	between 10^7 and 2×10^{10} ohm-cm
High	above 2×10^{10} ohm-cm

Source: - Wikipedia

The negatively charged particles start depositing at the metal surface of the collection plate. Since the collection plate is grounded its voltage is zero, however at the outer surface of dust layer the potential can be quite high as new particles and ions arrive and deposit on the dust.

The strength of the electric field develops due to this potential difference depends on the resistivity and the thickness of dust layer.

6.1.1 Low resistivity:

In low-resistivity dust layers, the dust is quite conductive so electrical charges can move through the dust layer i.e. the corona current is easily passed to the collection plate. Therefore only a weak electric field is developed across the dust layer. The collected dust particles of low resistivity don't adhere strongly to the collection plate. Now since there are not held together strongly enough and the flue gas stream moves across the plate with high velocity so these dust particles get easily dislodged and are re entrained in the flue gas stream.

6.1.2 Normal resistivity:

Particles with normal resistivity are easier to work with as compared to that of low or high resistivity. Particles that have normal resistivity do not lose their charge rapidly on reaching the collection electrode. These dust particles leak their charge slowly to the grounded plates and are held on the collection plate through intermolecular adhesive and cohesive forces. This allows a considerable built up of the dust layer and are then removed from the plates through rapping.

6.1.3 High resistivity:

In case of high resistivity dust particles, it is difficult for the electrical charges to move through the dust layer. Therefore electrical charges are accumulated beneath and on the dust layer surface thereby creating a strong electric field. If the potential difference across the dust layer, due to this strong electric field, gets too high numerous undesirable effects can occur.

Firstly, the voltage drop between the collection electrode and the discharge electrode gets reduced due to the big potential difference developed across the dust layer. This reduces the electric field strength that is used to drive the charged dust particles over to the collection plate. The migration velocities of especially the small particles are affected due to this.

Another difficulty that occurs with high resistivity dust is called back corona. This happens when the potential difference across the dust layer is so big that corona discharges begin to emerge in the gas that is trapped in the dust layer. Electrical breakdown of the dust layer results, producing small craters or holes from which back corona discharges happen. Positive gas ions are produced within the dust layers which are accelerated towards the "negatively charged" discharge electrode. The positive ions neutralize some of the negative charges present on the dust layer and nullify few of the negative ions on the "charged particles" moving towards the collection electrode. Disturbance of the normal corona process significantly reduces the ESP's collection efficiency, which may fall below 50% in severe cases. When back corona is there, the dust particles assemble up on the electrodes forming a layer of insulation. Most of the times this cannot be repaired without bringing the unit offline.

The third and often the most common problem is that of increased electrical sparking. If the sparking rate surpasses the ‘spark rate limit’, the automatic controllers limits the operating voltage of the field which results in reduced particle charging and the migration velocities are also reduced.

Even if the voltage across the dust layer does not become high enough to cause these problems the high resistivity dust particles do not lose their charge easily and are adhered to the plate too strongly making them hard to remove and causing problems with the rapping process.

The problem of high resistivity is generally tackled by doing the following –

6.2 Increasing the moisture content:

The electrical conductivity in a bulk of particles has both volume and surface contributions. Volume conduction i.e. the movement of electrical charges through the bulk of the particles, mainly depends on the temperature and the composition of the particles. Volume conduction dominates the conduction mechanism in the higher temperature zone i.e. above 500 °F

(260 °C). At temperatures below 450 °F (230 °C) electrical charges starts to flow across surface moisture and chemical films adsorbed onto the particles. This surface conduction lowers the resistivity values. Studies have shown that only a few molecules thick moisture films are enough to impart the required surface conductivity. Hence increasing the moisture content is an effective way to increase the conductivity or conversely decrease the dust resistivity.

6.3 Adjusting the temperature:

As already mentioned at temperatures below 230^0c contribution from surface conduction als come into play thereby decreasing the resistivity of the dust layer. Reduction of temperature also helps reduce the process of back corona. A typical industrial ESP operates at a temperature of about $120\text{-}150^0$c

6.4 Flue gas conditioning (FGC):

Flue gas conditioning involves insertion of chemical additives (i.e. ammonia, sulfuric acid, sulfur trioxide, ammonium sulphate etc.) to alter the electrical and physical properties of the fly ash to increase the collection efficiency of ESPs.

Flue gas conditioning generally aims at achieving these effects:

1. Modification of electrical resistivity of the dust
2. Improving dust cohesion to minimize losses during rapping

6.4.1 Sulfur trioxide conditioning:

The most frequently used conditioning agent to modify high resistivity of fly ash is sulfur trioxide. SO_3 reacts with the water vapours in the flue gas and forms sulfuric acid which gets adsorbed on the surface of the particles. This results in the formation of a very thin conducting film on the surface of the ash particles which reduces the surface resistivity. There are numerous types of sulfur trioxide gas conditioning systems like direct injection, vapourization of sulfuric acid, catalytic conversion of SO_2 and sulfur burning followed by catalytic conversion of SO_2 to SO_3. In the process of direct injection, liquid SO3 is initially metered into a vapourizer and is then air-diluted. Air dilution maintains a steady controllable volume of gas moving through the injection manifold; this provides sufficient dispersion in the flue gas. The Mixture is transmitted in heated lines to the injection point to stop the formation of sulfuric acid due to the condensation which leads to corrosion. While in an acid vapourization system, sulfuric acid is heated beyond its boiling point, vapourized and diluted with air. Next it is injected in the flue gas, ahead of the ESP. Water vapours are always present in the acid vapourization system, and therefore, heating is necessary to keep the gas temperature above dew point. The manifold inside the flue gas is insulated to avoid corrosion and early condensation.

In catalytic conversion of SO_3 from SO_2, liquid SO_2 is vapourized in steam-heated vapourizer; the SO_2 vapour will then be mixed with sufficient air to produce a mixture containing roughly 8% of SO_2 by volume. This mixture is then heated at approximately 450^0 C, during which around 70–75% of SO_2 is converted to SO_3. The resulting mixture then can be injected into the flue gas.

6.4.2 Ammonia conditioning:

Some fly ashes do not easily absorb sulfuric acid vapour, which are produced naturally from sulfur in the coal or due to the FGC with SO_3. This is primarily due to the presence of silica, iron and alumina in the fly ash, making the surface of the ash smooth and less absorbent. For such ashes, the addition of ammonia has been reported to be reasonably beneficial. During ammonia conditioning, ammonia reacts with the natural sulfur trioxide, or moisture present in the fly ash, producing ammonium bi-sulfate,

$$\mathbf{SO_3 + NH_3 + H_2O = NH_4HSO_4}$$

But if excess ammonia is present, then the end product is ammonium sulfate.

$$\mathbf{NH_4HSO_4 + NH_3 = (NH_4)_2SO_4}$$

NH_3 is used as coagulating agent to produce larger fly ash particles; therefore it provides a fly ash which is receptive to the available SO_3. When the temperature of the flue gas is above 150 ^oC, ammonium bisulphate melts and becomes a semi liquid, acting like glue when mixed with the fly ash. This makes highly cohesive and relatively bigger particles, resulting in high collection efficiency because of the reduced rapping losses and re entrainment. This effect is also called as agglomeration .This mechanism helps in particle-to particle interaction and particle-to-collection plate interaction of the ESP immensely improves.

It has been shown previously that the performance of the ESPs can be improved by changing the feed coal, using wet ESP to minimize re-entrainment, increasing the area of collection plate of the existing ESP, modifying the gas temperature, and by the addition of chemicals to alter the fly ash or the electrical conditions in the ESP. But, most of these options are not easy to implement at a power station, largely due to the constraints associated with the feed coal (i.e., cost associated with import, washing of the coal and environmental issues related to it, and ash content etc.); increasing the collection plate area in ESP (which requires more space and is expensive), installation and operating costs for employing wet ESPs, that are too high apart from lump formation of the ash and its deterioration as a construction material.

Under these circumstances, flue gas conditioning becomes the inevitable choice. It has been observed that a FGC system has numerous advantages over other systems like (i) lower cost input compared with the establishment of additional ESPs; (ii) shorter time to execute; (iii) more versatility and flexibility even if variations in operating parameters happen (such as coal variation, boiler load, ESP current and voltage change), SPM levels can be controlled easily by simply adjusting the amount of flue gas conditioning agents. These agents are quite helpful in reducing resistivity, and thus improving the surface conduction properties of the particles of dust/fly ash.

In order to demonstrate the influence of flue gas conditioning agents and their effectiveness in reducing SPM levels, a study was conducted on various coal-based power stations in India; the results are reported below.

Table 3 Details of the flue gas conditioning system at some power stations in India

Power Station	SC (%)	AC (%)	R ($\times 10^7 \Omega$ m)	T (^{0} C)	IR (kg/h) NH3	IR (kg/h) SO3	SPM (mg/Nm^3) BEFORE	SPM (mg/Nm^3) AFTER
1.	0.5	40	3	148	22	_	120.6	80
2.	0.5	40	3	150	15	_	350	120
3.	0.38	29.8	500	145	30	_	247	110
4.	0.4	51.4	50	142	30	_	800	140
5.	N/A	53	600	150	28	_	410	74
6.	N/A	42	4000	137	5	14	400	65
7.	0.63	42.1	1000	160	14	18	358	61
8.	0.4	37.5	40	133	24	_	310	120
9.	0.7	30	800	140	24	_	231	124
10.	N/A	34	5000	131	15	_	187	92
11.	0.7	38.1	100	131	15	_	620	128
12.	N/A	44	N/A	145	35	_	629	268

Source: - Reference no. 10

Where, SC is sulfur content, AC is ash content, R is resistivity, IR is injection rate and SPM is suspended particulate matter.

6.5 Dust Particle size distribution:

Information of the particle size distribution is necessary to estimate ESP collection efficiency. The dust (fly ashes) coming after combustion of solid fuels like coal are poly disperse and the diameter of the particles varies from fractions of micrometer up to few millimeters. Determination of particles size is a complicated task because of various shapes acquired by the particles, from spherical forms -produced as an effect of condensation and sublimation, spatially expanded, snow-flake like levelled particles, to fibrous particles. The fly ash size distribution are most of the times expressed as fraction of particles $q_r(d_i)$ in a range from di to $di + \Delta d$, or the total number of particles $Q_r(d_i)$ that are smaller than d_i (cumulative size distribution).

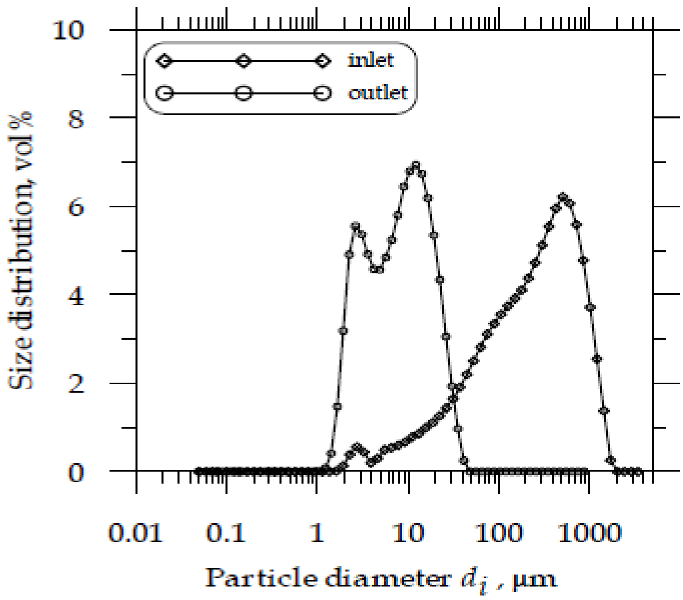

Figure 5 Dust size distribution vs. Particle Diameter

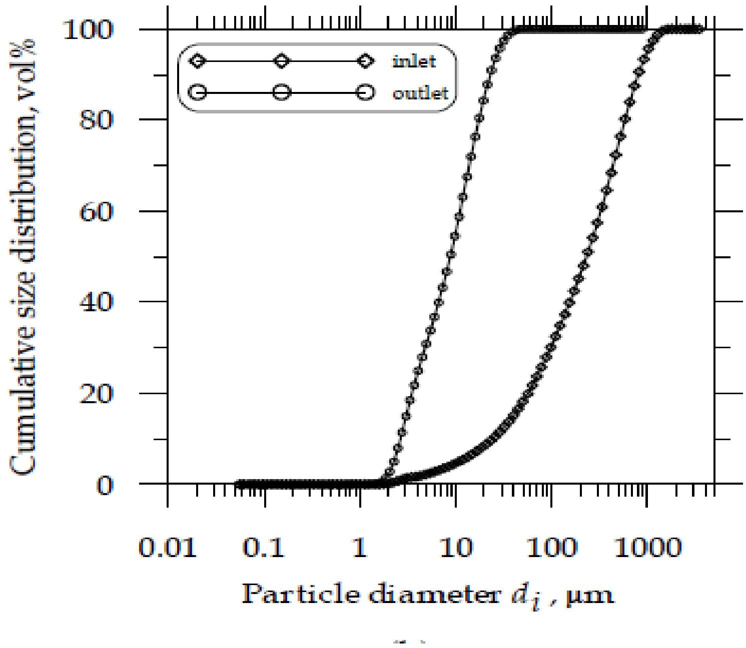

Figure 6 Cumulative size vs Particle Diameter

Source: - Reference no. 11

Typical Particle size distribution recorded at an ESP inlet and outlet (a) using particle size distribution (b) using cumulative size distribution recorded using an automatic particle size analyser.

7. Removal of particles:

The collecting electrodes are periodically cleaned on which dust is collected. Performance of ESP depends on the regular cleaning of the collecting electrodes. The dust is removed by introducing vibrations to the collecting plates by means of rapping. The rapping system creates vibrations in the collecting plates and due to vibrations the dust layer present on the collecting electrodes will get detached and get collected in dust hoppers.

The most commonly used rappers are:-

- Tumbling rappers: generally used in association with rigid frame discharge electrodes, are extremely efficient but require lot of maintenance when used in a moving gas stream.

Hammers are attached to a rotating shaft. As they rotate the hammers collide with a beam causing a vibratory shock to remove the caked-on dust. The hammer's weight and length of its mounting arm control the force of the rapping. Changing the speed of the rotating shaft changes the frequency of rapping.

- Mechanical rappers – they comprise of a big weight that is lifted to get potential energy and are then released, letting it to fall and collide with an anvil producing a vibratory shock to dislodge caked-on dust.

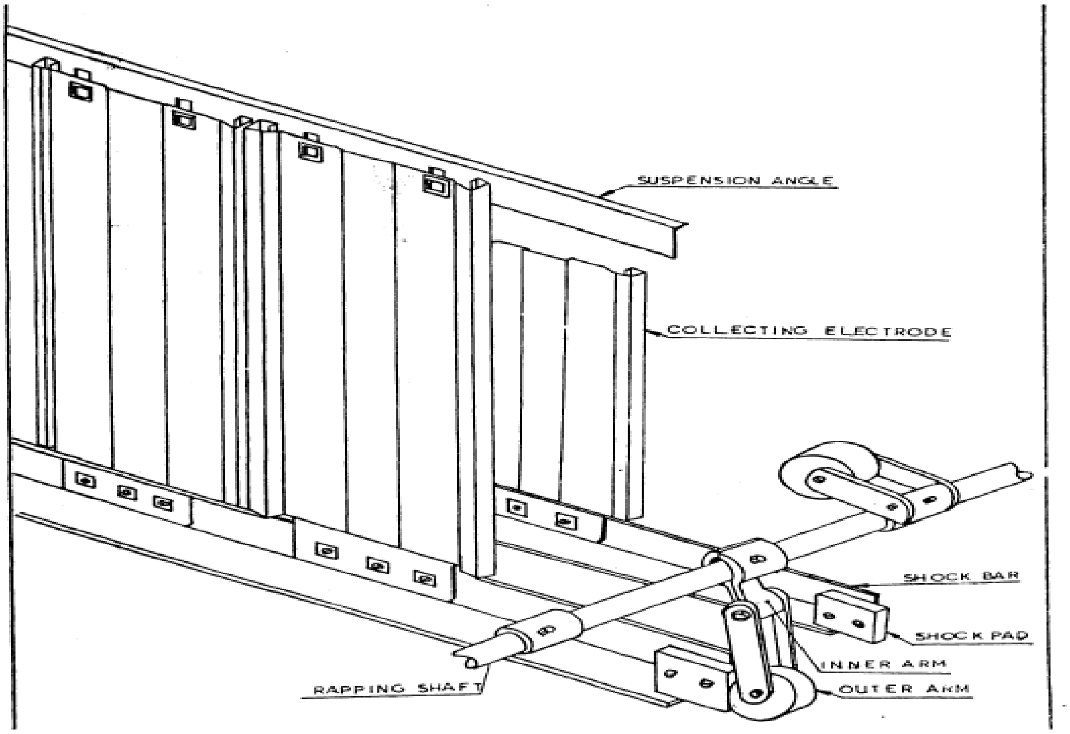

Figure 7 Arrangement of collecting electrode rapping mechanism

Source: - NTPC Vindhyachal

8. Recent Changes in ESP Design

China and India are the fastest growing countries, and being on the cusp of nuclear and energy independence calls for increased use of its resources to feed its rising population and industries. These countries have abundant coal resources and are heavily dependent on coal for energy. To speak in numbers, China and India are expected to account for 46% and 21%, respectively of total world coal consumption in the long term [a]. However, the impure air emitted by these coal based power plants are a major concern of caution. Therefore, many countries started tightening emission standards, small old power plants were being converted into new large ones, and various flue-gas treatment equipment were being installed. Consequentially, the precipitators also underwent changes from time to time. Some of the more recent changes in its design are as follows:-

A moving electrode type electrostatic precipitator is equipped with brushes to remove dust from the moving collecting plate surface. Its major advantage over conventional ESPs is in the fact that it is effective in collecting high resistivity dust. As mentioned earlier, high resistivity dust can lead to back corona and decrease the collection efficiency of the plates. In a MEEP, the collecting plates are not stationary, but divided into strips, which rotate through a chain mechanism and moved by driving wheels.

8.1 Basic Structure:

The conventional fixed electrode precipitators consist of discharge electrodes and collection plates. Dust from the air is collected onto the plates, which is then dislodged using a rapping system. This cycle continues every time the collection plates get adequately covered with ash. On the other hand, the moving electrode electrostatic precipitator has no rapping mechanism. Instead, the collection plate strips are rotated on a chain link in perpetual motion. In the bottom part of these strips (known as the non-collection zone), there are a set of roller brushes on each side, which remove the ash accumulated on the surface. Given below are diagrams of both a simple fixed plate ESP and a moving electrode ESP.

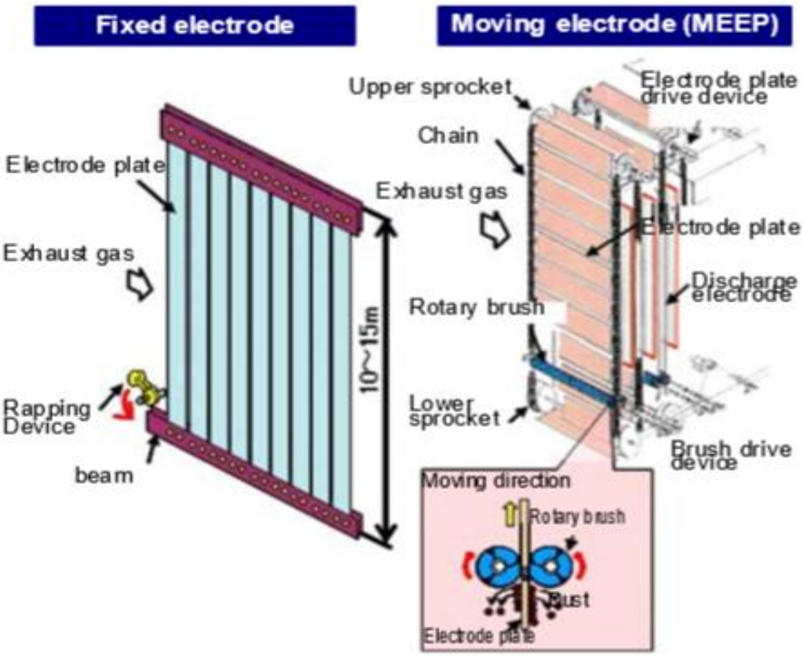

Figure 8 Structural comparison between fixed electrode and moving electrode

Source: - Reference no. 12

As a result, dust accumulation doesn't take place for a longer duration. It is continuously removed by the brushes at the bottom. Also, unlike in older ESPs, MEEP can collect high resistivity ash effectively along with low restivity dust. This significantly increases the dust collection efficiency. From the Matts equation, we know the efficiency of a fixed plate ESP as

$$\eta = \left[1 - \exp\left\{ -(\omega_k \cdot A/Q) \right\} \right] \times 100\,[\%]$$

Whereas for a moving electrode ESP, it is

$$\eta = \left[1 - \exp\left\{ -(\omega_k \cdot A/Q)^N \right\} \right] \times 100\,[\%]$$ [b]

Where N is the number of plate strips, A is the dust collection area, Q is the inflow gas amount and ω_k is the particle moving velocity, which is the velocity of dust particles moving toward the dust-collecting electrode in the discharge space. ω_k is an index of how easily dust can be collected, namely the dust collecting performance of a precipitator, which closely depends on electrical resistivity.

Thus, it can also help in reducing the area occupied by the collecting plates with the performance remaining intact and emissions under control. The graphs below better explain the facts mentioned above.

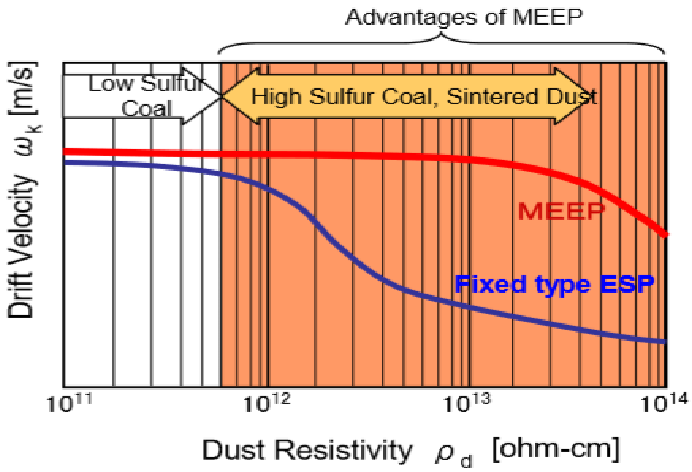

Figure 9 Relation between dust resistivity and particle drift velocity

Source: - Reference no. 12

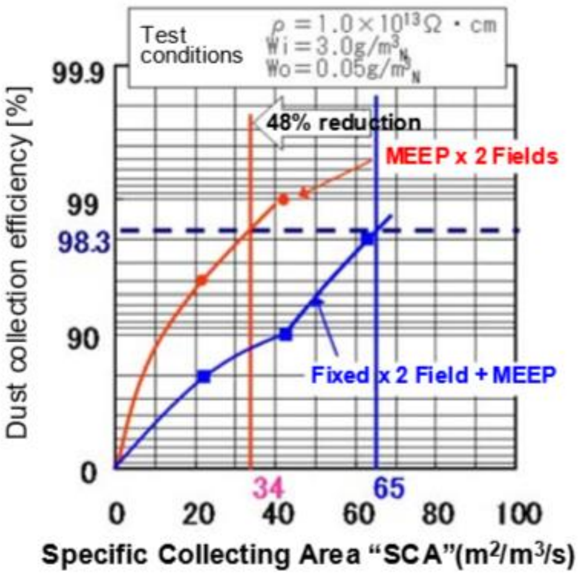

Figure 10 Example of ESP size evaluation

Source: - hitachi-infra.com

8.2 Problems:-

Under ideal conditions MEEP performs better than fixed plate ESPs in a lot of ways. But in the practical world, it has some drawbacks which hamper its performance, and the increase in efficiency over older ESPs is negligible. Some of them are:

8.3 Rotating brushes:

The rotating brushes in the non-collection zone are responsible for the continuous removal of ash from the collection. But as with all mechanical parts operating under stress and friction, its life decreases under prolonged use. And once installed, its removal requires the whole ESP to be shut down. This would be very detrimental to the emissions standards.

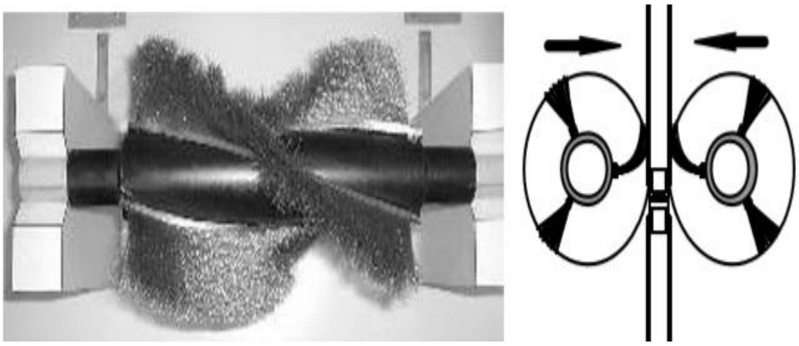

Figure 11 Segmental model of a rotating brush

Sources: - Reference no. 12

After several experimentations, it was found that a non-rotating straight brush at an angle of 45^o to the moving plates will lead to almost the same efficiency, with the life expectancy of the brushes increasing by at least 90%. While rotating brushes lasted around 2 years, the non-rotating brushes last close to 4 years. Also, these can be removed and new ones installed in a much simpler manner.

8.4 Chain and Elongation:

Chains are used to connect moving electrode elements and to move collecting plates by driving wheels. Conventionally, a link chain was selected for driving the moving electrode elements because of its simple shape and less trouble happened when catching dust. Nowadays, a roller chain is used considering the lifespan of the chain.

In case of a link chain, a lower pair is formed (only a point of contact). This means more stress and friction on the point, which wears off easily. Whereas in the roller chain case, it forms a higher pair (linear contact). So, the stress is spread over the entire length of the roller, thereby increasing its life.

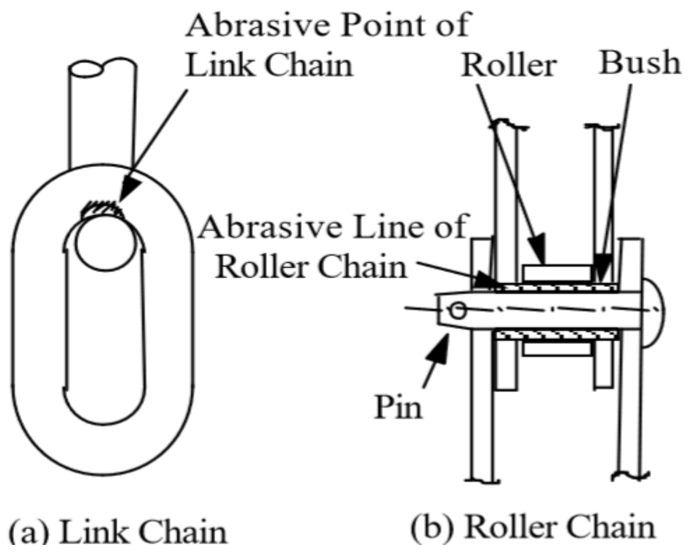

Figure 12 Contact point of chain

Source: - Reference no. 12

Another problem in the MEEP is that of elongation of the link/roller. Under duress, the chain stretches and dis-aligns the rotary motion of the plates. This is very harmful and dangerous to the working of the ESPs. This is caused due to dust accumulated on the chain by electrostatic adhesion caused by discharge in a dusty atmosphere. The figure below shows how the life increases when a roller chain is used before the exchange criterion is reached (1% elongation). The result - Elongation of a roller chain reduced to one fifth in comparison with a link chain, and the lifespan expanded.

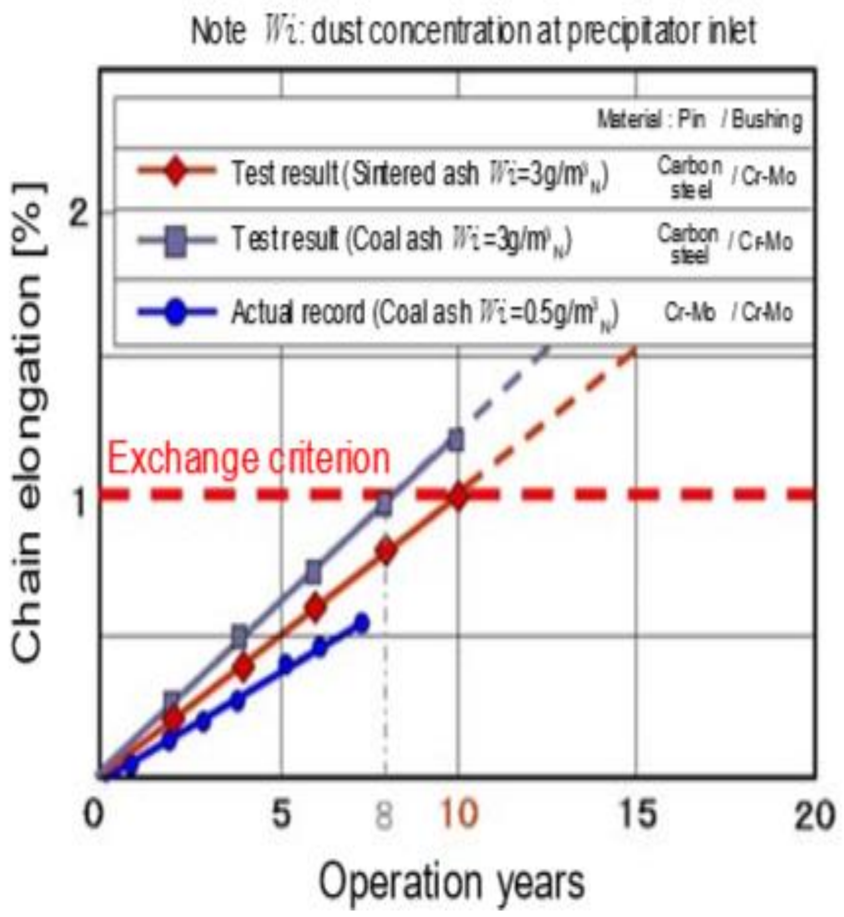

Figure 13 Operating life of chain (Abrasion test)

Source: -Hitachi-infra.com

To bring out the best results, nowadays, MEEPs are used along with standard ESPs. Generally, 1 or 2 fixed plate ESPs and a MEEP is placed in series. The flue gas enters the ESP system and passes through the fixed plate ESPs first and then through the MEEP. The following equations explain how this arrangement improves the dust collection efficiency.

While using the moving electrode section, the fixed electrode sections are always combined with a pre-collector to limit the dust density reaching the moving electrode section. Collected dust at the inlet side section is rather coarse and its dust resistivity is relatively low. Therefore, dislodgement by mechanical rapping is easy at inlet side section. Then the moving electrode type ESP is mainly used in combination with conventional fixed electrode sections upstream and a moving electrode section downstream.

To calculate the collection efficiency, Matts proposed a modified Deutsch equation. It is given as

$$\frac{C_o}{C_i} = \exp\left\{-(\omega k \times f)^k\right\}$$

In this modified equation, Matts introduced a coefficient 'k' regarded as a function of particle size distribution. In case of fly ash from coal fired boilers, the coefficient 'k' is assumed to be about 0.55). Here, wk is the migration velocity, f is specific collection area.

These can be calculated from 2 separate equations given by

$$\omega k = \frac{(-\log P2)^{\frac{1}{k}}}{f2}$$

&

$$k = \frac{\log \dfrac{\log P1}{\log P2}}{\log \dfrac{f1}{f2}}$$

These formulae can be used to compare the improvement in dust collection efficiency from the stand-alone ESPs.

9. ESPs in Vindhyachal

Since the boilers installed at NTPC Vindhyachal are of different capacities (210MW and 500 MW), they are accompanied by different sets of ESP. Some operational data for the two sets of ESPs is given in the adjoining tables.

Table 4 ESP data – 210MW Unit

No. of pass per boiler	4
No. of field in each pass	5
Pressure drop	20 mmWC
Gas flow rate	312.7 m^3/sec
Inlet temperature	136^o C
Velocity of gas inside ESP	0.839 m/sec
Total treatment time	32.18 sec
Plate wire spacing	150 mm
Emitting electrode type	Spiral with hooks
Size	2.7 mm diameter
Total no. of electrodes	29808
No. of plates each row	6
Total collecting plates	3456
Specific collection area	214.48 m^2/ m^3/sec

Source: - NTPC Vindhyachal

Table 5 ESP data – 500MW Unit

Gas flow rate	851.0 m^3/sec
Temperature	125o C
Inlet dust concentration	38.9 gm/Nm3
Outlet dust concentration	0.027 gm/Nm3
No. of precipitators per unit	4
No. of fields in each pass	8
Pressure drop	150 mm WC
Velocity of gas inside ESP	0.876 m/sec
Treatment time	41.1 sec
Emitting electrode type	Spiral with hooks
Size	2.7 mm diameter
Plate-wire spacing	150mm
No. of collecting electrodes per field	366
Specific collecting area	274.12 m^2 / m^3/sec

Source: - NTPC Vindhyachal

The frequency of rapping is the same for both these ESPs and varies from 20 per hour at the inlet field to 1 rap per hour at the exit field.

Let us calculate separately the efficiency of the ESPs installed at Vindhyachal.

For the 210MW unit, there are 4 pass and 5 fields in each pass. The Deutsch equation for efficiency is given by

$$\eta = \left[1 - \exp\left\{ -\left(\omega_k \cdot A/Q \right) \right\} \right] \times 100\,[\%]$$

Here, wk is the particle migration velocity and is of the order of 1 – 10 cm/sec. The term A/Q is known as the specific collection area. Putting the values of wk and A/Q from the tables above, we get the efficiency equal to

η = 1 – exp (-0.05 * 214.48)

= 1 – 0.002478

= 0.9975

This is in complete agreement with the efficiency provided in the table below.

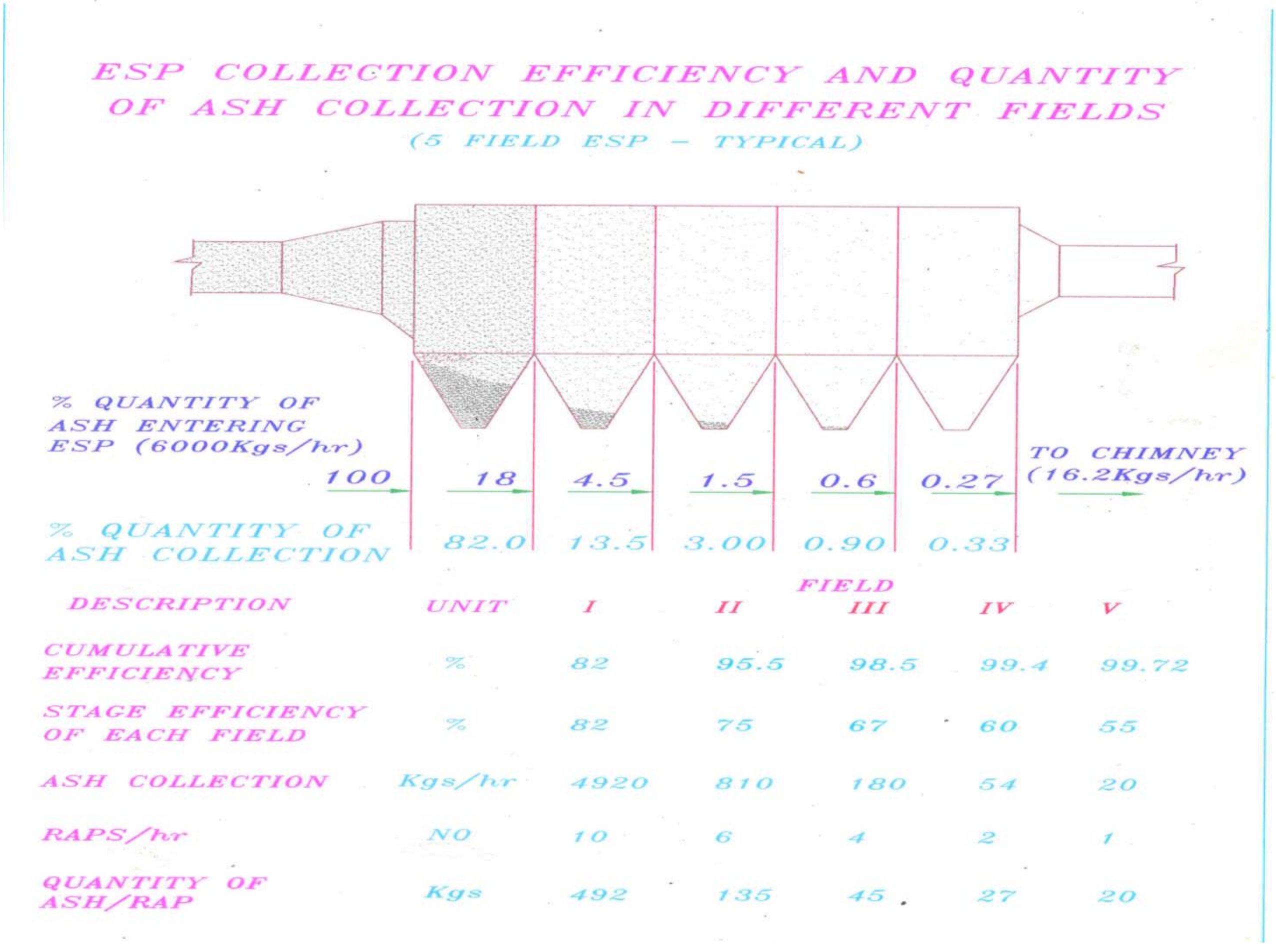

Figure 14 ESP collection efficiency and quantity of ash collected

Source: - NTPC Vindhyachal

Conclusion:

This was a study-based report on the various aspects of an electrostatic precipitator. This includes its design, working principle, its advantages over other flue gas treatment techniques and new advancements in this field. All ESPs work on the principle of Corona Discharge – ionization of a di-electric medium. It was proposed in its archaic design by Cottrell at the turn of the 20th century. But for many years, it was neglected due to its design and operation complications.

ESPs started being installed on a large scale after 1950s, finding its use in coal based power plants, cement factories, steel plants, etc. For each type of industry, different types of ESP are used, like, Wet ESPs in textile, paper and pulp, and metallurgical industries; while in thermal power plants and cement factories dry ESPs are used. Wet ESPs are more efficient at collection of dust particles, but lose this advantage due to rapping problems (dust sticks to the plates).

We attempted to understand the process involved in the charging of particles and its collection. The collection efficiency is given by the Deutsch equation, which is governed by two main particulate characteristics – dust resistivity and particle size distribution.

A new advancement in this field is Moving Electrode Electrostatic Precipitator (MEEP). It is a compact, highly efficient variant of an ESP. Rather than having fixed plates, it has continuously moving collection plates driven by chain-link mechanism. We found its usefulness over standard ESPs; its operational difficulties and their solutions.

The final chapter was about the ESPs installed at NTPC Vindhyachal. The ones here consist of either 5 or 6 fields per pass, which sequentially reduce the flue gas concentration at the output. We correlated the measured and observed efficiencies of such ESPs, and found out the degree of accuracy between them.

This report also outlined solutions to a range of common operating problems encountered with electrostatic precipitators. With the changes mentioned in the report, significant reductions in dust emissions are possible. The potential for improving the ESP performance depends upon the current operating conditions. The potential variation in measured and observed operational conditions due to one or more operational problems combined with the fact that different operational problems can produce similar results makes assessment difficult.

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