CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The concept of electrostatic precipitation has been in application since the sixteenth century. However, the first working model of an electrostatic precipitator was constructed in 1906 by Frederick garner Cottrell. He used electrostatic precipitator to collect sulfuric acid mist from the exhaust steam off the power work of the DuPont de Numerous plant. Soon he built another larger precipitator, which could treat five thousand cubic feet per minute of gas flow from which two gallons of sulfuric acid were collected per minute [3]. Frederick garner Cottrell found the western precipitator company in 1907. In a short period of time, the company made a huge amount of money by installing precipitator to remove a wide variety of pollutants. The first ever electrostatic precipitation employed to remove fly ash in a power generation facility was at Trenton channel plant of Detroit Edison in 1923. Within a short period of time with extensive research and critical changes in designs, a collection efficiency of 90% was achieved [3]. By the mid of 1970, the collection efficiency climbed to 99%. Today collection of most of the ESPs is greater than 99.9%.

The U.S.A federal government was forced to regulate the emissions from the power plant as the result of two ill-fated accidents in late 40 s and early 50s [1]. In Donora, Pennsylvania, a 4- day somg made 7000 people sick and killed 20 people in 1948. Four years late in 1952, in London, England, a 3-day smog killed over 4000 people. The first Clean Air Amendment Act was implemented in 1970. This bill was aimed at the prevention control, and abatement of air pollution from stationary and mobile source by setting up the National Ambient Air Quality

Standards (NAAQS). As the regulation started getting more stringent, many researchers studied the performance of electrostatic precipitation for collection of particulate matter.

In 1996, the United States Environmental Protection Agency [2]. Proposed new air quality standards for fine particulate matter focusing on the emissions of particulates below 2.5 µm in diameter (PM2.5). Particulate matter less than 2.5 µm in diameter readily penetrate the respiratory system and get deposited in the lungs and may cause various health problems [2]. By thoroughly understanding the concept of electrostatic precipitation and by extensive research, it might be possible to capture these hazardous particulates by advancement in the electrostatic precipitation technology. My research is a step towards achieving this target.

2.2 Electrostatic Precipitator

An electrostatic precipitation is the pollution control device used to separate particulate matter from a contaminated air stream. ESPs are most common industrial device for particulate control, with an estimated 70% of the total market. The reason for their wide popularity is the several advantages they offer compared to other control device. Since the collection forces act only on the particles, ESPs can treat large volumes of gas with low pressure drops. Unlike other collection technology, ESPs are efficient even for smaller particles as well. They can operate oven a wide rang of temperatures and their operating cost is lower as compared to other technologies. They are effective for collecting dry materials, fumes, or mists [4].

2.2.1 Basic Operation

The operation of an electrostatic precipitator involve three basic functions.

First, suspended particles must be charged. Second, the charge particles must pass through an electric field to direct their movement to a collecting as show in Figure

(2.1) third, the collected particle must be removed from the electrode with as little re-entrainment as possible [11].

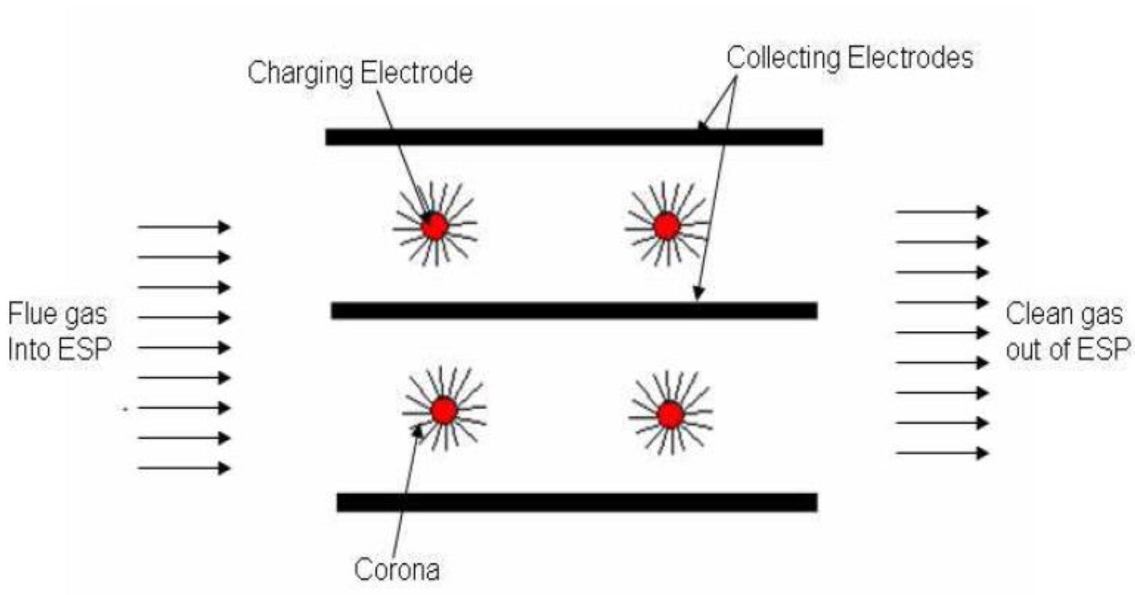

Figure 2.1: Particle charging

The particles are charged by the use of a high voltage direct current where ions and electrons are produced in corona discharge electrode as shown Fgure (2.1). The ions and electrons produced are influenced by the local electric field and move toward the collecting electrodes, intercepting particles. The charged particles under the influence of electric field are collected over the collecting surfaces. The electric force acting on a 1µm particle is about 3000 times that of gravity and the collecting field strength is generally around 4-5KV/cm.

There are two different charging mechanisms: filed charging and diffusion charging. Both field and diffusion mechanisms play a vital in charging the particles based on their size. Field charging is the dominant mechanism for particles larger than 0.5 µm. In field charging, ions from the corona stick onto the particle under the influence of electric field.

Diffusion charging is dominant charging mechanism for particles below 0.2 µm. Diffusion charging is associated with ion attachment resulting from random thermal motion also known as Brownian motion.

2.2.2 Types of electrostatic precipitators ESP

ESP can be classified into three major kinds as follows:

I. Tubular and plate ESPs

Tubular precipitators consist of cylindrical collection electrodes (tubes) with discharge electrodes (wires) located in the center of the cylinder as show in Figure 2.2. Dirty gas flows into the tubes, where the particles are charged. The charged particles are then collected on the inside walls of the tubes. Collected dust and/or liquid is removed by washing the tubes with water sprays located directly above the tubes. The tubes may be formed as a circular, square, or hexagonal honeycomb with gas flowing upward or downward. A tubular ESP is tightly sealed to minimize leaks of collected material. Tube diameters typically vary from 0.15 to 0.31 m (0.5to 1ft), with lengths usually varying from 1.85 to 4.0m (6 to 15ft). Tubular precipitators are generally used for collecting mists or fogs, and are most commonly used when collecting particles that are wet or sticky. Tubular ESPs have been used to control particulate emissions from sulfuric acid plants, coke oven byproduct gas cleaning (tar removal), and iron and steel sinter plants [5].

Plate electrostatic precipitators primarily collect dry particles and are used more often than tubular precipitators. Plate ESPs can have wire, rigid-frame, or occasionally, plate discharge electrodes. Figure 2.3 shows a plate ESP with wire discharge electrodes. Dirty gas flows into a chamber consisting of a series of discharge electrodes that are equally spaced along the center line between adjacent collection plates. Charged particles are collected on the plates as dust which is periodically removed by rapping or water sprays. Discharge wire electrodes are

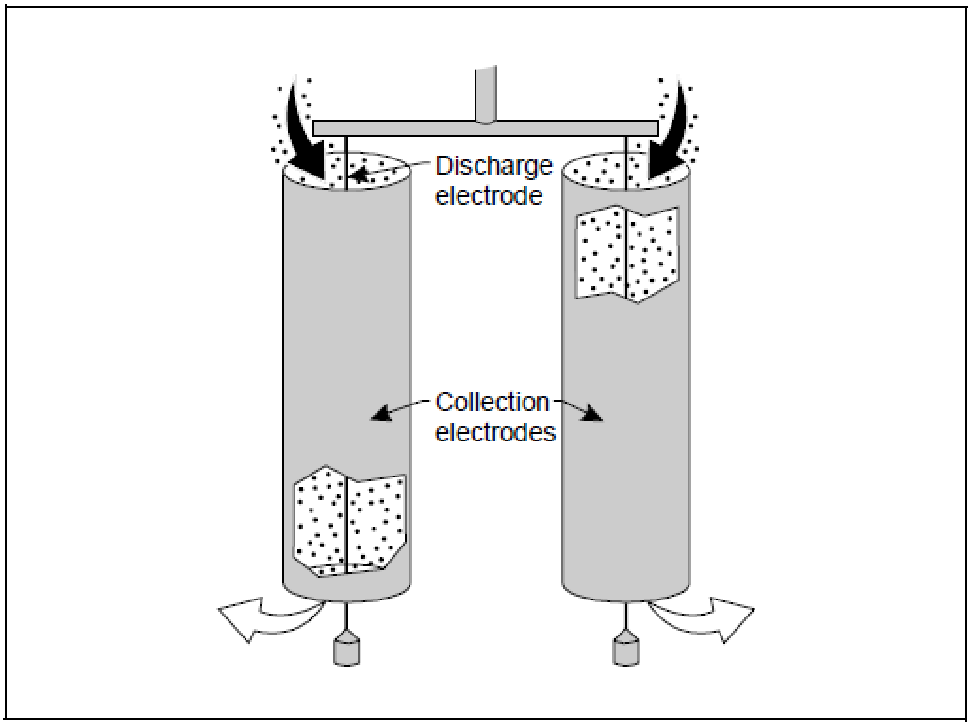

Figure 2.2: Gas flow through a tubular precipitator

Approximately 0.13 to 0.38cm (0.05 to 0.15 inch) in diameter. Collection plates are usually between 6 and 12m (20 and 40ft) high. For ESPs with wire discharge electrodes, the plates are usually spaced from 15 to 30cm (6 to 12 inch) apart. For ESPs with rigid-frame or plate discharge electrodes, plates are typically spaced 30 to 38cm (12 to 15 inch) apart and 8 to 12m (30 to 40ft) in height. Plate ESPs are typically used for collecting fly ash from industrial and utility boilers as well as in many other industries including cement kilns, glass plants and pulp and paper mills [5].

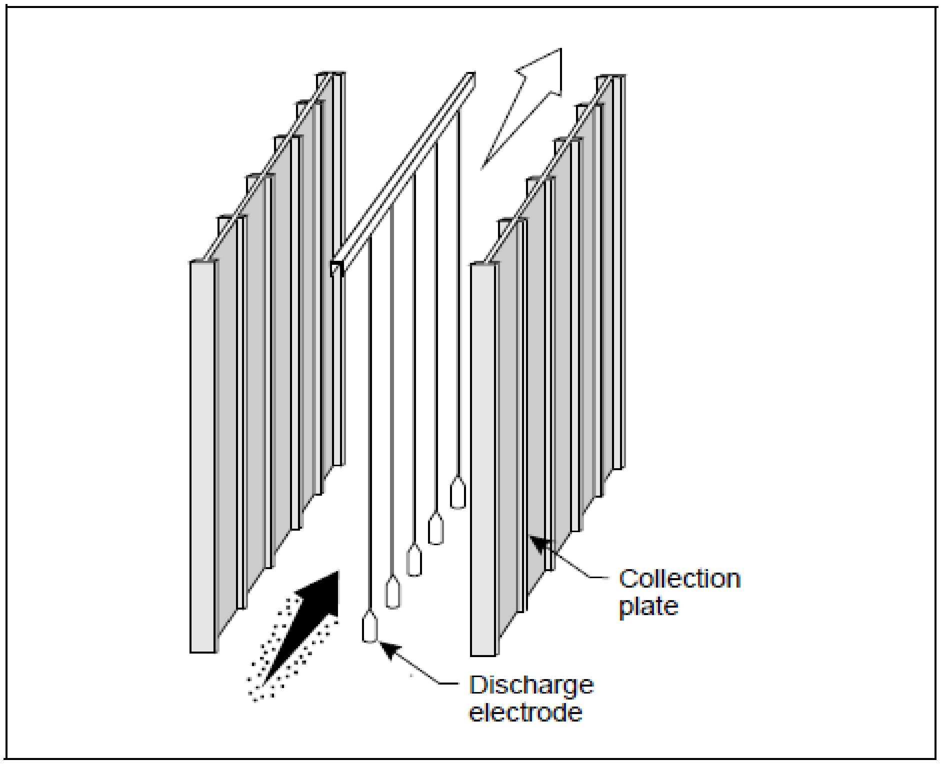

Figure 2.3: Gas flow through a plate precipitator

II. Single-stage and Two-stage ESPs

Another method of classifying ESPs is by the number of stages used to charge and remove particles from a gas stream. A single-stage precipitator uses high voltage to charge the particles, which are then collected within the same chamber on collection surfaces of opposite charge. In a two-stage precipitator, particles are charged by low voltage in one chamber, and then collected by oppositely charged surfaces in a second chamber.

i. Single stage: Most ESPs that reduce particulate emissions from boilers and other industrial processes are single-stage ESPs. Single stage ESPs use very high voltage (50 to 70kV) to charge particles. After being charged, particles move in a direction perpendicular to the gas flow through the ESP, and migrate to an oppositely charged collection surface, usually a plate or tube particle. Charging and collection occurs in the same stage, or field, thus, the precipitators are called single-stage ESPs. The term field is used interchangeably with the term stage and is described in more detail later in this course. Figure 2.2 shows a single stage tubular precipitator. A single-stage plate precipitator is shown in Figure 2.3 [4].

ii. Two Stage**:** The two-stage precipitator differs from the single-stage precipitator in both design and amount of voltage applied. The two-stage ESP has separate particle charging and collection stages Figure (2.4). The ionizing stage consists of a series of small, positively charged wires equally spaced 2.5 to 5.1 cm (1 to 2 inch) from parallel grounded tubes or rods. A corona discharge between each wire and a corresponding tube charges the particles suspended in the air flow as they pass through the ionizer. The direct-current potential applied to the wires is approximately 12 to 13kV. The second stage consists of parallel metal plates less than 2.5cm (1 inch) apart. The particles receive a positive charge in the ionizer stage and are collected at the negative plates in the second stage. Collected smoke or liquids drain by gravity to a pan located below the plates, or are sprayed with water mists or solvents that remove the particles and cause them to fall into the bottom pan.

Two-stage precipitators were originally designed for air purification in conjunction with air conditioning systems. They are also referred to as electronic air filters. Two stage ESPs are used primarily for the control of finely divided liquid particles. Controlling solid or sticky materials is usually difficult, and the collector becomes ineffective for dust loadings greater than 7.3x10-3g/m3 (0.4gr/dscf). Therefore, two-stage precipitators have limited use for particulate-emission control. They are used almost exclusively to collect liquid aerosols discharged from sources such as meat smokehouses, pipe-coating machines, asphalt paper saturators, high speed grinding machines, welding machines, and metal-coating operations [4].

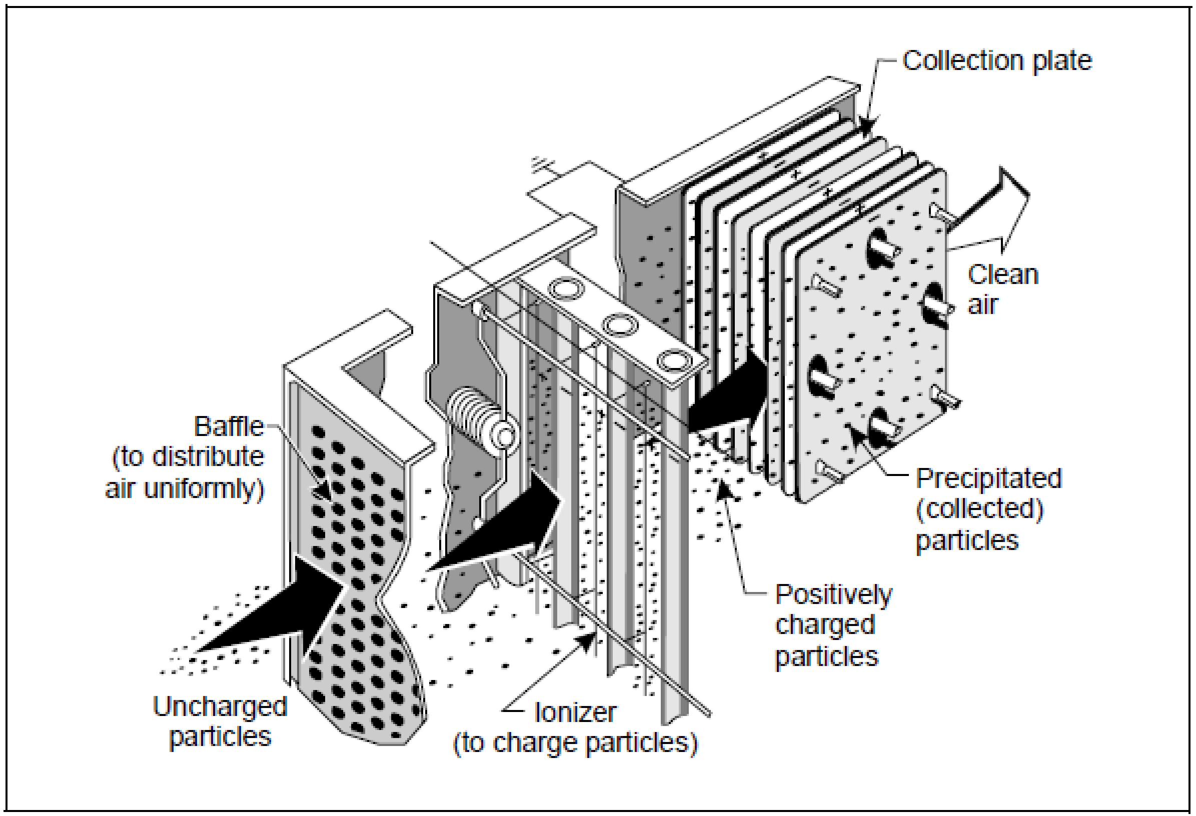

Figure 2.4: Representation of gas flow in two stage precipitator

III. Cold-side and Hot-side ESPs

Electrostatic precipitators are also grouped according to the temperature of the flue gas that enters the ESP: cold-side ESPs are used for flue gas having temperatures of approximately 204°C (400°F) or less, hot-side ESPs are used for flue gas having temperatures greater than 300°C (572°F). In describing ESPs installed on industrial and utility boilers, or municipal waste combustors using heat recovery equipment, cold side and hot side also refer to the placement of the ESP in relation to the combustion air preheater. A cold-side ESP is located behind the air preheater, whereas a hot-side ESP is located in front of the air preheater. The air preheater is a tube section that preheats the combustion air used for burning fuel in a boiler. When hot flue gas from an industrial process passes through an air preheater, a heat exchange process occurs whereby heat from the flue gas is transferred to the combustion air stream. The flue gas is therefore "cooled" as it passes through the combustion air preheater. The warmed combustion air is sent to burners, where it is used to burn gas, oil, coal, or other fuel including garbage. APTI Course SI: 428A Introduction to Boiler Operation describes boilers and heat recovery equipment in greater detail [4,5].

Cold-side ESPs as shown in Figure 2.5 have been used for over 50 years with industrial and utility boilers, where the flue gas temperature is relatively low (less than 204°C or 400°F). Cold-side ESPs generally use plates to collect charged particles. Because these ESPs are operated at lower temperatures than hot-side ESPs, the volume of flue gas that is handled is less. Therefore, the overall size of the unit is smaller, making it less costly. Cold-side ESPs can be used to remove fly ash from boilers that burn high sulfur coal. As explained in later lessons, cold-side ESPs can effectively remove fly ash from boilers burning low-sulfur coal with the addition of conditioning agents.

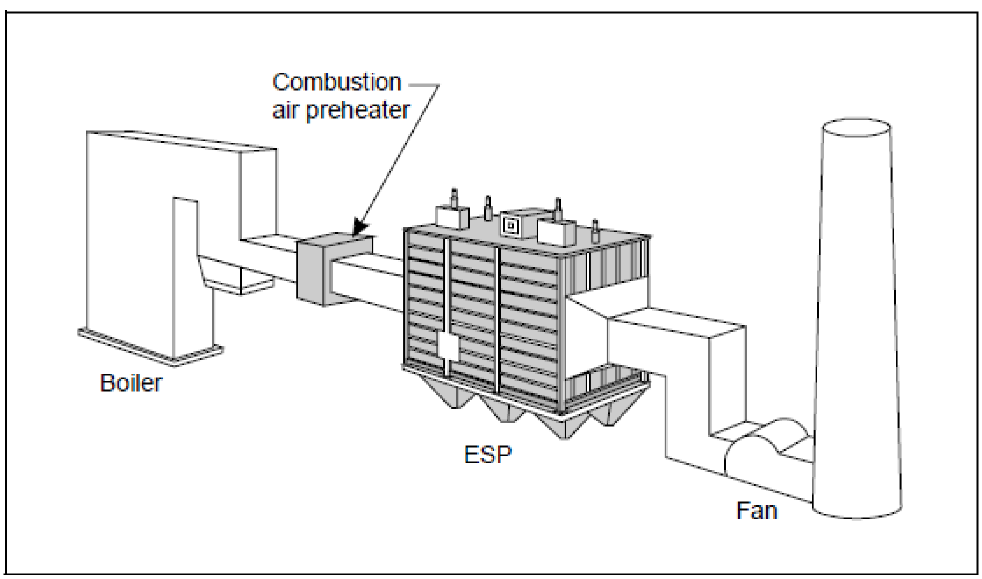

Figure 2.5: Cold side ESP

Hot-side ESPs as shown in Figure 2.6 are placed in locations where the flue gas temperature is relatively high. Their collection electrodes can be either tubular or plate. Hot-side ESPs are used in high-temperature applications, such as in the collection of cement kiln dust or utility and industrial boiler fly ash. A hot-side precipitator is located before the combustion air preheater in a boiler. The flue gas temperature for hot-side precipitators is in the range of 320 to 420°C (608 to 790°F).

The use of hot-side precipitators help reduce corrosion and hopper plugging. However, these units (mainly used on coal-fired boilers) have some disadvantages. Because the temperature of the flue gas is higher, the gas volume treated in the ESP is larger. Consequently, the overall size of the precipitator is larger making it more costly. Other major disadvantages include structural and mechanical problems that occur in the precipitator shell and support structure as a result of differences in thermal expansion.

For years, cold-side ESPs were used successfully on boilers burning high-sulfur coal. However, during the 1970s when utilities switched to burning low-sulfur coal, cold side ESPs were no longer effective at collecting the fly ash. Fly ash produced from low sulfur coal-fired boilers has high resistivity making it difficult to collect. As you will learn later, high temperatures can lower resistivity. Consequently, hot-side ESPs became very popular during the 1970s for removing ash from coal-fired boilers burning low sulfur coal. However, many of these units did not operate reliably, and therefore, since the 1980s, operators have generally decided to use cold-side ESPs along with conditioning agents when burning low sulfur coal. Hot-side ESPs are also used in industrial applications such as cement kilns and steel refining furnaces. In these cases, combustion air preheaters are generally not used and hot side just refers to the high flue gas temperature prior to entering the ESP [4,5].

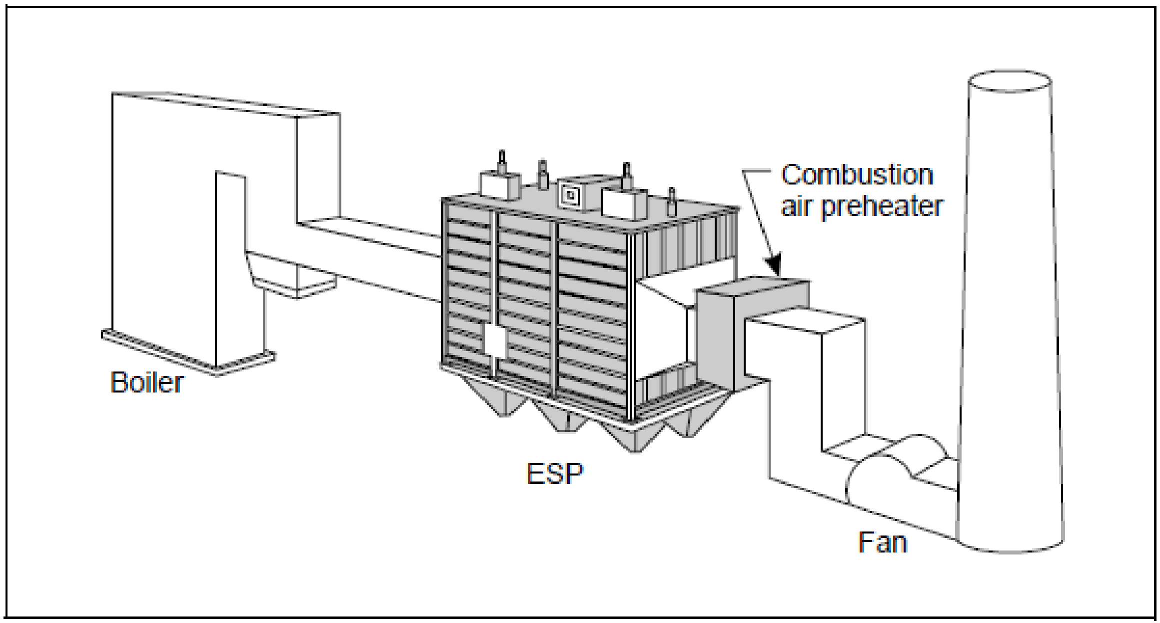

Figure 2.6: Hot side ESP

IV. Wet and Dry ESPs:

Wet ESPs, Any of the previously described ESPs can be operated with a wet spray to remove collected particles. Wet ESPs are used for industrial applications where the potential for explosion is high (such as collecting dust from a closed-hood Basic Oxygen Furnace in the steel industry), or when dust is very sticky, corrosive, or has very high resistivity. The water flow may be applied continuously or intermittently to wash the collected particles from the collection electrodes into a sump (a basin used to collect liquid). The advantage of using a wet ESP is that it does not have problems with rapping reentrainment or with back corona [6].

Figures 2.6 and 2.7 show two different wet ESPs. The casing of wet ESPs is made of steel or fiberglass and the discharge electrodes are made of carbon steel or special alloys, depending on the corrosiveness of the flue gas stream.

In a circular-plate wet ESP, shown in Figure 2.6, the circular collection plates are sprayed with liquid continuously. The liquid provides the electrical ground for attracting the particles and for removing them from the plates. These units can handle gas flow rates of 30,000 to 100,000 cfm. Preconditioning sprays located at the inlet remove some particulate matter prior to the charging stage. The operating pressure drop across these units is typically 1 to 3 inches of water.

Rectangular flat-plate wet ESPs, shown in Figure 2.7, operate similarly to circular plate wet ESPs. Water sprays precondition the gas stream and provide some particle removal. Because the water sprays are located over the top of the electrical fields, the collection plates are continuously irrigated. The collected particulate matter flows downward into a trough that is sloped to a drain.

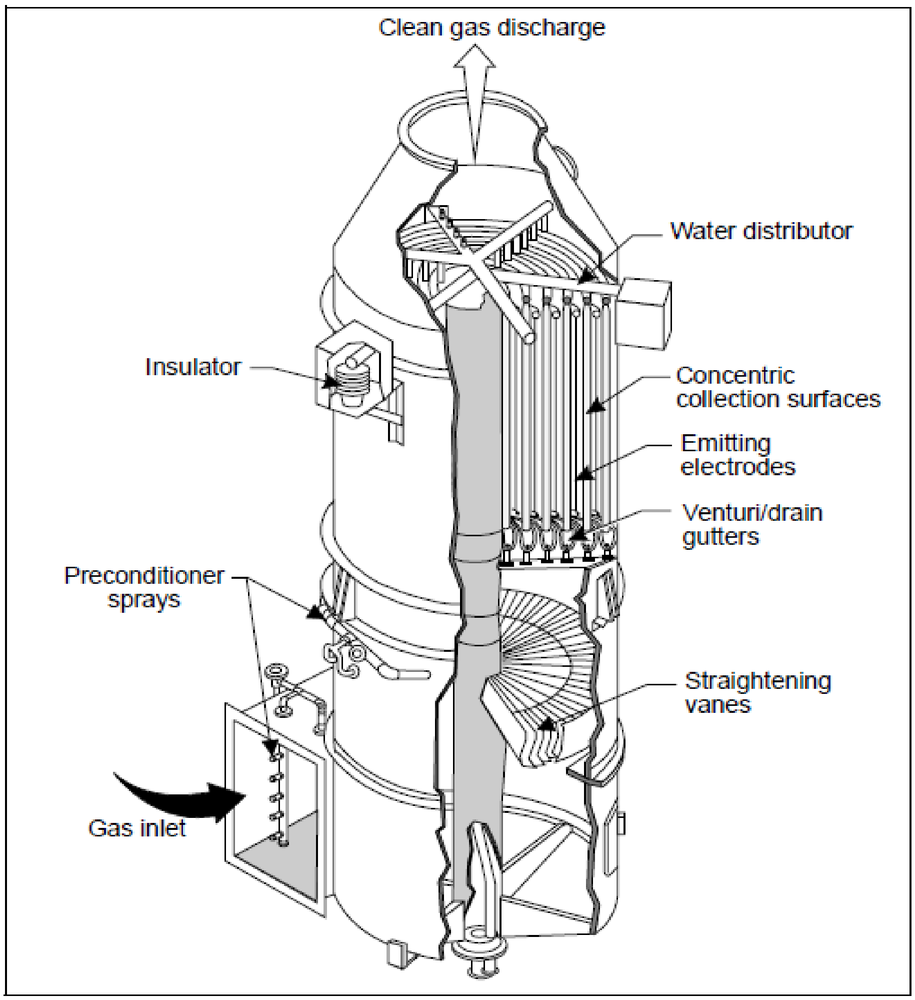

Figure 2.6: Circular plate ESP

Dry ESPs, most electrostatic precipitators are operated dry and use rappers to remove the collected particulate matter. The term dry is used because particles are charged and collected in a dry state and are removed by rapping as opposed to water washing which is used with wet ESPs. The major portion of this course covers dry ESPs that are used for collecting dust from many industries including steel furnaces, cement kilns and fossil-fuel-fired boilers.

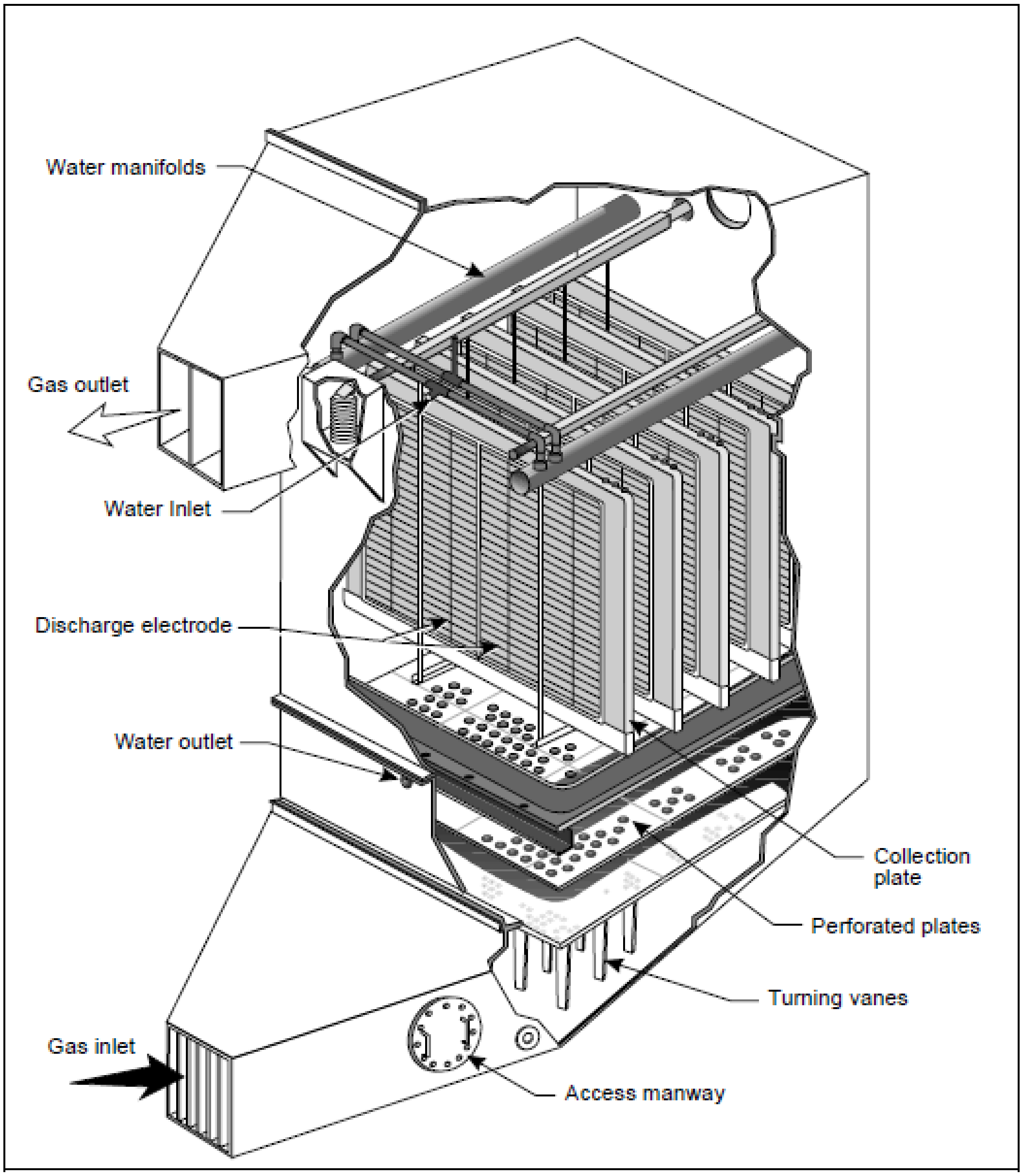

Figure 2.7: Flat plate modular wet ESP

2.3 Variables in operation

A number of parameters affect the performance of precipitator. The precipitator behavior depends on the gas and particles are treated , the type of coal burned, the design of furnace and its operation [3,4].

2.3.1 Furnace gases

The main constituent of furnace gases from coal-fired boilers are carbon dioxide, water vapor, nitrogen, oxygen, and minor constituents such as sulfur oxides, nitrogen oxides, and argon. The hydrogen and moisture content of the coal and the humidity of the combustion air determines the amount of water vapor, while the excess air used for combustion and air leakage into the unit determines the oxygen level. The amount of sulfur trioxide produced in the exhaust gas determines the resistivity of the fly ash. Sulfur trioxide reduces resistivity of fly ash thereby enhancing precipitator performance.

2.3.2 Coal

Coals are classified into peat, lignite, bituminous and anthracite with sub-categories within these categories being determined as per their age. The moisture content, volatile matter, fixed carbon, ash and heating value are some of the factors that determine the coal properties [3,4]. There are advantages and disadvantages of using lower sulfur coal. Using low sulfur coals is cheaper in the sense that it eliminates the need for sulfur scrubber and therefore eliminates large retrofit and operating costs associated with the installation of such equipment. However, they at the same time reduce precipitator performance by increasing the resistivity of the fly ash to be collected. The design and performance of a precipitator depends highly on the amounts of ash or residues of combustion, which are composed of inert oxides and silicate, contained in the coal. The amount of ash produced depends on the coal used. Collection of fly ash is difficult since wide varieties of coals are used, and the ash can vary widely between coals. A discussion of fly ash is given in the following sections.

2.3.3 Fly ash

Fly ash is the inert, inorganic residue of the coal after the combustion of charred particles fly ash normally consists of silica, alumina and iron oxide with traces of lead, barium, uranium, strontium and fluorine depending upon the type of coal burnt and the mining processes used. These trace elements do not affect the collection of the fly ash, but do pose a threat to humans. These trace elements are toxic and tend to concentrate in the fine particles, which are the most difficult to collect and which penetrate the respiratory system easily [4].

Fly ash particles are heterogeneous in shape depending upon the coal burnt. Particle size of fly ash varies from under 0.1µm to over 100µm. During incomplete combustion carbon gritty particles are formed which are larger in diameter than the bulk of the ash. However, the finer particles tend to dominate the bulk of the fly ash when good combustion conditions exist. Precipitator efficiency depends on the resistivity of the ash and it is best for resistivity between 10^2 and 10^{10} mΩ. At lower resistivity, the dust tends to fall off the collecting electrode and becomes re-entrained in the gas whereas at higher resistivity, back corona is generated by the collected particles that repel the movement of the other charged particles towards the collection surface [4].

2.4 Collection Efficiency

Electrostatic precipitators are capable of collecting greater than 99 percent of all sizes of particulate. Collection efficiency is effected by several factors including dust resistivity, gas temperature, chemical composition (of the dust and gas), and particle size distribution. The resistivity of a dust is a measure of its resistance to electrical conduction and it has a great effect on the performance of dry ESPs. The efficiency of an ESP is limited by the strength of the electric field it can generate, which in turn is dependent upon the voltage applied to the discharge electrodes. The maximum voltage that can be applied is determined by the sparking voltage. At this voltage, a path between the discharge and collection electrodes is ionized and sparking occurs. Highly resistive dusts increase sparking, which forces the ESP to operate at a lower voltage. The effectiveness of an ESP decreases as a result of the reduced operating voltage.

High resistivity dusts also hold their electrical charge for a relatively long period of time. This characteristic makes it difficult to remove the dust from the collection electrodes. In order to loosen the dust, rapping intensity must be increased. High intensity rapping can damage the ESP and cause severe reentrainment, leading to reduced collection efficiency. Low dust resistivities can also have a negative impact on ESP performance. Low resistivity dust quickly loses its charge once collected. When the collection electrodes are cleaned, even with light rapping, serious reentrainment can occur.

Temperature and the chemical composition of the dust and gas stream are factors which can influence dust resistivity. Current is conducted through dust by two means, volume conduction and surface conduction. Volume conduction takes place through the material itself, and is dependent on the chemical composition of the dust. Surface conduction occurs through gases or liquids adsorbed by the particles, and is dependent on the chemical composition of the gas stream. Volume resistivity increases with increasing temperatures and is the dominant resistant force at temperatures above approximately 350°F. Surface resistivity decreases as temperature increases and predominates at temperatures below about 250°F. Between 250 and 350°F, volume and surface resistivity exert a combined effect, with total resistivity highest in this temperature range [3].

For coal fly ash, surface resistance is greatly influenced by the sulfur content of the coal. Low sulfur coals have high resistivity, because there is decreased adsorption of conductive gases (such as SO3) by the fly ash. The collection efficiency for high-resistance dusts can be improved with chemical flue gas conditioning that involves the addition of small amounts of chemicals into the gas stream (discussed in Section 5.1, Pretreatment). Typical chemicals include sulfur dioxide (SO2), ammonia (NH3), and sodium carbonate. These chemicals provide conductive gases which can substantially reduce the surface resistivity of the fly ash, 10 Resistivity can also be reduced by the injection of steam or water into the gas stream.

In general, dry ESPs operate most efficiently with dust resistivities between 5×10^3 and 210^{10} ohm-cm^{-2}. Electrostatic precipitator design and operation is difficult for dust resistivities above 1011 ohm-cm. Dust resistivity is generally not a factor for wet ESPs. The particle size distribution impacts on the overall performance of an ESP. In general, the most difficult particles to collect are those with aerodynamic diameters between 0.1 and 1.0m. Particles between 0.2 and 0.4m usually show the most penetration. This is most likely a result of the transition region between field and diffusion charging.