

## FOSSIL FUEL WASTE PRODUCT HANDLING

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### Contents

1. Exhaust Gas
  - 1.1. Exhaust Gas Constituents
2. Electrostatic Precipitators
  - 2.1. General Principles
  - 2.2. Design Aspects
  - 2.3. Charging Wires
  - 2.4. Collecting Plates
  - 2.5. Wet Electrostatic Precipitators
3. Baghouses
  - 3.1. General Principles
  - 3.2. Configuration
  - 3.3. Baghouse Types
  - 3.4. Filter Fabrics
  - 3.5. Comparison with Electrostatic Precipitators
4. Flue Gas Desulfurization
  - 4.1. General
  - 4.2. Wet Limestone Scrubbers
  - 4.3. Dry Limestone Scrubbers
5. Nitrogen Oxides Removal
  - 5.1. General
  - 5.2. Selective Non-catalytic Reduction (SNCR)
  - 5.3. Selective Catalytic Reduction (SCR)
6. Carbon Dioxide
  - 6.1. Background
  - 6.2. Removal of Carbon Dioxide
  - 6.3. Disposal of Carbon Dioxide
7. Exhaust Gas Stacks
  - 7.1. General Requirements
8. Ash
  - 8.1. Ash Formation
  - 8.2. Types of Ash
  - 8.3. Ash Distribution
9. Ash Handling Systems
  - 9.1. Methods of Ash Removal
  - 9.2. Bottom Ash Removal
  - 9.3. Clinker Grinders
  - 9.4. Pneumatic Vacuum System
  - 9.5. Pneumatic Pressure System

- 10. Ash Disposal Systems
  - 10.1. Transport Methods
  - 10.2. Dry Ash Disposal
  - 10.3. Wet Ash Disposal
- 11. Environmental Considerations
  - 11.1. Choice of Fuel
  - 11.2. Choice of Clean-up System
  - 11.3. Role of Regulatory Requirements
- Acknowledgement
- Glossary
- Bibliography
- Biographical Sketch

## Summary

All solid fuel fired steam-generating units require ash disposal facilities. Coal, which is widely used, has great variability in the ash that is produced. First, the ash content varies greatly in coals from different regions and, second, the ash itself may be caking or non-caking. Caking coals (such as most bituminous coals) form semi-molten ash, which solidifies into hard clinker. Most ash handling systems, therefore, have to deal with ash from very fine fly ash to large lumps of clinker.

In pulverized fuel fired plants, the majority of the ash produced is carried out of the furnace with the exhaust gas. Electrostatic precipitators or fabric filters collect this and discharge it into hoppers. From the hoppers it is conveniently conveyed by a stream of air to the point of disposal or transport off the site. With all solid fuel fired plants, a significant amount of heavier ash, including some clinker, collects in the hopper at the bottom of the furnace. This may be sluiced away with a jet of water or dragged away with a mechanical scraper.

Electrostatic precipitators remove fly ash by electrically charging the dust particles and attracting them to an oppositely charged plate. Fabric filters remove the ash by filtering the flue gas through a filter bed established on a woven fabric. However, the two methods have different operational characteristics. Electrostatic precipitators have a constant efficiency and so let through more dust when the exhaust gas is excessively laden, as can happen during soot blowing. Fabric filters or baghouses can maintain a constant effluent quality but suffer increased pressure drop as ash builds up on the filters.

When fuels containing sulfur are burned, the exhaust gas contains sulfur dioxide, which, if released to the atmosphere, will increase the acidity of rain. Certain reagents in a flue gas desulfurization unit can remove sulfur dioxide. The most common system in use is the wet system where a slurry of limestone in water is sprayed into the flue gas. During all combustion processes some nitrogen oxide is formed from nitrogen in the fuel and atmosphere. This may be quite substantially reduced by using catalytic reactors.

Ultimately, ash may be disposed of in a wet or dry state. For wet disposal, the ash is mixed with water to form a slurry, which is pumped to a settling pond. For dry disposal,

the ash is partially agglomerated by mixing with some water to avoid a dust nuisance and transported by road or rail to a suitable disposal site.

## **1. Exhaust Gas**

### **1.1. Exhaust Gas Constituents**

Exhaust gas leaving the last heat recovery component of the steam-generating unit, that is, the air heater, is unsuitable in several ways for release into the environment. First, it contains ash in the form of fine fly ash particles. In pulverized coal fired boilers some 80% of the ash is carried out by the exhaust gas. If the coal has high ash content, this is a substantial burden in the gas stream. Second, depending upon the sulfur content of the fuel, it usually contains some oxides of sulfur, especially sulfur dioxide. In the atmosphere these combine with moisture to form acidic compounds, such as sulfuric acid, which eventually fall to earth as acid rain. Third, it contains vast amounts of carbon dioxide and water vapor arising directly from the combustion of hydrocarbon fuels. The ratio depends upon the type of fuel. Water vapor is of no consequence but carbon dioxide is a so-called “greenhouse gas,” which may contribute to global warming. Ideally these detrimental components should be eliminated or at least minimized.

The choice of fuel naturally has an impact on the quantity of undesirable products emitted. Economic considerations, however, dictate the use of a particular fuel in any given application. The amount of gaseous effluent per unit of electricity generated depends upon the thermodynamic cycle efficiency, which in turn is also based on economic considerations. Any particular power plant therefore will produce a particular combination of these major products and it is a question of how best to minimize their impact on the environment.

Fly ash in the exhaust gas is highly visible and has an immediate impact on the area surrounding the plant if not almost entirely eliminated. Appropriate technology has been applied for over half a century to deal with this problem and highly efficient methods are currently available for removing fly ash. The two methods widely adopted are electrostatic separation of ash particles in precipitators and fabric filtering in baghouses. Both methods can achieve extremely high removal efficiencies of as much as 99.9% to give a clear exhaust gas plume.

Sulfur oxides in the exhaust gas are invisible so, until comparatively recently, no serious attempts were made to reduce them, except in specific locations where acidic fallout from the exhaust gas had a detrimental effect on the immediate area surrounding the plant. Currently technology provides for the dry or wet treatment of the exhaust gas to chemically fix the sulfur in inert compounds and to remove it. Removal efficiencies of about 90% are achievable in wet scrubbers.

Carbon dioxide is a major constituent of the exhaust gas and cannot be removed. It is a harmless gas produced by many natural processes but it is the total quantity in the atmosphere that is of concern. Carbon dioxide allows radiation from the sun to penetrate the atmosphere of the earth but inhibits its reflection. It thus acts as a so-called

“greenhouse gas,” which traps heat in the atmosphere. Since the beginning of the industrial age its concentration in the atmosphere has increased by almost one-third and there is concern that this may alter the global climate.

Water vapor is also harmless but is highly visible when condensed and so appears to be a pollutant when in fact it is not. Water vapor plumes however may carry undesirable contaminants in solution or suspension. This can cause local fallout of these contaminants if the plume is not carried to a high elevation and dispersed.

## 2. Electrostatic Precipitators

### 2.1. General Principles

Particulate removal from the exhaust gas is generally carried out after the hot gases have left the air heater but before they enter the induced draught fan and discharge stack. Figure 1 shows the typical location and size of an electrostatic precipitator in a coal-fired plant. If the plant were equipped with a baghouse, it would be in the same location. Figure 2 shows the construction of an electrostatic precipitator.

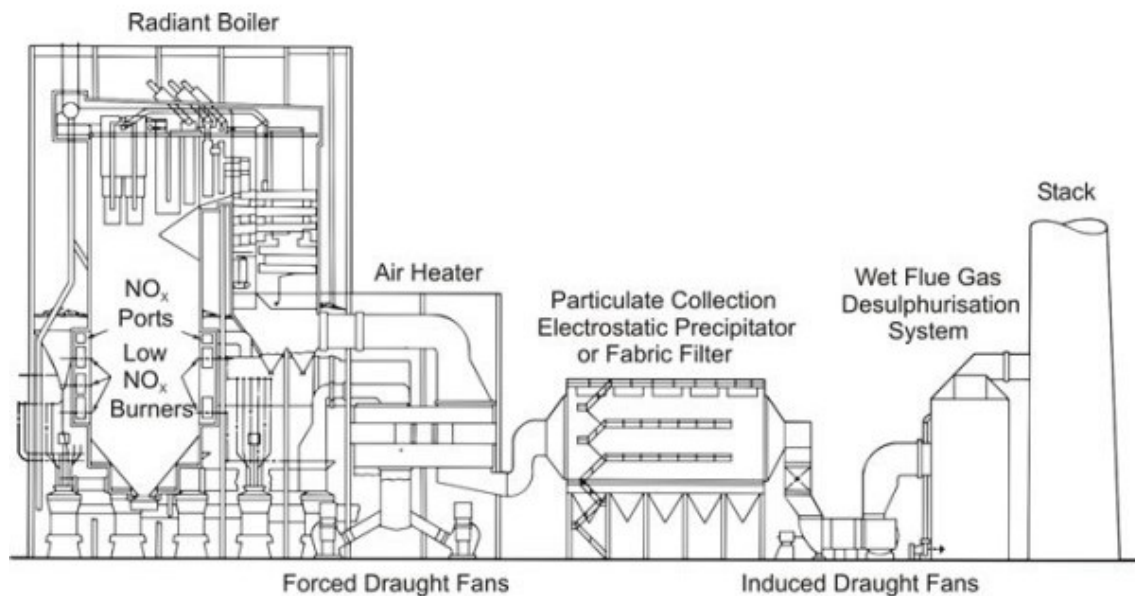


Figure 1. Coal fired plant with electrostatic precipitator (courtesy of Babcock and Wilcox)

When ash or dust particles suspended in a gas flow are subjected to a strong electric field they become negatively charged and are attracted towards the positive electrode.

The accumulation of particles on the positive electrode leaves the gas flow clear. Provision must be made for an adequate area on which the particles can accumulate and for their periodic removal without re-entrainment in the gas flow.

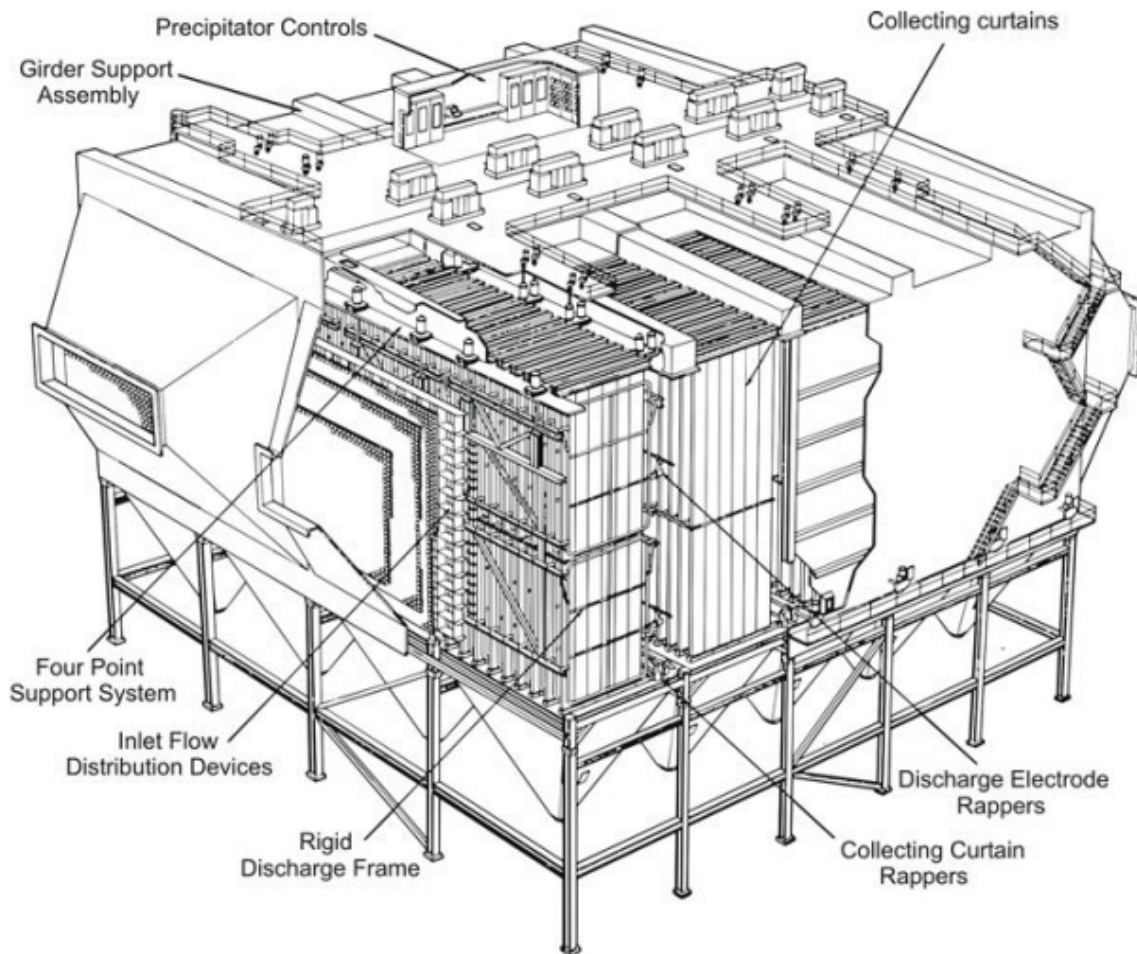


Figure 2. Electrostatic precipitator (courtesy of Babcock and Wilcox)

In a typical electrostatic precipitator, negatively charged wires are suspended vertically between vertical grounded plates and the ash-laden gas is passed horizontally through the precipitator between the wires and plates. The high negative voltage on the wires creates a strong electric field between the wires and the plates. The electric field must be sufficiently strong to create a corona discharge around the wire as shown in Figure 3. This ionizes the gas close to the wire and generates a steady flow of negative ions towards the positive grounded plates, while the positive ions are discharged on the negatively charged wires.

The net result is a field of negative ions or free electrons flowing between the negative corona surrounding the wires and the large grounded plates. The free electrons generated by the corona attach themselves to electronegative gases such as oxygen to create negative ions, which in turn are adsorbed onto the particles. The now negatively charged particles are driven by the strong electric field, between the wires and the plates, towards the plates where they collect as shown in Figure 4. On the positive grounded plates they are slowly discharged but remain held by mutual attraction. Periodically the plates are rapped and the ensuing vibration dislodges the accumulated ash, which falls off as a sheet of agglomerated particles.

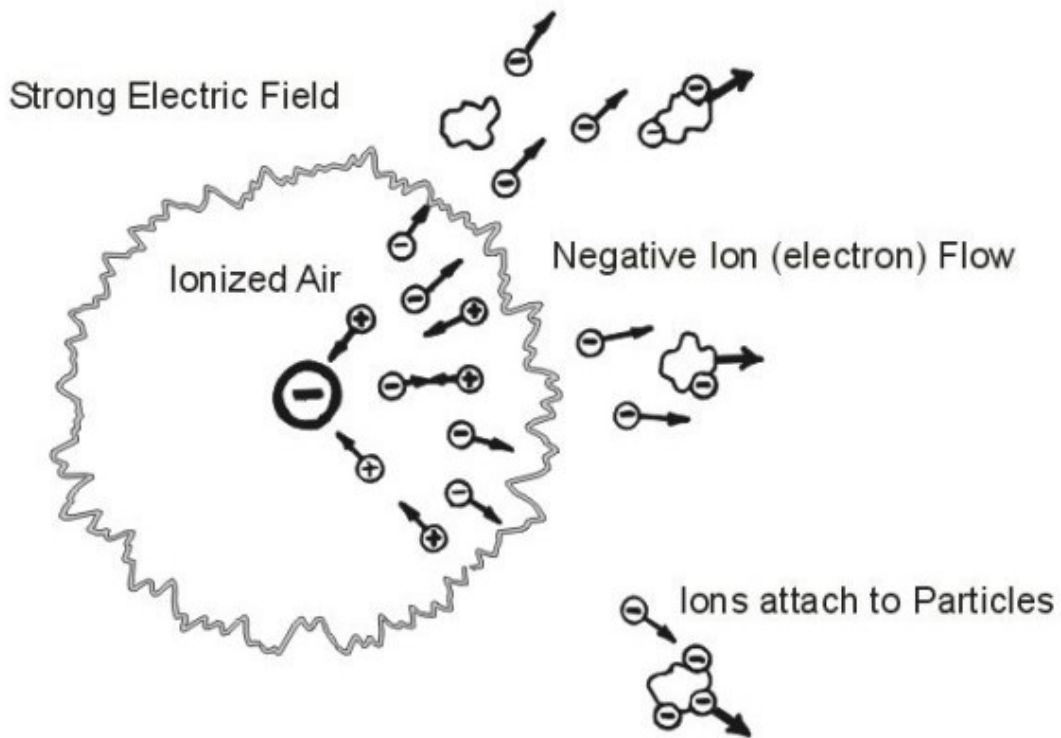


Figure 3. Corona discharge around a negatively charged wire

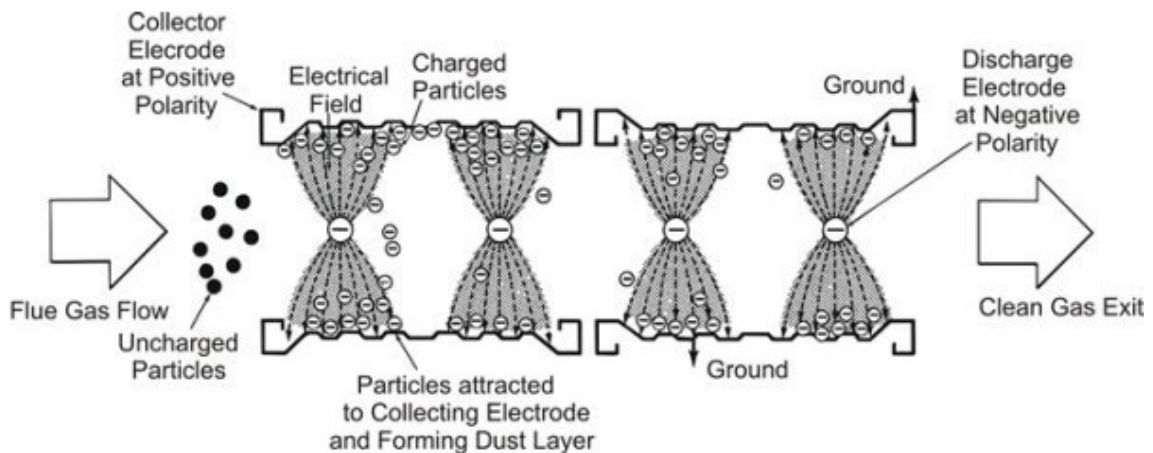


Figure 4. Charged particle migration to a positively charged plate (courtesy of Babcock and Wilcox)

A negative corona is more suited in this type of application because it has a higher sparking or flashover voltage than a positive corona. This allows greater voltages, in the range of 55 kV to 75 kV, to be employed, thus increasing the driving force on the charged particles.

An important factor in the design of an electrostatic precipitator is how easily the ash particles acquire a negative charge, while subject to negative ions, and how quickly they lose their charge once they have collected on the plates. This is related to the resistivity



of the ash. Ash with too low a resistivity acquires a charge easily but loses it quickly once on the collection plates. This prevents it from adhering well to the plate and it is readily re-entrained in the gas flow. Ash that has too high a resistivity is not easily charged and is difficult to remove from the gas stream. For efficient collection of the particles, their resistivity should be within the range of  $1 \times 10^9$  ohm-cm and  $5 \times 10^{11}$  ohm-cm. Some ash, however, has a resistivity as low as  $1 \times 10^8$  ohm-cm and some as high as  $1 \times 10^{14}$  ohm-cm.

At the upper end of the range of ash resistivities a further problem arises. As the ash particles accumulate on the positive plates, their high resistivity prevents their negative charge from draining away and eventually their overall negative charge is sufficient to prevent the attraction of further negatively charged particles. This seriously affects precipitator performance and limits the allowable build-up of ash before its removal from the plates. The relationship between ash resistivity and gas temperature is shown in Figure 5.

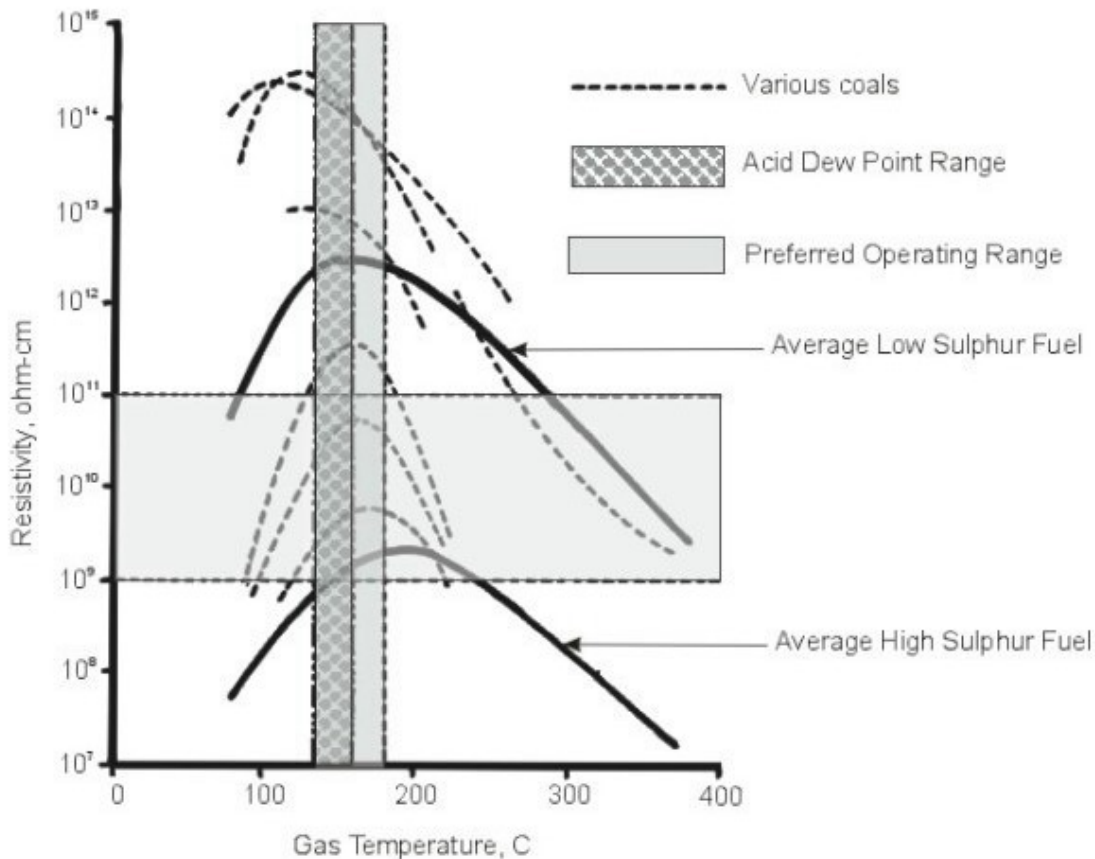


Figure 5. Ash resistivity and gas temperature ranges

A number of factors affect the resistivity of the ash. Temperature and chemical composition of both the ash and gas are the major factors. Resistivity is at a maximum between temperatures of about 120 °C and about 175 °C. This is a problem with ash of higher resistivity as the gas temperature cannot be reduced below the acid dew point without causing excessive corrosion, or raised to too high a value without suffering excessive exhaust heat loss. For ash of lower resistivity, the range of maximum

resistivity is right within the operating range so there is a good match between the desired and actual resistivity. With regard to chemical composition, resistivity is proportional to the quantity of calcium, magnesium, alumina, and silica and inversely proportional to that of sodium, potassium, and carbon in the ash. Various coals therefore produce ash with different resistivities. The amount of moisture and sulfur trioxide in the gas also has an effect. Ash resistivity is inversely proportional to the concentration of both of these compounds. Coal with high sulfur content therefore produces ash with a low resistivity. The effect of the moisture and sulfur trioxide is to provide a partial coating of conductive sulfuric acid on the particles thus reducing their resistivity.

This provides a useful method for reducing the resistivities of ash with too high a resistivity. By injecting a small amount of sulfur trioxide upstream of the precipitator the ash particles become coated and the performance of the precipitator is improved. Provided the amount of sulfur trioxide injected is not excessive the emission of sulfur oxides is not increased since all the additional sulfur trioxide is trapped on the surface of the particles.

## 2.2. Design Aspects

In the negative corona surrounding the discharge wires, the gas is ionized and a stream of negative ions produced. Between the corona and the positive collecting plates the stream of negative ions interacts with the particles in the gas stream giving them a negative charge. For a given particle size and gas conditions this charge  $q$  is proportional to charging field strength  $E_{\text{charging}}$

$$q \propto E_{\text{charging}} \quad (1)$$

The total electrostatic force on a particle  $F$  is proportional to the charge on the particle  $q$  multiplied by the collecting field strength  $E_{\text{collecting}}$

$$F \propto E_{\text{charging}} E_{\text{collecting}} \quad (2)$$

The terminal drift velocity  $w$  of the particle within the electrical field is proportional to the electrostatic force  $F$ .

$$w \propto E_{\text{charging}} E_{\text{collecting}} \quad (3)$$

Since the charging and collecting field strength are essentially the same, the particle drift velocity is proportional to the square of the field strength  $E$ .

$$F \propto E^2 \quad (4)$$

It is evident therefore that there is a strong incentive to operate with as high a field strength as possible to maximize the particle velocity towards the collecting plate.

The drift velocity multiplied by the average particle concentration between the inlet and outlet  $C_{\text{average}}$  and the collecting area  $A$  gives the amount collected in the precipitator.



$$\text{mass collected} = w C_{\text{average}} A \quad (5)$$

The mass collected is also the change in concentration between the inlet and the outlet multiplied by the volume flow rate  $Q$ .

$$\text{mass collected} = (C_{\text{inlet}} - C_{\text{outlet}}) Q \quad (6)$$

Combining these equations and integrating gives:

$$\Delta C / C_{\text{average}} = - w A / Q$$

$$\text{Ln} (C_{\text{outlet}} / C_{\text{inlet}}) = - w A / Q$$

$$C_{\text{outlet}} / C_{\text{inlet}} = e^{-w A / Q} \quad (7)$$

This can be related to the collection efficiency  $\eta$  which is the amount collected or change in concentration divided by the inlet concentration.

$$\eta = (C_{\text{inlet}} - C_{\text{outlet}}) / C_{\text{inlet}}$$

$$\eta = 1 - e^{-w A / Q} \quad (8)$$

This is known as the “Deutsch–Anderson equation.”

In designing an electrostatic precipitator there are various factors to consider.

### 2.2.1. Ash Resistivity

The resistivity of the ash particles is very variable, depending upon the type of coal used, and hence so is the charge received by the particles. This in turn affects the drift velocity and the overall design of the precipitator.

### 2.2.2. Drift Velocity

The drift velocity depends upon the charge on the particle and the electrical field. There is, however, some re-entrainment due to particles that fail to adhere to the plates and to particles that are freed during removal of ash from the plates. Turbulence within the gas path also affects the drift velocity, which is based on quiescent conditions. An effective drift velocity rather than the theoretical drift velocity should therefore be used in the equations. Since variations in resistivity, degree of re-entrainment, and effect of turbulence cannot be calculated accurately, empirical values from pilot plants have to be used for the effective drift velocity, making the design somewhat more of an art than a science. Effective drift velocities are anywhere up to  $20 \text{ cm s}^{-1}$  in pilot plants and  $8 \text{ cm s}^{-1}$  in commercial applications, with lower figures more likely to prevail in practice.

### 2.2.3. Specific Collection Area

In the Deutsch–Anderson equation:

$$\eta = 1 - e^{-wA/Q} \quad (9)$$

The ratio  $A/Q$  is collection area over gas volume flow rate and is known as the “specific collection area.” For good efficiency a high specific collection area is required. It is obvious that this basic parameter for precipitator design is dependent upon the effective drift velocity  $w$ , a highly variable empirical value.

#### 2.2.4. Flow Area

The gas flow area must be selected to obtain suitable gas velocities over the collecting plates. To minimize re-entrainment of the particles, gas velocities within the precipitator should be about  $1 \text{ m s}^{-1}$ .

#### 2.2.5. Treatment Time

The minimum treatment time must be sufficient to allow a particle to acquire its electrostatic charge and to drift the full width of the space between the discharge wires and the collecting plates while passing through the precipitator. Treatment times are generally in the range of 7 to 20 seconds.

#### 2.2.6. Aspect Ratio

The aspect ratio is the ratio of the horizontal treatment length to the collection plate height. This ratio must be sufficiently high so that, when the plates are rapped to remove the agglomerated ash, it falls clear of the bottom of the plates and into the ash hoppers before being carried out of the precipitator with the gas stream. Aspect ratios of 1.2 to 2.0 are used, with higher values where emissions during ash removal must be minimized.

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### **Biographical Sketch**

**Robin Chaplin** obtained a B.Sc. and M.Sc. in mechanical engineering from the University of Cape Town. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom, and obtained an M.Sc. in nuclear engineering from Imperial College, London University. On returning and taking up a position in the head office of Eskom he spent some twelve years there, initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of the Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa, being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation, he obtained a Ph.D. in mechanical engineering from Queen's University in Canada. He was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick, where he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and teaching of courses in both nuclear and non-nuclear aspects of the program.