ELECTROSTATIC PRECIPITATORS

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KeyWords: Collector plate, Cottrell filter, Deutsch formula, Electrofilter, (Dry, or wet) electrostatic precipitator, emission electrode.

Contents

Summary

A survey is given of the main applications, the construction, operating mode, characteristics, and advantages and limitations of dry Electrostatic Precipitators (ESP). Important parameters are field strength, particle size, and resistivity. Most particles are

field charged, then attracted. Submicron particles can be thermally charged, so that these particles are also collected efficiently.

In Wet Electrostatic Precipitators (WESPs) the collector electrodes are cleaned wet; especially under condensing conditions a deep removal of fumes becomes possible. Some special effects, acting upon aerosol particles, are also considered.

1. Survey

1.1. Historical

In 1906 Dr. Frederick Cottrell, professor of physical chemistry at Berkeley, successfully precipitated sulfuric acid fumes in a small electrostatic precipitator (ESP) test unit using a high voltage transformer and the newly-invented synchronous mechanical rectifier. The commercial feasibility of the electrostatic precipitator was first demonstrated in a sulfuric acid plant of E.I. DuPont de Nemours, where arsenic vapors were impacting the operation of their catalytic converters. In 1911 Western Precipitation designed and constructed the first large electrostatic precipitator, which was installed at the Riverside Cement Company in Crestmore, California for the recapture of cement kiln dust. This unit remained in service for 54 years.

1.2. Main Characteristics

Characteristics	Typical Values
Operating Voltage, kV	10 to 100
Gas Flow, $m^3 h^{-1}$	Ranging from less than 10,000 to more than 2,000,000
Gas Linear Velocity, $m s^{-1}$	0.3 to 3
Gas Temperature, ° C	Dry: up to 450 Wet/condensation: typically at ca. 70 (i.e. gas dewpoint)
Dust load in Raw Gas, $g m^{-3}$	Up to 100 For high dust loads pre-separation is recommended
Dust load in Clean Gas, $mg m^{-3}$	Proportional to the raw gas load! Dry: 5 to 50 Wet: up to < 5 Condensation: up to < 1
Collection Efficiency, wt.%	Dry: 95 to 99.9 Wet and condensation: > 99.5
Pressure Drop, Pa	50 to 300 Depending on gas velocity and flow length
Operating Pressure, Pa	$8\ 10^4$ to $3\ 10^5$
Power Consumption, kWh per 1000 m^3	0.05 to 2
Particle Sizes Separated, µm	All, with a minimum Collection Efficiency at 0.5 to 2
Dust Electric Resistivity, Ohm cm	10^4 to 10^{11} (Preferred values)

Dust Migration Rate, cm s^{-1}	2 to 30

[Source: Adapted from Bank M. (2000). *Basiswissen Umwelttechnik : Wasser, Luft, Abfall, Lärm und Umweltrecht – 4., komplett neue, bearbeitete Auflage*, Wurzburg: Germany: Vogel, ISBN 3-8023-1797-1]

Table 1: Important characteristics in Electrostatic Precipitator operation

Dust particles are imparted an electric charge in a corona discharge and then the charged particles are attracted in a strong electrostatic field and precipitated onto collector electrodes. This is the working mode of an electrostatic precipitator (ESP), electrofilter, or Cottrell filter, three different names for the same type of dust collector, which has been the principal workhorse in large-scale dust collection (see, *Pollution Control in Industrial Processes, Control of Pollution in Power Generation* , *Control of Pollution in the Chemical Industry* , *Control of Pollution in the Petroleum Industry* , *Control of Pollution in the Iron and Steel Industry* , *Control of Pollution in the Non-ferrous Metals Industry* , and *Control of Pollution in the Pulp and Paper Industry*) It is generally encountered in thermal power plant, cement kilns, ore roasting, metal smelting, waste incineration, the pulp and paper industry, and in the manufacture of sulfuric acid. The success of the Electrostatic Precipitator is due to its very high separating efficiency (generally > 98 percent) obtained over a very wide range of particle size, as well as a dependable and trouble free operation. Dust is collected at a very low-pressure drop (generally some 100 to 200 Pa) and operating cost (power consumption typically amounts to 0.1 to 0.3 kWh per 1000 m^3 gas treated). Investment cost, on the other hand, is sizeable, for these ESP filters operate at low linear gas velocities, and hence tend to be bulky and expensive. Some of their most important characteristics are given in the Table 1.

Conventional (dry) Electrostatic Precipitators also exist in a wet version, used for special purposes, mainly collecting metallurgical fumes, acid and salt mists and capable of very high efficiency under arduous conditions, especially in a condensing mode (see, *Wet Scrubbers*).

1.3. Subdivisions in Electrostatic Precipitators

Electrostatic Precipitators can be subdivided according to:

1) Operating mode, with three types: dry (the most usual), wet, and condensing (wet) units.
2) Flow direction, with horizontal gas flow (the most usual), or vertical,
3) Shape of the earthed collector surfaces, either tubular, with a single central emission wire electrode, or (most frequently) flat or corrugated plates, with rows of emission electrodes situated in between them.

Tubular units are only used in small-scale equipment, and in condensing wet units. They consist of single or multiple units, with a typical diameter of 10 cm, and a height of 0.6 up to 6 m. Plate units normally consist of a large box, containing sets of vertical collector plates, with a mutual distance of 20 to 60 cm, and emission electrode wires situated at a regular distance halfway in the middle of two plates.

Parameter	Range
Distance between plates, cm Duct width, cm	20-30 20-23 optimum
Gas velocity in ESP, m s^{-1}	1.2-2.4; 1.5-1.8 optimum
SCA, m^2 per 1000 m^3 h^{-1}	11-45; 16.5-22.0 optimum
Aspect ratio* (L/H)	1-1.5
Particle migration velocity, cm s^{-1}	3-15
Number of fields	4-8
Corona power/flue gas volume, W per 1000 m^3 h^{-1}	59-295
Corona current density, μA m^{-2}	107-860
Plate area, m^2 per electrical TR set	465-7430; 930-2790 optimum

* keep plate height less than 9 m for high efficiency.

[Source: White, H.J. (1977). Electrostatic precipitation of fly ash – Parts: I, II, III and IV. *Journal of Journal of Air Pollution Control Association*, **27**, APCA Reprint Series 1, 2, 3 and 4, 1977.]

Table 2: Typical ranges of design parameters for fly ash precipitators

1.4. Design Parameters - Collection Efficiency

A large number of factors affect ESP performance in a complicated fashion. This implies that design is difficult, requiring experience and investigations. A basic parameter is the voltage selected for operation.

When the voltage is increased above a certain threshold value (the corona onset voltage, V_c) a corona discharge starts on the wire as either spots (negative corona emission electrode) or uniform glow (positive corona), representing regions of gaseous ionization. Monopolar ions of the corona polarity are emitted from the emission electrode and move across the electrode gap towards the collecting electrode.

When the voltage is raised the corona current increases according to:

$$I \quad = \quad A\ V\ \left(V - V_{\mathrm{c}}\right) \tag{1}$$

At a certain voltage, V_s sparking occurs and unless the voltage is interrupted this turns into arcing.

The working interval V_s - V_c is much wider with a negative corona than with a positive one. The latter is used in air purification, since it generates much less ozone. The latter, however, may be put to good use in case disinfection and deodorizing are required.

The average and maximum gas flow rates through the ESP, the temperature, moisture content, chemical properties such as dew point, corrosiveness, and combustibility of the gas should be identified prior to final design. If the ESP is going to be installed at an existing source, a stack test should be performed to determine the process gas stream properties. If the ESP is being installed at a new source, data from a similar plant or operation may be used, but the ESP should be designed conservatively, with a large **specific collection area** SCA, a high aspect ratio, and high corona power.

Collection Efficiency can theoretically be calculated, but the value really achievable is considerably affected by phenomena such as non-ideal collection and especially re-entrainment of deposited particles. Mostly used is the Deutsch equation:

$$efficiency = 1 - e^{-\frac{v.A}{Q}}, \qquad (2)$$

where v represents the effective particle migration velocity, A - the projected surface of the collector electrode, Q - the volumetric gas flow. The Deutsch formula has a theoretical basis, but fails to describe the actual collection efficiency with a sufficient level of accuracy, because of entrainment of collected particles and other phenomena causing inefficiencies, such as sparking, local turbulences, misdistribution, hydraulic short-circuiting (hot gas riding on top of colder strata) and other flow irregularities.

The effective velocity v of particles can be related to the charging field, E_1, the collecting field, E_2, and the viscosity μ by:

$$v = \frac{E_1 . E_2 . D}{4 . \mu} \qquad (3)$$

The migration velocity v at preset values of E_1 and E_2 is proportional to particle size and inversely proportional to gas viscosity. The migration velocity of a 5 µm particle typically attains 30 cm s^{-1} at 350° C and 48 cm s^{-1} at 20° C.

In practice, each constructor uses proprietary data for determining migration velocities, taking into account the nature of the particles, the probability of their re-entrainment, the type of charging and collecting electrodes, operating conditions, etc. These data are based upon collection efficiencies, experimentally observed under similar conditions.

The collection efficiency is markedly affected by particle size and conductivity. The charge of an individual particle is proportional to its surface. Hence, the ease of collection is inversely proportional to the particle diameter. The best efficiency is attained on particles having an intermediate electric resistivity (10^5 - 10^{10} ohm cm). Highly conducting particles are rapidly discharged and often re-entrained. Highly insulating particles build up an electrically insulating layer on the collecting electrode, eventually leading to disruptive discharge and sparking. Salt fumes, soot, and flakes of charred paper are difficult to collect.

Another delicate point is dislodging the deposited dust layer from the collector plates. Ideally, it glides down as a solid sheet when periodically a hammer knocks on an anvil attached to the collector plate, or when a vibrator, or (in wet units) a spray is activated. In practice, part of the dust is re-entrained, leading to a puff of extra dust in the exhaust. For this reason, an electrostatic precipitator normally consists of two, three, or four successive fields, exposed to decreased load and rapping frequency.

Calculation	Deutsch-Anderson	Matts-Ohnfeldt
Collection efficiency	$\eta = 1 - e^{-w(A/Q)}$	$\eta = 1 - e^{-w_k (A/Q)^k}$

Collection area to meet a required efficiency	$A=\frac{-Q}{w}\left[\ln\left(1-\eta\right)\right]$	$A=\left[-\left(\frac{Q}{w_k}\right)^k\left[\ln\left(1-\eta\right)\right]\right]^{1/k}$
Legend	η = Collection efficiency, wt. % A = collection area, m^2 w = migration velocity, m s^{-1} Q =gas flow rate, m^3 s^{-1} ln = natural logarithm	η = Collection efficiency, wt. % A = collection area, m^2 w_k = migration velocity, m s^{-1} Q =gas flow rate, m^3 s^{-1} k = constant (usually 0.5) ln = natural logarithm

[Source:http://yosemite.epa.gov/oaqps/EOGtrain.nsf/fabbfcfe2fc93dac85256afe00483cc4/d11a01df332fbdbc85256b66004ecb8e/$FILE/12bles4.pdf, *Lesson 4 - ESP Design Review.*]

Table 3: Equations used to estimate collection efficiency and collection area

2. Characteristics

2.1. Construction

At the inlet of the precipitator, the dust-laden gas must be evenly distributed over the entire cross-section by means of two or three perforated plates in series, a diffuser. These plates create sufficient head loss to prevent most of the gas from passing on top (when it is hotter) or at the bottom (when it is cooler than the average). Another distribution problem arises when – due to space limitations – the dusts leading to or from the filter are curved, causing a gyratory movement and uneven dust distribution at the entrance: this should be corrected by providing parallel lamella guiding the flow through a number of parallel channels sufficient to ensure equal distribution.

The gas then passes, generally in horizontal flow, between rows of grounded collector plates and of high-voltage charging electrodes. The latter are formed by wires, with circular or sometimes a star-formed cross-section, tensioned by a weight or by spiral wires mounted in a framework. The charging electrodes are suspended from quartz insulators. During starting-up these insulators are electrically heated, to avoid short-circuiting by condensation of moisture.

The electrical part of the plant consists of a high voltage transformer and of silicon or other rectifier diodes in a bridge circuit. The transformer-rectifier aggregate is contained in an oil and air cooled housing. The high voltage is controlled automatically with transducers or thyristors, connected in series. An automatic electronic controller makes it possible to vary the duration of the controlling impulses, to limit the current in the precipitator to a predetermined maximum value, to switch off selectively and temporarily in case of sparking, and to switch off automatically in case of short-circuiting. The electric aggregate is installed either on top of the precipitator, or in a special room. Generally the precipitator contains several electric fields in series, each field being controlled by its own high voltage aggregate. The sequence of at least two fields enhances efficiency during rapping or sparking.

At least three independent, consecutive fields are specified in case low emission values, e.g. 50 or even 30 mg per Nm^3 are required. The collecting surfaces are suspended from beams welded to the roof of the precipitator. The collecting and charging electrodes are rapped periodically by tumbling hammers. The collecting electrode has a smooth surface, to avoid sparking, and is placed in a region of low gas velocity, to restrict re-entrainment. The collected dust falls into a hopper hermetically closed at the bottom by e.g. a rotary valve or a set of sliding valves. The latter discharge the dust into a mechanical or pneumatic conveying system. Mechanical systems involve screw and also drag conveyors. Pneumatic systems may be confronted with fly ash solidification, in case it has hydraulic properties or of spontaneous ignition and sintering.

Precipitators with tubular collecting electrodes, surrounding the charging electrode are more expensive. The gas flow in these precipitators is vertical and in upflow. A vertical arrangement is but rarely used, e.g. when space is at a premium.

2.2. Design and Operating Factors

Discharge electrodes and electrode supports should be positioned centrally, free from swaying. The bottom and top of each wire should be covered with shrouds to help minimize sparking and metal erosion at these points. Newer ESPs generally use rigid-frame or rigid-electrode discharge electrodes.

Property	Effect
Particle Size Distribution	Small particles are more difficult to collect and become re-entrained more easily than larger particles. A minimum collection efficiency is experienced around 0.5 – 2 µm. Additional fields may be required to meet regulatory limits
Concentration in gas stream	When the dust concentration is too high, the automatic voltage controller may respond by totally suppressing the current in the inlet fields: • a cyclone or multicyclone may remove larger particles and conveniently reduce the dust concentration before the flue gas enters the ESP • installing a larger ESP with more plate area would be more costly.
Resistivity	Resistivity varies with flue gas temperature, the chemical composition of dust, and moisture content. For fly ash from coal-fired boilers, resistivity moreover depends on the sulfur content of the coal burned: the lower the sulfur content, the higher the resistivity. For boilers burning low-sulfur coal the ESP must be designed to deal with potential problems. Spraying water, injecting SO3 or other conditioning agents can reduce resistivity. A medium resistivity is desirable.
Chemical composition	Explosiveness, e.g. due to carbon or carbon monoxide Dew point, corrosiveness, and combustibility

[Source:http://yosemite.epa.gov/oaqps/EOGtrain.nsf/fabbfcfe2fc93dac85256afe00483cc4/3cf51317b4891fcb85256b66004ee90e/$FILE/12bles5.pdf. *Lesson 5 - Industrial Applications of ESPs*.]

Table 4: Dust properties affecting ESP performance

Collection electrodes: tubes are chosen only for small plants or for wet operation. For ESPs using wire discharge electrodes, the spacing between collection plate electrodes usually ranges from 15 to 30 cm. For ESPs using rigid-frame or rigid electrodes, the spacing is typically 30 to 38 cm. Equal spacing is important. Stiffeners may help preventing the plates from warping, particularly when hot-side precipitators are used.

Proper **electrical sectionalization** is important to achieve high collection efficiency in the ESP. it refers to the division of a precipitator into a number of different fields and cells, each powered by its own T-R set. ESPs should have at least three to four fields to attain high collection efficiency. There should be approximately one T-R set for every 1000 to 3000 m^2 of collection-plate area.

The **specific collection area (SCA)** is typically 10 - 50 m^2 per 1000 m^3 h^{-1} of flue gas through the precipitator.

The **Aspect ratio**, the ratio of effective length to height of the collector surface, is usually 1.3 to 1.5 and occasionally as high as 2.0 for limiting re-entrainment.

Even distribution of gas flow across the entire precipitator unit is critical to ensure collection of the particles. To assure even distribution, gas should enter the ESP through an expansion inlet plenum containing perforated diffuser plates and straightening vanes should be installed if a curved inlet must be used.

The optimum gas velocity is usually between 1.5 and 1.8 m s^{-1}.

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Biographical Sketch

Alfons Buekens was born in Aalst, Belgium; he obtained his M.Sc. (1964) and his Ph.D (1967) at Ghent University (RUG) and received the K.V.I.V.-Award (1965), the Robert De Keyser Award (Belgian Shell Co., 1968), the Körber Foundation Award (1988) and the Coca Cola Foundation Award (1989). Dr. Buekens was full professor at the Vrije Universiteit Brussel (VUB), since 2002 emeritus. He lectured in Ankara, Cochabamba, Delft, Essen, Sofia, Surabaya, and was in 2002 and 2003 Invited Professor at the Tohoku University of Sendai.

Since 1976 he acted as an Environmental Consultant for the European Union, for UNIDO and WHO and as an Advisor to Forschungszentrum Karlsruhe, T.N.O. and VITO. For 25 years, he advised the major industrial Belgian Bank and conducted more than 600 audits of enterprise.

Main activities are in thermal and catalytic processes, waste management, and flue gas cleaning, with emphasis on heavy metals, dioxins, and other semi-volatiles. He coordinated diverse national and international research projects (Acronyms Cycleplast, Upcycle, and Minidip). Dr. Buekens is author of one book, edited several books and a Technical Encyclopedia and authored more than 90 scientific publications in refereed journals and more than 150 presentations at international congresses. He is a member of Editorial Boards for different journals and book series.

He played a role in the foundation of the Flemish Waste Management Authority O.V.A.M., of a hazardous waste enterprise INDAVER, and the Environmental Protection Agency B.I.M./I.B.G.E. He was principal ministerial advisor in Brussels for matters regarding Environment, Housing, and Classified Enterprise (1989). Since 1970 he has been a Member of the Board of the Belgian Consumer Association and of Conseur, grouping more than a million members in Belgium, Italy, Portugal, and Spain.

He is licensed expert for conducting Environmental Impact Assessments (Air, Water, Soil) and Safety Studies regarding large accidents (Seveso Directive).