

Utilization of electrostatic precipitators for healthy indoor environments

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Abstract. A healthy and comfortable indoor environment is the most basic requirement of human beings. The importance of indoor air quality has been increasing day to day. Although ventilation systems have an essential role in improving indoor air quality, it is inevitable to clean the particulates, microorganisms and pollutant gases in the outside fresh air before being transferred to the indoor environment. Electrostatic precipitators are commonly used for collecting particles mostly in industrial plants. This paper presents a review of electrostatic filtration technology. In this study, theoretical and technical developments of electrostatic precipitators, design parameters that effect filtering performance, advantages, challenges, and limitations are discussed.

1. Introduction

Today, urbanization increased population density in cities. Building occupants spend most of the day in the indoor environment. As a result, the issue of “indoor air quality” has been received increasing attention. Air quality is of great importance regarding health. Due to energy efficiency regulations, building envelopes are becoming more airtight, and this situation generally worsens indoor air quality in environments such as houses and office buildings where people spend most of their time. The poor indoor environment has a direct impact on humans regarding working efficiency, health and life comfort. Every human being breathes about 22,000 times a day, and with each breath, 40,000 to 70,000 dust particles enter into the body. The size characterization for a dust particle is expressed as a micron (μm) or a micrometer [1]. Depending on the source origin, dust particles differ in size. The human hair strand can be a good reference to compare large and small size particles. The different particle sizes are as follows:

- Human hair strand (50-150 μm)
- Pollen (10-110 μm)
- Cigarette smoke (0.01-1 μm)
- Virus and bacteria (0.001-10 μm)

Atmospheric particulate size ranges from a 0.001 μm up to 100 μm and most of them settle because of gravity [2]. Particles larger than 10 μm may be cleared from nose and throat by nose blowing, coughing etc. [1]. However, particles smaller than 10 μm may cause respiratory system problems. A healthy human body can filter out the particles generally larger than 5 μm . Exposure to particles smaller than this size may pose health risks to humans. Particles smaller than 2.5 μm , would deposit within the lungs with carrying other irritating agents such as bacteria and endotoxins [1]. Particles smaller than 2.5 μm ($\text{PM}_{2.5}$) is characterized as “fine” particles and they are more hazardous than larger ones in terms of mortality and

respiratory and cardiovascular illnesses [3]. Air filtration is very important for air purification and enhances indoor air quality. There are various air filtration techniques, and it is important to consider not only filtering efficiency but also additional energy load related to filter’s resistance to air passing through it and economic behavior (initial, operating and maintenance costs) when choosing an appropriate air filter [4]. Electrostatic filters are widely used in industrial facilities including chemical engineering, metallurgy, power station, cement production, paper production fields to capture suspended dust particulates using electrostatic force [5]. They are mostly preferred at coal plants and chemical facilities to filter exhaust gas. Fiber-based filters consist of a dense mesh of fiber into the path of the airflow which increases the energy consumption of the fan to overcome the pressure drop. Even though fiber-based filters could reach high efficiencies for the fine particles, such as HEPA filters, it also has a relatively high-pressure drop when compared to electrostatic precipitators [6]. Additionally, fiber filters do not operate properly at high-temperature applications [7]. Electrostatic precipitators use plate electrodes placed along the airflow path, accordingly do not increase pressure drop that much [8]. Both high filtration efficiency and low-pressure drop make electrostatic precipitators very attractive air filtering devices [2]. Some of the advantages electrostatic filters are presented below [9], [10];

- High collection efficiencies, more than 99% of particles including sub-micron sizes even at very low dust concentrations.
- Low-pressure drop (50-300 Pa), accordingly lower operating cost when compared to fibrous filters.
- Possible operating temperatures up to 650°C.
- Handling high gas velocities

However, there are three important issues about electrostatic precipitators that scientists are currently

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working on to solve which are back-corona discharge, sub-micrometer particle removal and particle re-entrainment [11]. The objective of this paper is to investigate various parameters that affect the collection efficiency of electrostatic precipitators and review previous studies.

2. Electrostatic Precipitators

2.1. Principle of Operation

There are five important steps regarding the operation of electrostatic precipitators [1, 12]:

- Corona discharge
- Particle charging
- Particle transport (via electrostatic and drag forces)
- Settlement of the dust particles on the collecting electrodes.
- Removal of the dust from the collecting electrodes.

A basic operation principle of electrostatic precipitators is that suspended dust particles passing through the filter are charged by corona electrode which operates at a high voltage, then charged particles move toward the grounded collecting electrodes and settle down on the collecting electrodes (Figure 1).

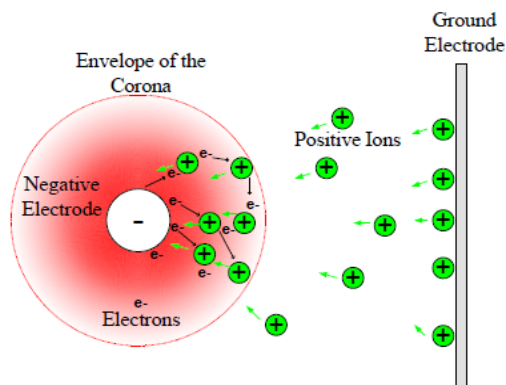


Fig. 1. Principle of electrostatic precipitation [13]

An electric field is created by the high electric potential difference between the discharge electrode and collection electrodes [14]. A corona is a gas discharge phenomenon that produces the ionization of gas molecules by electron collision in high electric field regions [15]. Subsequently, charged particles migrate and settle down on the grounded collection electrodes by the effect of Coulomb forces. Coulomb force that effects the suspended dust particles within the electric field is presented below:

$$F=q.E \quad (1)$$

In this equation, F represents Coulomb force (N), q is the particle charge (C), and E is the electric field intensity (V/m).

2.2. Modeling

There are several mathematical models to estimate the collection efficiency of electrostatic precipitators such as Deutsch-Anderson equation. The Deutsch model developed at the beginning of the 20th century, and it is still very popular to use. According to this model, the collection efficiency of electrostatic precipitators can be defined with the help of two equations presented below (Eq.2, 3):

$$w_e = \frac{q.E}{3.\pi.\mu.d_p} \quad (2)$$

$$\eta = 1 - e^{-w_e\left(\frac{A}{Q}\right)} \quad (3)$$

In Eq.(2) and (3), w_e are the migration or drift velocity of the particles that move towards the collecting electrodes. According to Eq. (2), migration velocity of the particles is dependent on the particle diameter (d_p), electric field strength (E), gas viscosity (μ), amount of particle charge (q). Typical effective particle-migration velocity rates for various industrial applications are presented in Table 1 [16]. Dust collection efficiency based on the Deutsch-Anderson model is presented in Eq.3. In this equation, η represents the collection efficiency, A is the collection surface area (m^2), Q is the volumetric gas flow rate (m^3/s). This model is proposed for ideal conditions and neglects many different operating parameters and particle size variations. As a result, researchers developed new models for the prediction of collection efficiency also applicable to micro-sized particles [17]. Some others modified Deutsch-Anderson model for estimating collection efficiency more realistic.

Table 1. Typical effective particle-migration velocity rates for various applications [16]

Application	Migration velocity (cm/s)
Utility fly ash	4.0-20.4
Pulverized coal fly ash	10.1-13.4
Pulp and paper mills	6.4-9.5
Sulfuric acid mist	5.8-7.62
Cement (wet process)	10.1-11.3
Cement (dry process)	6.4-7.0
Gypsum	15.8-19.5
Smelter	1.8
Open-hearth furnace	4.9-5.3
Blast furnace	6.1-14.0
Hot phosphorous	2.7
Flash roaster	7.6
Multiple-hearth roaster	7.9
Catalyst dust	7.6
Cupola	3.0-3.7

Matts-Ohnfeldt model is a modification of the Deutsch-Anderson model which calculates the collection efficiency more accurately, in cases where particles are not the same size.

$$\eta = 1 - e^{-w_e \left(\frac{A}{Q}\right)^k} \quad (4)$$

In Eq.(4), k is a constant which depends on the particle size distribution and can be obtained experimentally [18]. As it can be seen in Eq. (4), if the constant k is equal to 1, the equation is the same with Eq. 3.

Table 2. Collection efficiency estimations using Deutsch and Matts-Ohnfeldt models [16]

Relative size (A/Q)	Deutsch k=1.0	Matts-Ohnfeldt		
		k=0.4	k=0.5	k=0.6
1	90	90	90	90
2	99	95.1	96.2	97.2
3	99.9	97.2	98.1	98.8
4	99.99	98.1	99	99.5
5	99.999	98.7	99.6	99.76

Theodore model is another important model to estimate the collection efficiency of electrostatic precipitators. In this model, instead of the one-equation approach, collection efficiency is estimated with the use of a statistical technique. Theodore model, [19], shows that collection efficiency is sensitive to particle size distribution, in contrast, in the Deutsch–Anderson model, in its unmodified form, it is required to use of a single representative particle size.

The collection efficiency of electrostatic precipitators depends on several parameters including charging efficiency, airflow rate, collecting mechanisms, electrode geometries and particle properties [20].

2.3 Categorization of electrostatic filters

Electrostatic filters can be categorized in many ways, including:

- Structural design and geometry of the discharge electrodes
- Charging methods (single stage-two-stage)
- Operating temperatures
- Methods of particle removing from collecting electrodes.

Electrostatic precipitators can be classified into two types, single stage and two-stage according to their operation stages. Single stage electrostatic precipitators charge and collect particles at the same time, and two-stage electrostatic precipitators charge and collect particles at different sections as shown in Fig.2. Particles are charged in the first stage when they move along the charger and they are collected in the second stage where there are both collecting and repelling electrodes [21]. The electric field strength between repelling and collecting electrodes is much stronger than that between corona wires and the collecting electrodes of single stage electrostatic precipitators due to a larger surface area of the repelling electrodes [22].

Single-stage, wire-plate type electrostatic precipitators with negative discharge are very common in industrial applications, whereas corona electrodes with positive voltage are preferable in residential applications due to lower ozone emissions [1]. Electrostatic precipitators are also classified according to their geometrical design as wire-pipe, wire-plate, and wire- duct types. Due to its simple structure and low resistance to air flow, wire-plate type electrostatic precipitators (ESP) are the most common ones especially for the applications where the volumetric air flow rate is high. Wire-pipe type electrostatic filters consist of cylindrical collection electrodes and corona electrodes at the center. Since the geometrical structure of the wire-pipe type electrostatic filters is not as flexible as the wire-plate type filter, they are not widespread. ESPs can also be categorized as a wet type and dry type. Dry type ESPs has high particle collection efficiencies for 1-10 μm particle diameter ranges, however wet type ESPs are much more efficient than dry types for collecting submicron particles [23]. Moreover, dry type electrostatic precipitators should not be used for collecting explosive dust.

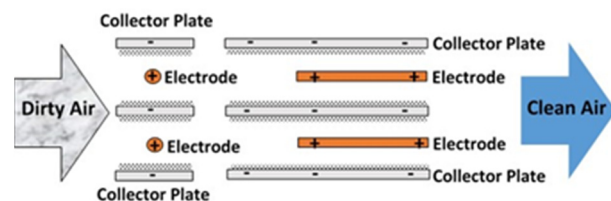


Fig. 2. A schematic of the two-stage ESP.

2.4 Electrostatic precipitator design

Back corona, particle re-entrainment, submicron particle removal, and ozone generation are the main problems of the electrostatic precipitators. Dust resistivity is an important parameter that affects the collection efficiency of the electrostatic precipitator. When high resistivity dust ($\rho_R \geq 10^{11} \Omega \cdot \text{cm}$) deposits on the collecting electrode, back corona takes place [24]. Back corona occurs where the accumulated charge cannot reach to the ground electrodes because of the high resistivity dust layer. As a result, large numbers of ions of opposite polarity is emitted to space and collide with the charged dust particles, thus decreasing their charge and particles couldn't be collected by the precipitator [25], [11]. Accordingly, the collection efficiency of the electrostatic precipitators decreases and energy consumption increases.

When designing an electrostatic precipitator parameters like dust concentration, chemical and physical properties of the dust such as dust diameter and explosiveness, resistivity, gas flow rate, type and geometry of discharge electrodes, type and shape of collecting electrodes, specific collection area (m^2 collection area per 1000 m^3/h of gas through the precipitator), aspect ratio (ratio of effective length to height of the collector surface) are very important and should be considered [26]. Brocilo, investigated the collection efficiency of submicron (0.1-1 μm) and

ultrafine particles ($<0.1 \mu\text{m}$) for various geometries of discharge and collection electrodes, numerically and experimentally [12]. Typical discharge electrode geometries are presented in figure 3 [12]. According to the results of the study, discharge and collecting electrode geometries highly affect the collection efficiency of the electrostatic precipitators. For the same applied voltage of 30 kV, the spike type discharge electrode with I type collecting electrode has better collection efficiency when compared to wire or rod type discharge electrodes. Moreover, the author concluded that the collection efficiency of the ESP increases with the increasing values of the voltage. In addition to shape, collecting electrode length and spacing also influences the collection efficiency. A decrease in plate-to-plate spacing increases collection efficiency.

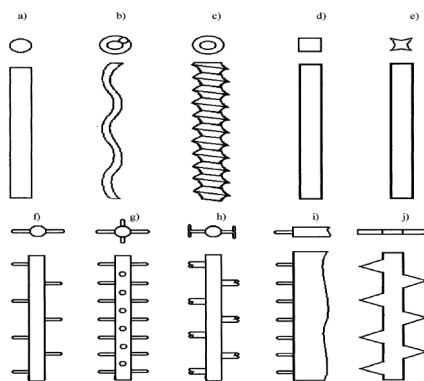


Fig.2. Typical discharge electrode geometries [12]: a) smooth wires or rods, (b) helical or spiralling wires, (c) threaded wires and rods, (d) rectangular rods or twisted square, (e) star-shaped rods, (f) rod with needles arranged in staggered or opposing way, (g) rod with cross arranged needles, (h) rod with emitters, (i) plate with needles, and (j) band-type with spikes.

One of the main problems of electrostatic precipitators is the re-entrainment of the particles caused by disturbances. It reduces the collection efficiency. Particle re-entrainment is the re-entry of collected dust particles into the inter-electrode spacing [25]. Particle re-entrainment in precipitators takes place in two different ways [27]:

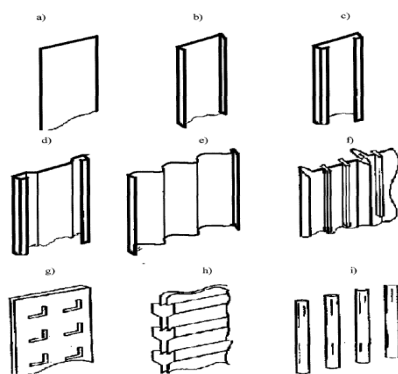


Fig.3. Typical collecting electrode geometries: [12] a) smooth-plate or I type, b) U type, (c) C-type, (d) G-type or sometimes referred as Z type, e) sine-wave type, (f) fence-type, (g) plate with L-pockets, (h) plate with tulip pockets, (i) rod curtain.

- Because of the particles rebounding from the collector surfaces to the inter-electrode spacing,
- During rapping of the electrodes in dry ESPs.

As a result, authors of the following studies developed two novel particle trapping mechanism which is foam covered and guidance plate covered electrostatic precipitators [20], [21], [22], [27]. Particles that are trapped inside the pores of the foam or particles go through the holes of the guidance plates and stay between the guidance plate and the collecting electrode, consequently have a lower chance to re-enter to the air stream [27]. As a result, the authors showed that with proposed particle trapping mechanisms, the collection efficiency of the electrostatic precipitator increases.

Another important concern related to electrostatic precipitation is ozone generation. Ozone is a natural by-product of high voltage equipment [1]. Despite the fact that ozone emissions due to electrostatic precipitation is lower than related indoor air standard levels in most cases, it is still an important concern that restricts the domestic applications of electrostatic precipitators. Boelter and Davidson conducted an experimental study to investigate ozone generation by electrostatic precipitators [28]. Influences of discharge polarity, current, relative humidity, air temperature, wire diameter and material on ozone generation is investigated. According to the results of the article, the authors concluded that reduction in current reduces ozone generation but at the same time reduces the collection efficiency of the ESP. Additionally, ozone production can be decreased by reducing the corona wire diameter, changing material of the wire (changing the material from tungsten to silver caused a reduction in ozone emissions by 50%), increasing air temperature and relative humidity. Authors also concluded that using a positive polarity discharge instead of negative polarity can reduce the amount of ozone emitted into the indoor environment.

Pressure drop and collection efficiency are two important parameters when selecting a filter. However, those parameters are not usually linearly dependent. Wen et al., [20], proposed an approach to evaluate a precipitator's performance by considering both electrostatic collection efficiency and pressure drop. With taking into account the pressure drop through the filter, energy consumption of the system and collection efficiency, authors derived a parameter named key energy performance. They also made a parametric analysis of a guidance plate covered electrostatic precipitator to see how changing corona and repelling electrode voltages, and airflow velocity would influence the key energy performance of the precipitator. According to the results of the study, the authors highlighted that higher corona and repelling electrode voltages increases the key energy performance of ESPs because of the better collection efficiencies. Additionally, they also concluded that lower airflow velocities also improves the key energy performance of the ESPs because of the lower energy consumption.

Fournier [1], conducted an experimental study to investigate the removal of dust particles from swine housing with the use of electrostatic precipitators. She used an electrostatic precipitator with 44 discharge wires and 12 grounded collection plates. The influence of airspeed (0.55 m/s, 0.76 m/s, 0.95 m/s), applied voltages (-10.3 kVDC, -11.0 kVDC, -12.1 kVDC), electrode spacing and lengths on collection efficiency was investigated. According to the results of the study, increasing applied voltage has a significant impact on collection efficiency. Airspeed did not vary the collection efficiency that much. Similarly, the author concluded that increasing the precipitator length may increase the collection efficiency due to a longer residence time within the ESP but does not influence significantly. For the case of inter-electrode spacing, the author highlighted that increasing the spacing between electrodes usually decreases the collection efficiency.

Swierczok and Jedrusik, [9], conducted a study to compare the experimental results of the collection efficiency of an electrostatic precipitator and mathematical calculations with using Deutsch model. During their experimental part of the study they used an electrostatic precipitator with spiked type discharge electrodes and fly ashes with two different sizes (The median diameter of fly ash A is $47\mu\text{m}$ and for fly ash B is $18\mu\text{m}$) were injected to the testing chamber at 0.6 g/m^3 mass concentration. Inlet and outlet concentrations of the dust were measured, and the collection efficiency of the ESP was calculated. Authors highlighted that since fly ash A mostly consisted of larger particles compared to fly ash B, overall collection efficiency is higher for fly ash A. It was concluded that collection efficiencies that were determined experimentally for both ash types are 1-2% lower than the one calculated with the Deutsch model. This can be explained as the re-entrainment of larger particles from the collecting electrodes decreases the collection efficiency and Deutsch model in its basic form do not consider that.

Experimental investigation of electrostatic precipitators is very complicated and expensive, so it is much easier and convenient to simulate the process numerically [29]. Computational fluid dynamics is a common tool for estimating the performance of the electrostatic precipitators. Numerous studies in the literature analyze the influence of design parameters on collection efficiency of the ESPs [30, 31, 32, 14]. Arif et al., [14], conducted a study on CFD modeling of an electrostatic precipitator with the use of a CFD software named as STAR-CCM+. In this study, first, researchers validated their CFD model with the results of a previous experimental study. Later on, they investigated the effects of different ESP geometry, inlet velocity, particle diameter, wire to plate spacing and discharge electrode geometry. According to the results of the article, the authors highlighted that, with increasing particle diameter, the collection efficiency of the ESP also increases. However, with increasing inlet fluid velocity, collection efficiency decreases. With increasing the applied voltage on the corona electrode, the collection

efficiency of the ESP also increases. Authors also compared the performance of ESP with spike and wire type discharge electrode and concluded that ESP with spike discharge electrodes has better collection efficiencies.

3. General evaluation and further research directions

Air filters are an indispensable component of the HVAC systems: they clean up the air from dust and airborne pollutants. However, most of the air filters in the market offer similar performance, the recent researches show that it is not usually the actual case. Unfortunately, due to their common usage in the HVAC systems, price became a crucial parameter in selecting air filters. However, the total life-cycle cost and related long-term energy costs should also be considered for the selection of filter systems. In general, an operating cost may be several times higher than the initial investment and maintenance costs. The annual energy consumption and the total life-cycle cost of the filtration system increase with the magnitude of the pressure drop occurred in the system. Therefore, the application of the electrostatic technology in the air filter system presents an efficient method to clean indoor air.

Considering the present knowledge about the electrostatic filter technology further researches should be conducted on the subjects as follow:

- Combination of electrostatic technology with other filtering systems,
- Robust design and employment of new materials to increase filtration efficiency,
- Determination and reduction of ozone production,
- Prevention of the back-corona discharge and particle re-entrainment into the air,
- Safety concerns about the system,
- Reduction of the initial cost of the system.
- Decreasing energy usage during the operation.

4. Conclusions

Electrostatic precipitation is a popular air filtration technique due to lower pressure drop during operation and high particle collection efficiency. They are widely used in industrial facilities since they can operate at high temperatures and they can handle high-speed gas velocities. However, it is important to design electrostatic precipitators appropriately in order to get the best performance. Some of the most critical parameters that influence collection efficiency of electrostatic precipitators are geometric design, properties of the particles (resistivity, diameter), environmental conditions

(temperature, relative humidity, concentration) and operating conditions.

In this study, basic operation principles, different types, calculation of collection efficiency, advantages and disadvantages of electrostatic precipitators are investigated and various studies related to electrostatic precipitation is reviewed. Some of the main remarks of this study are summarized below:

-It is crucial to select the most appropriate type of ESP according to the application considering operating temperature, physical and chemical properties of the particle (resistivity, explosiveness, diameter, etc.).

-Back-corona, particle re-entrainment, ozone generation are the main problems related to electrostatic precipitators, and there are still limited scientific studies concerning these problems.

-Increasing applied voltage increases the collection efficiency remarkably, but at the same time increases energy consumption and ozone generation.

-Decreasing inter-electrode spacing, increasing precipitator length, decreasing inlet fluid velocity, changing the corona electrode geometry from wire to spike type are some of the methods to increase the collection efficiency of the electrostatic precipitators that many researchers validated with their experimental or numerical studies.

Finally, the usage of the electrostatic air filter technology is continuously increasing. This technology can be used with other filtration technologies to improve their performance via the synthesized advantages of the different systems. Since it suffers some drawbacks, further researches should be conducted to sort out these problems.

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