Modern electrostatic devices and methods for exhaust gas cleaning: A brief review

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Abstract

Conventional electrostatic precipitators (ESPs) have been modernized over the last few decades. In recent years, many new methods of construction have been proposed with the goal of increasing cleaning efficiency, particularly for particles in the submicrometer size range. Adding electrical forces to traditional filters has also resulted in an increase in their collection efficiency for removing dust particles. This paper reviews modifications to ESPs aimed at increasing overall collection efficiency, as well as electrostatically assisted non-electric gas cleaning devices such as cyclones, fibrous filters, and granular-bed filters assisted by electrostatic field or ionization current.

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Keywords: Electrostatic precipitation; Review; History; Particle removal gases

Contents

1. Introduction .......................................................... 133
2. Current trends in electrostatic precipitation .......................................................... 134
   2.1. Operational properties of dry ESPs .......................................................... 134
   2.2. Gas conditioning .......................................................... 136
   2.3. Wide-plate-space ESPs .......................................................... 136
3. Modified ESPs .......................................................... 137
   3.1. Multi-stage ESPs .......................................................... 137
   3.2. Electrostatic particle agglomerators .......................................................... 142
   3.3. ESPs with modified electrodes .......................................................... 143
   3.4. Electrically energized cyclones (electrocyclones) .......................................................... 145
4. Electrically assisted filters .......................................................... 146
   4.1. Electrically energized fibrous filters .......................................................... 146
   4.2. Electret filters .......................................................... 150
   4.3. Electrically energized granular-bed filters .......................................................... 151
5. Conclusions .......................................................... 151
References .......................................................... 152

1. Introduction

Rigorous new regulations in dust emission by power plants and industrial processes have caused new demands for dust control devices. These new regulations will require
maximum particle emissions on the level of 10–50 mg/Nm³ and restrictions to the emission of fine particles smaller than 2.5 μm. To meet these requirements, new methods of gas cleaning with collection efficiency higher than 99% have been developed and tested.

The main components of fly ash emitted into the atmosphere by coal-fired power plants consist of Al₂O₃, SiO₂, and Fe₂O₃, which constitute about 80–90% of the total mass. Other non-volatile trace elements in fly ash at levels higher than 1 mg/g include Ca, Na, Mg, K, Ti, S [1–3]. Toxic metals such as Se, As, Cd, Hg, Ni, Pb, Cr, Sr, Be, V, and U have also been found [1,2,4,5,6,7]. The concentration of trace elements in particles larger than 1 μm is inversely related to particle diameter. The fraction of toxic metals is significantly higher in submicrometer particles, and it is independent of particle size. Volatile elements such as Hg are usually depleted in the fly ash and are frequently ignored in the analysis [5]. The particles leaving the typical boiler are in the approximate size range of 20 nm to 200 μm [8]. The fraction of particles of diameter smaller than 1 μm constitute only 1% of the total mass, but 99% of the number concentration [9].

At the outlet of an electrostatic precipitator (ESP), the size distribution of particles is usually bimodal, depending on the boiler load. Finer particles (first modal diameter of about 0.07 μm) contain vaporized and condensed matter, usually toxic elements. Larger particles (second modal diameter of 0.4 μm) contain unburned mineral materials, mainly SiO₂ (about 1/2) and Al₂O₃ (about 1/4) [10]. The mean mass density of fly ash is about 2.45 × 10³ kg/m³ [5,10] which is close to the density of SiO₂.

Large fly ash particles are usually spherical, whereas those smaller than 0.1 μm in diameter are irregular in shape and frequently form short dendrites attached to the larger ones. Submicrometer particles are formed by the bursting of large particles as an effect of gas release during their rapid heating. When cooled, the particles condense and adsorb volatilized elements to form particles in the size range 0.1–1 μm [3].

Research in particulate control technology has tried to find new, improved, and less costly methods for collection of small particles that save energy and structural materials. Two general groups of dust removal devices—dry and wet [11]—can be distinguished. The category of dry devices includes cyclones, fabric filters, ceramic filters, electret filters, and ESps. The wet devices include inertial, centrifugal, Venturi or electrostatic scrubbers, foam precipitators, and irrigated ESps.

Cleaning devices usually use mechanical (mainly inertial and gravitational) forces to precipitate the particles from a gas, or molecular forces to capture particulate matter on a solid or liquid collector. Dense obstacles in the form of fibrous or porous media are also used for this purpose. ESps utilize electrical energy to remove particulate matter from the gas. Over the past few decades, substantial progress has been made in the development of new electrical techniques for gas cleaning with the goal of increasing cleaning efficiency in the small particle size range. These particles, which are a potential danger to human airways, are very difficult to remove by conventional devices.

The current state of development in ESps and some of the unsolved problems in the field of gas cleaning were recently summarized by Mizuno [12] and Porle [13]. The paper by Hackam and Akiyama [14] focuses on gaseous pollution control by electrical discharges. Currently, there is a tendency in the gas cleaning industry to enhance the collection efficiency of conventional devices by using electrical forces. The simultaneous removal of gaseous contaminants and particulate matter is also a new trend in gas cleaning technology [15,16].

The present paper reviews current trends in the field of electrostatically assisted methods and devices, which are used to remove fine particles from gases. Special emphasis was put on new designs, which still are the subject of laboratory investigation or pilot-plant tests. The first part of the paper presents briefly the methods used to improve the collection efficiency of conventional ESps, such as gas conditioning or intermittent energization. The remainder of the paper considers newly developed modifications to conventional ESps, including new collection electrode configurations, as well as methods for improving non-electrostatic devices such as fibrous or granular-bed filters via electrostatic forces.

2. Current trends in electrostatic precipitation

2.1. Operational properties of dry ESps

Electrostatic devices used for cleaning gases exploit electrical forces to facilitate the removal of particulate matter. Electrical energy is required for gas ionization, particle charging, particle coagulation or agglomeration, or vapor condensation. The overall collection efficiency of any gas cleaning device, regardless of its type, can be determined from the formula:

\[ \eta = 1 - \frac{m_{\text{out}}}{m_{\text{in}}}, \]  

where \( m_{\text{out}} \) and \( m_{\text{in}} \) are the particle mass concentrations at the outlet and the inlet of the device, respectively.

If the collection efficiency is close to unity, the performance of a filter or precipitator can be better characterized via the outlet dust loading, usually in mg/m³, or by penetration, which is defined as

\[ \lambda = 1 - \eta = \frac{m_{\text{out}}}{m_{\text{in}}}. \]

The ESP is a device which uses electrostatic forces to remove particles from an exhaust gas. The ESP contains a set of sharp discharge electrodes placed between two parallel collection plates (for example, the so-called parallel-plate ESP of Fig. 1a), or a thin wire stretched along the axis of a cylinder (the tubular ESP shown...
in Fig. 1b). Electrical discharge from these types of electrodes, usually maintained at high negative potential, produces gaseous ions by attachment of free electrons to gas molecules. It is the gas molecules colliding with particles that charge them. The rate of particle charging is given by the following differential equation:

$$\frac{dQ}{dt} = \frac{3\pi n E \mu r^2}{2} \left(1 - \frac{Q}{12\pi \rho r^2 E} \frac{\nu}{\nu_r} + 2\right)^2 + \pi n \nu^2 r. \tag{3}$$

Here, $n$ is the space charge density in the charging zone, $\mu$ is the ion mobility, $r$ is the aerosol particle radius, and $\nu$ is the mean velocity of the gaseous ions.

The two most important mechanisms for charging particles by ionic current consist of [17]:

1. Field charging [the first term in Eq. (3)], whereby ions are driven to the particle due to electrostatic force caused by an external electric field. This force is balanced by the repulsive force of the charge imparted to the particle.
2. Diffusion charging [the second term in Eq. (3)], which is due to the kinetic energy of gaseous ions which bombard the particle independently of the electric field.

For particles larger than 1 $\mu$m, field charging is the dominant mechanism. For particles smaller than 0.1 $\mu$m, charging is principally due to ion diffusion.

The collection electrodes are rapped periodically by mechanical forces to dislodge the collected dust into a hopper beneath. In a modern ESP, the typical gas treatment time is 10–30 s, depending on dust loading, which usually ranges from 1 to 50 g/N m$^3$. The gas velocity within the precipitator is usually in the range 0.5–1.5 m/s, and the typical migration velocity of particles to the collector lies between 0.02 and 0.15 m/s. The current density on the collection electrode is usually of the order of 0.1–1 mA/m$^2$. The pressure drop within a conventional ESP is not higher than about 1–2 kPa, and the energy consumption lies within the range of 0.3–1.8 MW/1000 N m$^3$ [18].

Two issues, back-corona discharge and submicrometer particle removal, stimulate current research activity in the field of electrostatic precipitation. An additional unsolved problem is particle re-entrainment form the collector electrode back into the flowing gas. Such re-entrained particles can then be expelled into the atmosphere. Up to 30% of particles leaving an ESP are due to losses from the collection electrodes [19,20]. Particles larger than 3 $\mu$m in diameter and smaller than 0.1 $\mu$m can be effectively removed by an ESP. The minimum in the fractional collection efficiency is observed in the 0.1–1 $\mu$m diameter range [12], where it is usually lower than about 90% [21]. The low precipitation efficiency of submicron particles in ESPs is due to the difficulty in charging them to levels higher than a few elementary charges. Low charge results in low particle mobility and low collection efficiency. In the 0.03–0.2 $\mu$m size range, a fraction of particles can remain uncharged, but they can adhere to larger ones [22]. Fine particles, smaller than 50 nm, can almost entirely penetrate an ESP [23,24].

The collection efficiency of an ESP can be estimated from the Deutsch formula [11,17]

$$\eta = 1 - e^{-\nu_m A / \dot{V}}, \tag{4}$$

where $\nu_m$ is the mean migration velocity of the particle across the precipitator, $A$ is the cross-sectional area of the precipitator channel, and $\dot{V}$ is the gas flow rate. This
formulas indicates a possible means of increasing collection efficiency, namely increasing the migration velocity or cross-sectional area by increasing the distance between plates, or by decreasing gas velocity. Nowadays, other technical means such as pulse or intermittent energization, gas conditioning, and electrical, chemical or ultrasonic agglomeration of particles are used to increase collection efficiency. Thermal precipitation of particles has also been proposed for achieving this goal [25].

ESPs can usually operate effectively over a wide range of dust resistivity from $10^3$ to $10^6$ Ω·m. Highly conducting dust with resistivity lower than about $10^2$ Ω·m can be charged and collected very effectively. However, the particles can easily discharge on the collection electrode, reverse their polarity by electrostatic induction, and finally be re-entrained into the flowing gas by the electrostatic field. Dust of higher resistivity over $10^6$ Ω·m forms a tight barrier on the collection electrode, causing accumulation of electric charge which leads to back-corona discharge [17,26–33].

Back corona is initiated at the surface of a dust layer, where the accumulated charge does not leak to the ground electrode. The potential difference across the layer increases up to the value causing dust breakdown. Positive ions are then generated from the craters formed in the layer. The ions are emitted into the interelectrode space and collide with negatively charged dust particles, thus increasing their charge. These particles cannot be removed by the precipitator and are exhausted into the atmosphere. In very adverse conditions, the positive ions can recharge the particles, causing their deposition at the discharge electrode. All of these phenomena reduce the collection efficiency of an ESP. Additional consequences of back-corona discharge include lower spark-over voltage and higher discharge current, which results in high-energy consumption. Back-corona discharge is extremely difficult to control.

The problem of contamination of the discharge electrode was studied by Kanazawa et al. [34,35]. When the discharge electrode is contaminated, the corona can easily develop into a streamer discharge, causing ozone generation and dispersion of the dust deposited on the collection electrode. Fine wires are more resistant to contamination effects than point electrodes. Rapping is another source of re-entrained particles. Dust is re-entrained mainly from the regions on the collection electrode where the current density is relatively low, usually at the midpoint between discharge points, where the cohesive forces are too weak to form a tight cake [36].

Several remedies have been proposed and tested for fighting against back-corona discharge. One method is to decrease dust resistivity by adding conditioning agents or irrigating the collection electrode. Another solution is to use pulse or intermittent energization. In newly designed precipitators, the control of discharge current allows suppression of back-corona by temporally decreasing the supply voltage [37].

2.2. Gas conditioning

Gas conditioning is required for low-sulfur coal containing less than 1.5% of S when gas humidity is lower than 15%. Conditioning agents cause adsorption of moisture on the particle surface, thus increasing its conductivity. Water, steam, ammonia (NH₃), sulfur trioxide (SO₃), sulfuric acid (H₂SO₄), sodium chloride (NaCl), hydrogen chloride (HCl), calcium chloride (CaCl₂), sodium sulfate (Na₂SO₄), lithium iodide (LiI), sodium carbonate, ammonium sulfate ((NH₄)₂SO₄), ammonium bisulfate (NH₄HSO₄), sulfamic acid (NH₂SO₃H), phosphorus pentoxide, ferric sulfate, triethyloamine, or cyclohexylamine are used as conditioning agents to increase dust conductivity [31,38–47]. More complex organic mixtures have also been proposed for gas conditioning [48], but NH₃ and SO₃ are still the most popular agents used. The effect of a particular conditioning agent depends on fly ash composition. The ammonia additive is used at levels up to 20 ppm by volume, but it can be more effective when there is a small amount of chloride compound (about 0.5% by volume) in the coal, which allows formation of HCl in the gas moisture [49]. The concentration of SO₃ is usually lower than 1000 ppm by volume, but it can be used at temperatures lower than 190 °C, when acid can condense on the particles. Gaseous SO₃ results in almost 100% adsorption by fly ash, while its aqueous solution is absorbed only about 20–70%. The adsorption is higher at lower gas temperatures. Sodium carbonate and sodium sulfate can be used at the boiler inlet by mixing them with coal [48]. These additives cause an increase in electrical conductivity of fly ash. Ammonia also increases cohesiveness of the particles, allowing their agglomeration [40]. The number of particles re-entrained during electrode rapping is also reduced [42]. Ammonia can be used in conjunction with sulfur trioxide that makes it possible to reduce ammonia concentration [48].

The disadvantage of certain conditioning agents is that they can decrease the breakdown potential, change the acid dew point in flue gas, and increase adhesion and cohesion forces, thus making rapping more difficult.

2.3. Wide-plate-space ESPs

Wide-plate spacing is used for increasing overall collection efficiency. The velocity of dust particles migrating to the collection electrode increases with an increase in interelectrode distance [44,50–52]. In newly designed ESPs, the collection electrode distance is up to 600 mm; however, the upper limit of this distance is difficult to predict [44]. Supposed the optimum electrode spacing to be between 400 and 600 mm, but there is a lack of theoretical evidence for that assumption [53]. Demonstrated that a plate spacing of 400 mm is optimal for the collection of high resistivity dust, while a lower spacing, of the order of 300 mm, is better for collecting dust of low resistivity. For particles larger than 1 μm, Kim et al. [54], obtained maximum collection efficiency and optimal energy consumption for a plate
spacing of about 450 mm, but for smaller particles no significant effect was noticed. A large distance between electrodes allows the applied voltage to be higher, and electric fields at the collection electrode can also be higher due to decreased space charge effects. Particle agglomeration in the interelectrode space and a more uniform current density distribution on the collection electrode were also observed [31] for wide interelectrode distances.

Chang and Bai [55] showed numerically that optimal plate spacing is 395 mm due to the trade-off between the back-corona and spark discharge limits. Wide duct spacing causes an increase in the power consumption required to sustain corona discharge conditions.

3. Modified ESPs

3.1. Multi-stage ESPs

To avoid difficulties with fly ash of high resistivity, the charging and collection processes can be separated and accomplished in two different stages. Such devices are known as two-stage ESPs. Two-stage ESPs were considered first by Masuda and Hosokawa [56] to control emission of dust of high resistivity. A schematic diagram of a two-stage ESP is illustrated in Fig. 2. The charging stage can be similar to conventional ESPs, but the voltage is reduced to a magnitude at which the back-corona discharge is eliminated. The precipitation stage is formed by a set of parallel plates every second of which is maintained at high potential and the reminder are grounded. The electrodes can also be excited by an ac voltage [57].

The following types of chargers were developed and tested for this purpose:

1. **Boxer charger** [56,58,59], in which the particles are charged by negative ions generated by a high-frequency surface discharge from strip electrodes embedded in ceramic duct walls. An additional pair of electrodes produces a low-frequency electric field, which causes the particles to oscillate during their flow through the charger, thus preventing them from precipitating on the charger electrodes.

2. **Wire-plate corona charger** [22,60,61] with the plates sufficiently short to avoid particle precipitation within the charging section.

3. **Dielectric barrier discharge precharger** with high-frequency excitation [62].

4. **Corona-nozzle charger** [31] in which the particles flow through a nozzle equipped with corona electrodes. The particle velocities are sufficiently high to prevent them from being collected on the charger walls before they reach the collection stage.

5. **Corona-triode charger of parallel-plate** [31,57] or co-axial [63,64] configuration. The polarity of the grid is the same as that of the discharge electrode, but the voltage magnitude is reduced. The grid prevents ignition of back-corona discharge.

6. **Quadrupole precharger** [65,66] consisting of four parallel rods arranged in a square with a discharge electrode placed in their center. The particles are charged when flowing along this electrode system.

7. **Alternating electric field charger** [67–70]. The particles are charged by an ionic current in an alternating electric field produced by two additional grids. The charge imparted to dust particles within this type of charger can be higher than that achieved in a dc charger, and is close to the Pauthenier limit.

The technical data of two- and multi-stage ESPs are summarized in Table 1. A three-stage ESP collecting fly ash was tested by Jayaram et al. [76]. With a specially designed precharger, pulse energization and limestone conditioning, the collection efficiency increased by 40%. Chang et al. [65] proposed a four-stage ESP with a quadrupole precharger. The precharger was placed between the second and third stages of a conventional ESP. The particle number collection efficiency was higher than 96%, while mass collection efficiency was as high as 99.99%. No significant effect of particle precharging was noticed for particles smaller than 0.1 μm.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Precipitator type (parameters)</th>
<th>Charging device (voltage, current, current density)</th>
<th>Collection electrodes geometry</th>
<th>Dust particle size and charge (resistivity)</th>
<th>Gas flow rate (velocity, residence time)</th>
<th>Dust loading (particle concentration)</th>
<th>Collection efficiency (reduction ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[56]</td>
<td>Two-stage ESP (100 °C)</td>
<td>Masuda boxer charger</td>
<td>Parallel plates, 4 sections, 0.76 m high, 0.5 m long, 150 mm space</td>
<td>Fly ash 8 μm (10^{8–10^7} Ω m); 11.8 μm (10^{13—10^{14}} Ω m)</td>
<td>(0.15 m/s—the precharger); (0.82 m/s—the collector)</td>
<td>4–6 g/m^3</td>
<td>95% (1 μm), (75% without precharging and agglomeration)</td>
</tr>
<tr>
<td>[71]</td>
<td>Moving-belt ESP + agglomerator, 6 mm space</td>
<td>Barbed electrode in cylinder precharger (1.5 MV/m), (2.5–8 mA/m^2)</td>
<td>Moving parallel plates (1.2 m/min), barbed discharge electrodes</td>
<td>Diesel engine soot 0.01 μm; town-gas soot 0.06–2 μm</td>
<td>(0.25–1 m/s)</td>
<td>0.12 g/m^3</td>
<td></td>
</tr>
<tr>
<td>[21]</td>
<td>Two-stage parallel plate ESP (0.1 m^2 cross section)</td>
<td>Corona charger, wire plate, 325 mm long</td>
<td>Parallel plates, 80 mm long, 3 mm space, 4.4 kV</td>
<td>DOP 0.1–1.5 μm</td>
<td>235 m^3/h (0.65 m/s)</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>[72]</td>
<td>Barbed plate ESP</td>
<td>Barbed-plate discharge electrode, 2 × 152 mm space (–56 kV) (1.6 mA/m^2)</td>
<td>Parallel plates, 2 × 152 mm space</td>
<td>TiO_2–0.6 μm; Al_2O_3–0.7 μm</td>
<td>(1 m/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[57]</td>
<td>Two-stage ESP, ac excitation</td>
<td>Corona triode</td>
<td>Parallel plates, 5 mm space, ac voltage 5.35 kV rms/2–500 Hz; ac voltage 10 kV</td>
<td>DOP 0.62 μm</td>
<td>(2.8–8 m/s)</td>
<td>31.3–74.8%</td>
<td></td>
</tr>
<tr>
<td>[34]</td>
<td>Parallel plate ESP + agglomerator</td>
<td>Bipolar charger, wire plate, 100 mm long, 90 mm space, tungsten wire; 250 μm dia. (pos.), 80 μm dia. (neg.); (+10 kV, −7 kV)</td>
<td>Parallel plates, 100 mm space</td>
<td>Smoke particles 0.3–1 μm; 30–174e (+), 25–148e (−)</td>
<td>(0.25–0.8 m/s)</td>
<td>&gt;80% (25% for uncharged); (24% for &lt;1 μm)</td>
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</tr>
<tr>
<td>[73]</td>
<td>Rod-parallel-plates agglomerator, 60 mm dia. rods, (0.5 × 0.5 mm cross section), (30 kV ac + 11 kV dc)</td>
<td>Corona charger</td>
<td>Wire-parallel plates</td>
<td>Carbonic particles or fly ash 0.06–12 μm</td>
<td>(0.1 g/m^3)</td>
<td>98%</td>
<td></td>
</tr>
<tr>
<td>[74]</td>
<td>Parallel plate ac agglomerator, 400 mm high, 100 mm long, 500 mm space, (25 kV/50 Hz)</td>
<td>Wire plate, 400 mm high, 30 mm long, 35 mm space, 50 μm wire (+ 7 kV)</td>
<td>Vegetable oil mist 0.1 μm, 6 mC/kg</td>
<td>90 m^3/h (0.25 m/s, 1 s)</td>
<td>1–2 g/m^3 (600 ml/h) (30% for 0.3–2 μm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[75]</td>
<td>Parallel plates ac agglomerator, 50 mm space, 1.5 m long, 0.5 m high, 520 kV/m, 50–200 Hz</td>
<td>Corona charging positive/negative</td>
<td>Limestone powder 5 μm, 4400e</td>
<td>(2.1 s)</td>
<td>4.2 g/m^3</td>
<td>(50% for &lt;1 μm)</td>
<td></td>
</tr>
<tr>
<td>[76]</td>
<td>Three-stage ESP (+ limestone conditioning)</td>
<td></td>
<td></td>
<td>Fly ash (10^6 Ω m)</td>
<td></td>
<td>2 g/m^3</td>
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</tr>
<tr>
<td>Page</td>
<td>Description</td>
<td>Details</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>Parallel plate ac agglomerator, 40 mm high, 1000 mm long, 40 mm space (520 kV/m, 50 Hz)</td>
<td>Bipolar charger, wire-plate, 26 mm long, 40 mm space, 100 µm wire</td>
<td>Vegetable oil mist 0.03-1 µm, 0.5 µm mass mean, 1-2e (0.04 µm), 100e (1 µm) 1.2 m³/h (4.8 s) 0.2 g/m³ (5 x 10⁻²/m³) (17-19% for 0.1-1 µm)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>Transverse collection electrodes ESP (130-190 °C)</td>
<td>Corona wire 4 x 4 mm cross section (–80 kV), (50 µA/m²)</td>
<td>X and V shaped, 35 mm high</td>
<td>Fly ash (2000 kg/m³) (10⁻²-10⁻¹ Ω m) 10,000-13,000 m³/h (0.6 m/s) 40-70 g/m³ (6.7 x 10⁻¹/m³) &gt;99% (outlet 0.08-0.1 g/m³)</td>
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<td></td>
</tr>
<tr>
<td>60,61</td>
<td>Two-stage ESP</td>
<td>Wire plate, 10 mm long, 12 or 40 mm space, 100 µm tungsten wire (+6 kV or +12 kV)</td>
<td>Parallel plates, 12, 60, 80, 100 mm long, 5 or 20 mm space (±2 kV or 6 kV)</td>
<td>DOP 0.5-5 µm, max 100 e (1.5 m/s) 0.02 g/m³ 90-99% (1 µm), 60-80% (total)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>79</td>
<td>Parallel plate ESP with elongated barbs</td>
<td>Barbed wire-plate, 40 mm long barbs, (45-65 kV)</td>
<td>Parallel plates, 200 mm space</td>
<td>Limestone 0.4-0.6 µm 0.1 g/m³ 99.9% (0.4-0.6 µm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Two-stage ESP (13 x 53 mm cross section)</td>
<td>Wire-plate, 4 sections, 60 mm long plates, 45 mm space, 200 µm wire (+12 kV)</td>
<td>Parallel plates, 197 mm width, 5.9 mm space (+6 kV)</td>
<td>NaCl particles 0.03-0.2 µm, 200 e (1 µm), (additional aerosol was also sprayed) (1.9-4.1 m/s) (6 x 10⁸/m³) 93-98%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>118,119</td>
<td>Lentoid-type ESP, 4.5 m long, (4.65 x 2.7 m total cross section)</td>
<td>Wire-hollow electrode</td>
<td>Hollow collection electrode with positive discharge</td>
<td>Fly ash 30,000 m³/h 99.5% (outlet 40 mg/m³)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>Lentoid type ESP (8 m² total cross section)</td>
<td>Wire-hollow electrode (–10.5 kV)</td>
<td>Hollow collection electrode with positive discharge, 600 mm space</td>
<td>Cement dust (8.3 x 10⁻³-3 x 10³ Ω m) 25,000 m³/h 99.8-99.9%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>Four-stage ESP (23-100 °C)</td>
<td>Wire-quadrupole precharger, 300 mm long, 9.5 mm dia. rods, 50 mm square, 1500 µm wire (–25 kV dc or –30 kV pulse)</td>
<td>Wire plate, 100 mm long, 300 mm high, 50 mm space (–25 kV)</td>
<td>Incense smoke 0.2-1.5 µm 12 m³/h 0.005-0.155 g/m³ (10⁻³-10⁸/m³) &gt;96% (number), 99.99% (mass)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>Quadrupole agglomerator (25 kV/50 Hz + 10 kV dc)</td>
<td>dc corona charger</td>
<td>Wire plate, 6 mm space, 260 µm tungsten wire (+11 kV)</td>
<td>Diesel exhaust particles (7 m/s) 0.03-60 µm &gt;60% (0.03-1 µm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>82</td>
<td>Two-stage ESP</td>
<td>Wire plate, 6 mm space, 260 µm tungsten wire (+11 kV)</td>
<td>Parallel plates, 6 mm space (5.5 kV)</td>
<td>Diesel exhaust particles 0.03-60 µm (7 m/s) &gt;60% (0.03-1 µm)</td>
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<tr>
<td>83</td>
<td>Parallel plate ac agglomerator, 80 mm high, 100 mm long, 80 mm space (3 kV, 300 Hz)</td>
<td>Wire plate, 40 mm high, 60 mm long, 80 mm space (–10 kV)</td>
<td>Parallel plates</td>
<td>NaCl particles 0.1-1.2 µm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>84</td>
<td>Assistant-electrodes ESP</td>
<td>Wire plate, 190 mm width, 600 mm length, 100 mm space, 170 µm wire (–15 kV)</td>
<td>Parallel plates with assistant parallel electrodes, 100 mm space</td>
<td>SiO₂ 1-4.5 µm 1.73 m³/h (1 m/s) (1.8 times better than without assistant electrodes)</td>
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Table 1 (continued)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Precipitator type (parameters)</th>
<th>Charging device (voltage, current, current density)</th>
<th>Collection electrodes geometry</th>
<th>Dust particle size and charge (resistivity)</th>
<th>Gas flow rate (velocity, residence time)</th>
<th>Dust loading (particle concentration)</th>
<th>Collection efficiency (reduction ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[85]</td>
<td>Tubular ESP, 6 m high (3 m² total cross section)</td>
<td>Barbed discharge electrode (−75 kV)</td>
<td>Cylindrical</td>
<td>Cement dust</td>
<td>8600 m³/h (0.8 m/s)</td>
<td>128 g/m³</td>
<td>99.9% (outlet 86 mg/m³)</td>
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<td>[86]</td>
<td>Electrocyclone, 50 mm dia. (1.5 m/min)</td>
<td>Wire-cylinder precharger</td>
<td>Cylindrical (1600kV/m)</td>
<td>SiO₂ 1–20 μm</td>
<td>4–12 m³/h</td>
<td>75% (55% for uncharged)</td>
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<td>[87]</td>
<td>Moving plate ESP</td>
<td>Wire plate, 460 mm space (−40 to −60 kV pulse 120Hz/8.3ms width)</td>
<td>Parallel plates</td>
<td>Fly ash 0.5–10 μm</td>
<td>9400–11,400 m³/h (0.9–1.1 m/s)</td>
<td>2–10 g/m³</td>
<td>42% (1 μm), 80% (10 μm)</td>
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<td>[62]</td>
<td>Two-stage ESP</td>
<td>Dielectric barrier discharge (12.3 –13.1 kV ac)</td>
<td>Parallel plates (9.6kV)</td>
<td>fly ash 0.03–3 μm</td>
<td>(1.5 m/s)</td>
<td>90%</td>
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<td>[88]</td>
<td>Parallel plate agglomerator, 6 mm space (1–8 kV)</td>
<td>Bipolar charger, ac discharge, wire-plate, 38.5 mm space, 260 μm tungsten wire (15kV ampl)</td>
<td>Parallel plates</td>
<td>Diesel exhaust particles 0.03–0.5 μm, 0.07 μm max.</td>
<td>(2.5 m/s)</td>
<td>(10¹²/m³)</td>
<td>~100% (1 μm), 10% (0.03 μm)</td>
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<td>[89]</td>
<td>Electrocyclone, 75 mm dia., 240 mm height</td>
<td>Wire cylinder, 330 μm wire (−4 to −9 kV)</td>
<td>Cylindrical</td>
<td>Fly ash &gt;1 μm</td>
<td>36–1300 m³/h (0.5–30 m/s surface velocity)</td>
<td>8–23 g/m³</td>
<td>92% (72% for uncharged 10 μm)</td>
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<td>[90]</td>
<td>Electrocyclone, 480 mm dia., 3280 mm height</td>
<td>Wire cylinder</td>
<td>Cylindrical</td>
<td>Diesel engine soot</td>
<td>470 m³/h</td>
<td>1 g/m³</td>
<td>50–80%</td>
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<tr>
<td>[91,92]</td>
<td>Parallel plate ESP, 360 mm space (600 x 600 mm cross-section) (82 or 170 °C)</td>
<td>Corona charger, 250 mm space (−30 to −50 kV), (1–3 mA)</td>
<td>Soft membrane (carbon and silicone fibers), (300 x 300 mm or 6 x 0.65 m membrane sheets)</td>
<td>Fly ash 20–25 μm, (1–5 μm iron oxide, 2–3 μm calcium carbonate)</td>
<td>0.08 m³/h (1–2 m/s)</td>
<td>1500 g/m³</td>
<td>96% (&lt;2.5 μm), (0.7–1.9 l/min water consumption)</td>
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<tr>
<td>[93]</td>
<td>Electrocyclone, Three-stage ESP (45 °C)</td>
<td>Wire cylinder (25 kV)</td>
<td>Corona charger, 2300 μm wire, 20 mm space (25 kV/100 Hz)</td>
<td>Wire plate, 200 mm long, 50 mm space, (−25 kV)</td>
<td>Fly ash</td>
<td>495–2660 m³/h</td>
<td>22–35 mg/m³ (fly ash), 0.03–0.35 mg/m³ (Hg)</td>
</tr>
<tr>
<td>[94]</td>
<td>Parallel plate ESP, 65 x 62 mm, 5.5 mm space</td>
<td>Wire-cylinder, dielectric layer: glass plate 0.5 mm thick with hoks 0.6, 1, 3.1 mm (11.5–14 kV/50Hz, 0.2–1 mA)</td>
<td>Wire-cylinder, pulse excitation (80 kV, 2.1 mA)</td>
<td>Diesel engine exhaust &gt;0.3 μm</td>
<td>(1.5 m/s)</td>
<td>99.9% (mass)</td>
<td></td>
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<tr>
<td>[66]</td>
<td>Two-stage ESP (160 x 160 mm cross section)</td>
<td>Wire-cylinder, 6 x 160 mm, 130 mm long (15 kV rms, 60 Hz)</td>
<td>Parallel plates, 130 mm long, 30 mm space (10–20 kV)</td>
<td>MgO 10 μm; fly ash 10 μm</td>
<td>(0.5–1.5 m/s)</td>
<td>&gt;95% (MgO), &gt;60% (fly ash)</td>
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<tr>
<td>[95]</td>
<td>Electrocyclone, 1.5 m long</td>
<td>Wire-cylinder, pulse excitation (80 kV, 2.1 mA)</td>
<td>Cylindrical</td>
<td>MgO 10 μm; fly ash 10 μm</td>
<td>(0.5–1.5 m/s)</td>
<td>&gt;95% (MgO), &gt;60% (fly ash)</td>
<td>97.7–99.1%, (41% uncharged, 5 μm)</td>
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<tr>
<td>Reference</td>
<td>Description</td>
<td>DOP</td>
<td>Flow Rate</td>
<td>Collection Efficiency</td>
<td>Remarks</td>
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<tr>
<td>[96]</td>
<td>Quadrupole (2 plates + 2 rods agglomerator), 1 kV/700 Hz</td>
<td>0.5-0.75 µm, 6 µm</td>
<td>0.03 m³/h (10 min–1 h)</td>
<td>0.8–1.5 × 10⁹/m³</td>
<td>not determined</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[97]</td>
<td>Single electrocyclone, 46 mm dia.; double electrocyclone, 46/23 mm dia., 69 mm height</td>
<td>Wire-cylinder corona charger (4–9 kV)</td>
<td>Cylindrical</td>
<td>PSL 0.5–4.3 µm</td>
<td>1.2 or 2.4 m³/h</td>
<td>73-90% (single @ 2.4 m³/h, 9 kV), (55–82% uncharged); 98% (double @ 2.4 m³/h, 9 kV), (92% uncharged)</td>
<td></td>
</tr>
<tr>
<td>[98]</td>
<td>Parallel plates ac agglomerator, 100 × 36 mm (20 kVpp, 390 kVrms/m) 60–500 Hz</td>
<td>Wire-plate corona, bipolar charger, 250 µm wire, 40 mm space (± 8 kV)</td>
<td>0.07–0.6 µm, 3–70 e</td>
<td>0.5 m/s (1 s)</td>
<td>0.25 g/m³, 5 × 10¹²/m³</td>
<td>(25–29% for 0.1–1 µm)</td>
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<tr>
<td>[63,64]</td>
<td>Two-stage tubular ESP, 100 mm dia., 450 mm length</td>
<td>Co-axial corona triode charger, 25 µm silver wire (6-12 kV), (+ 2 kV—grid), (3.7 µA, 10⁷/cm² ion concentration)</td>
<td>Cylindrical (2 or 3 kV)</td>
<td>Particles in ambient air 0.3–13 µm, 15e; PSL 18–255 nm; NaCl 4-11 µm</td>
<td>1 m³/h (1 s)</td>
<td>0.5–3 µm/m³</td>
<td>96% (particles in ambient air); 99.7% (PSL); 99.9% (NaCl)</td>
</tr>
<tr>
<td>[99]</td>
<td>Electrocyclone, 430 mm dia., 3.1 m long</td>
<td>Wire cylinder, 10 mm stainless steel wire with 10 mm long barbs, pulse excitation (93 or 105 kV, 50–100 pulse/s, 30 µs pulse width), (30 mA)</td>
<td>Cylindrical</td>
<td>Dense particles (NH₄Cl + NH₃ + H₂O) 3.1 µm (mean)</td>
<td>15,000 m³/h</td>
<td>50 g/m³</td>
<td>90% (93 kV pulse), 92.6% (105 kV pulse) (75–80% for 62–70 kV dc or 42.5% uncharged)</td>
</tr>
</tbody>
</table>
A two-stage ESP with ac excitation in the collection section was tested by Bart et al. [57]. The amplitude of particle oscillation was of the order of magnitude of 1 mm or smaller. The motion of the particles to the electrodes was due to turbulent diffusion, because the typical Reynolds number was \(10^4\). Close to the collection plates, the particles were deposited due to the electrical oscillations. The collection efficiency in this type of precipitator decreased with increasing frequency.

The disadvantage of two-stage ESPs is that the cohesion between the particles deposited on the electrodes is reduced, and dust re-entrainment from these electrodes is easier due to the lack of discharge current [69]. Surfactants were proposed as a remedy to particle re-entrainment from the collection electrodes. Kawada et al. [82] used water with non-ionic surfactant at a concentration of 0.1%, which reduced the surface tension to \(33.5 - 43.4 \times 10^{-5}\) N/m. The surfactant was sprayed upstream and improved adhesion between the particles and the electrode, particularly for larger particles.

It can be concluded that in a two-stage ESP, back discharge can be eliminated and the collection efficiency increased. However, re-entrainment can be observed for particles of low cohesiveness.

3.2. Electrostatic particle agglomerators

Another way to fight against emission of fine particles is to increase their mean size before precipitation. Agglomeration is a process in which small particles come together (coagulate) to form a larger one, or in which small particles adhere to a larger one. Acoustic coagulation [100] or water vapor condensation [101] are the most frequently mentioned methods. Both processes are very energy consuming in industrial conditions. Stairmand [102] estimated megawatts of power necessary for effective acoustic coagulation of submicrometer particles in an industrial scale precipitator. Not all coagulated agglomerates are sufficiently coherent and stable to reach a precipitation stage. Vapor condensation is more efficient but also requires too much energy [102].

Electrostatic agglomerators were therefore proposed as a way to coagulate submicrometer particles while operating with higher energy efficiency [73,103]. Particles smaller than 1 \(\mu\)m are usually difficult to agglomerate; by charging them to opposite polarities, however, the coagulation can be accomplished more easily. A schematic diagram of an electrostatic agglomerator is shown in Fig. 3. In the first stage, the particles are charged to opposite polarities, and in the second, they are subjected to alternating electric field, which causes the particles to collide. The experimental properties of electrostatic agglomerators are summarized in Table 1.

The following different types of agglomerators were proposed to coagulate dust particles:

1. **Bipolar parallel-plate agglomerator** (tested by Kobashi in 1979, and Mitchner and Self in 1983 [34,74,75,98]: The particles are charged oppositely in two dc corona discharges, and next mixed and coagulated in a dc or ac electric field. The number concentration of submicron particles can be reduced by about 30% (cf. [74]) or even four times (from 75% to 18% [34]).

2. **Unipolar alternating electric field agglomerator** [74,77,83]: The particles are first charged to a single polarity, then subjected to oscillations in an alternating electric field. The amplitude of oscillation depends on the particle size and mass, and it is about 100 \(\mu\)m for particles of 0.1–1 \(\mu\)m in diameter [77]. The particles collide and agglomerate during their oscillating motion due to difference in their charge and mobility. The number concentration of particles smaller than 1 \(\mu\)m was decreased to below 19% of its initial value. Smaller particles (<0.1 \(\mu\)m) experience easier agglomeration than larger ones (>1 \(\mu\)m) [77]. Within the submicron range, the amplitude of particle oscillations increases...
with increasing particle size. The size of agglomerated particles increases with increasing frequency. For example, a size of 4–8 μm is obtained at a frequency of 50 Hz, and 30–50 μm at 300 Hz [83].

3. Bipolar ac/dc agglomerator [88,103]: The particles are charged bipolarly in an ac wire-plate corona discharge and next agglomerated in a dc electric field. After particle agglomeration, the collection efficiency was close to 100% for particles of size 1 μm, but it decreased to 10% for smaller particles (0.03 μm).

4. Quadrupole agglomerator (proposed by Watanabe and Suda in 1988 [cf. [74]]) in which the charged particles are focused in the axis of a set of quadrupole electrodes. A concentration reduction of about 20% for particles in the size range 0.06–1 μm and charged to about 1 mC/kg, was obtained. Nakajima and Sato [96] constructed a quadrupole agglomerator of two rods and 2 plates. They utilized only polarization forces, without charging fine particles, and additional acoustic excitation of fine particles. In case of charging of small particles, the charge on larger ones is neutralized, thus decreasing the agglomeration efficiency.

The agglomeration efficiency is limited due to the charge depletion effect, which occurs when two particles of nearly equal charge but opposite polarity collide with each other. These particles cannot further participate in an agglomeration process to form larger particles [77]. In the agglomerators discussed above, the particles are charged in a dc or ac corona discharge, similar to conventional ESPs. Alternating electric field chargers—for example, those developed by Masuda et al. [59] (cf. also Ref. [58]) and Jaworek and Krupa [68]—have also been proposed.

Electrostatic agglomerators help to increase mean particle size to more easily precipitate them via conventional ESPs or other filters. An alternating electric field promotes agglomeration of charged particles in addition to that caused by Brownian motion. The agglomeration efficiency increases with increasing total mass concentration of the particles, but it decreases for particle number concentrations above $5 \times 10^{12}/m^3$ [77], probably due to particle loss in the charger. However, it can be concluded from the data presented in Table 1 that the efficiency of the referenced devices is still too low for industrial scale applications.

### 3.3. ESPs with modified electrodes

Traditional wire-to-plate precipitators are characterized by an inhomogenous current distribution in the interelectrode space in both axial and longitudinal directions. This characteristic is disadvantageous for fine particle precipitation. Miller et al. [104], Mochizuki et al. [105], and Blanchard et al. [106] studied the geometrical patterns of dust layers deposited in an ESP and found four zones of the deposited layer that depend on the ionic current density. There exist zones of low ionic current, in which the layer is softly packed and of dendrite-like structure. The particles can easily be removed from these zones due to lack of cohesive forces, which are proportional to the discharge current. In the zones where the ionic current density is high, the layer is densely packed and not susceptible to particle re-entrainment [106].

From these results it can be deduced that removal of dust particles by a two-stage ESP (cf. Section 3.1), in which the collection stage is free of electrical discharge, is of low efficiency due to particle re-entrainment. The re-entrainment is more likely when the cohesive forces between fly ash particles and adhesive force to the electrodes are weak, and when dust has low resistivity [107]. Secondary flow caused by corona wind, which produces strong upstream and downstream vortices, most likely also participate in particle re-entrainment [108].

Different types of emitter electrodes, for example smooth or barbed wires, cylinders, strips, or plates, were tested for optimization of current distribution and particle transport to the collection electrode. The barbed cylinder (tube) is more effective because it can emit current of higher density than can smooth wires [71], and offer better collection efficiency due to faster transport of particles towards the collection electrode [109–111]. Longer barbs allow the current to be higher, and the collection efficiency, especially for small particles, is also higher. Better precipitation results are also obtained for short distances between barbs and for a short discharge electrode module. The optimal distance between discharge electrodes is nearly equal to half the gap spacing between plates [79].

A tubular precipitator in which the barbs of the discharge electrode are longer downstream, was proposed by Feng et al. [85]. This construction allowed increasing the discharge current and electric field close to the precipitator outlet by simple maintaining the entire electrode at the same potential. The higher current density is required for precipitation of small particles.

A barbed-plate (multipoint) emitter electrode in a parallel-plate ESP was proposed in [72,112–115]. This type of electrode generates a more uniform electric field and allows higher migration velocities [109,110]. It also provides more uniform current density and uniformly distributed turbulence in the precipitation space compared to a wire-plate configuration of the same electrode space. An optimization of the discharge current from a multipoint electrode was carried out theoretically by Davidson et al. [114], and experimentally by Jaworek and Krupa [116].

Non-conventional collection electrode configurations were also proposed and tested by many authors for effective control of particle emission. The most important of these are the following:

1. **Moving-electrode ESP** [71,87,117]: The collection electrode was made in the form of a belt or from segmented plates, and it circulates with velocity of 0.5–1.5 m/min between two separated chambers. The fly ash collected on this electrode within the precipitation chamber, is
mechanically removed (scrapped) in the scratching chamber. The separation of the precipitation and removing processes prevents particle re-entrainment, and increases overall collection efficiency as compared to a conventional ESP. For example, the collection efficiency for the removal of soot particles emitted by a diesel engine was higher than 95% in a moving-belt precipitator operating in conjunction with a precharger and agglomerator [71].

2. **X/V-shaped collection electrodes (Fig. 4)** [78]: Electrodes of V- and X-shape were arranged in an alternating pattern and positioned transverse to the gas flow. This type of electrode configuration has been shown to reduce back-corona discharge and increase the overall collection efficiency. Back-corona is avoided because ions and electrons flow along the field lines to the edges of the electrodes, while dust particles, which have lower mobility, are driven by inertial force to the inner surface of the electrodes.
3. **Assistant collecting electrodes** consist of additional narrow collection plates placed in the space between the discharge electrodes and collection electrode halfway between the discharge electrodes, where the electric field is minimum (Fig. 5) [84]. The collection efficiency of particles smaller than 1 μm was shown to be higher, probably due to increased discharge current which increased up to 1.6 times for grounded assistant electrodes.

4. **Lentoid type (electrostatic-lens like) precipitator** [81,118,119]: In this design, the collection plates typically used in ESP were replaced by hollow collection electrodes having longitudinal slots facing the discharge electrode (Fig. 6). A flow-free chamber was formed between two collection electrodes. An additional positive discharge electrode was placed inside this chamber, in front of the slot. The plate with such a slot operates like an electrostatic lens, focusing negative ion trajectories onto the positive electrode in the hollow. The electric wind drives charged dust particles through the lens aperture towards the positive electrode. Unlike conventional ESPs, the corona wind penetrates the cavity, but the collected particles are not re-entrained by this wind because they still remain in the hollow chamber where there is no gas flow. Within the chamber, the particles tend to agglomerate due to Coulomb force and turbulent motion, and they are more easily precipitated on the positive electrode, i.e. on the inner side of the lens. The migration velocity was several times higher compared to a conventional wire-plate ESP. This type of ESP also prevents back-corona discharge. The precipitator is particularly suitable for the collection of small dust particles of high resistivity without the need for either gas conditioning or pulse energization.

5. **Membrane collection electrodes** [91,92]: The collection electrodes are made as soft membranes woven from carbon and silica fibers. They replace the stiff, sheet-metal collection electrodes usually found in ESPs. Collection electrodes of this type can be used in dry or wet ESPs. In a wet precipitator, water can be more uniformly spread on the membrane due to capillary forces. This allows lower water consumption, non-interrupted electric field operation, and higher collection efficiency. In the case of a dry ESP, the membrane electrode requires lower acceleration forces for its rapping.

6. **Collection electrodes covered with a dielectric layer** [94]: Such electrodes are supplied with ac voltage. Small pinholes made in this layer cause an increase in the collection efficiency. However, earlier results [120,121] indicate that back-corona can easily be initiated in this configuration.

The technical parameters of ESPs with modified electrodes are shown in Table 1.

3.4. **Electrically energized cyclones (electrocyclones)**

Cyclones utilize centrifugal acceleration of dust particles to precipitate them on the chamber walls. The acceleration can range from 5 g for large installations to 2500 g for small cyclones. Conventional cyclones are suited for removing particles larger than a few microns. For fine particles, the centrifugal force is lower than the drag force, hence the collection efficiency can be increased only by imposing electrical forces, for example, by placing an electrode in the axis of the cyclone (Fig. 7). Such a device is known as an electrocyclone. Ions emitted from the high-voltage electrode charge the particles, and the electrostatic field, in conjunction with the centrifugal force, drives the particles to the cyclone walls. Primary particles of the size range 10–30 nm can form aggregates of a few microns in diameter and dendrites on the walls [90]. The diameter of electrocyclones is usually limited to about 1.8 m, and the dust loading is similarly limited to 4.5 g/m³, due to corona quenching at larger dimensions and loading [122]. Electrocyclones are usually supplied from dc power source but Li and co-workers [95,99,123] used pulsed voltage excitation that resulted in faster particle migration to the collection electrode and higher collection efficiency.

Particles can also be charged by corona discharge before their entry into the cyclone. In this case, a corona-free electrostatic field causes the particles to be deposited on the cyclone walls. However, particles may also be deposited on the central electrode in such a device [124]. The removal of small particles by electrical forces in an electrocyclone is more efficient than larger ones [89,97], but only for very
high electric fields and low flow rates [93]. When the flow rate is too high, the electrically energized cyclones have low collection efficiencies for the removal of particles smaller than 1 μm, because the drag force is larger than the electrostatic force. Decreasing gas velocity within the cyclone improves electrostatic effects but also decreases inertial forces, thus preventing centrifugal precipitation of larger particles. Electrocyclones are also ineffective for particles of high resistivity due to the low value of charge on the particles. For these reasons, the electrocyclones appear to be of low practical value.

The properties of electrocyclones tested by various authors are summarized in Table 1.

### 4. Electrically assisted filters

#### 4.1. Electrically energized fibrous filters

Filters are made of media with small pores or openings, usually smaller than the size of particles to be captured. The gas to be cleaned flows through the filter, but the particles are too large, and remain on the upstream side of the filter or within the pores, building up a dust cake. Electrical energy has also been used with this type of filter to produce an electric field and/or charge the particles. Three classes of electrostatically assisted filters can be found in the literature: fabric filters, electret filters, and granular-bed filters.

Fabric filters use a textile fabric as the filtration media, usually in the shape of a bag or envelope. Gas can flow from inside to outside of the bag or, less frequently, from outside to inside. The lifetime of conventional bag filters is 3–5 years. The bag is changed when the residual dust cake is too thick and difficult to remove, causing too high a pressure drop. Typical gas flow rate in a bag filter is about $10^3$–$10^4$ m$^3$/h. For a full-size bag of 10 m length and 0.3 m diameter, this flow rate results in a specific gas velocity of about 0.01 (m$^3$/s)/m$^2$. Dust loading in the bag filter may vary between 1 and 1000 g/m$^3$. Particle penetration through a fabric or tissue filter decreases exponentially with the filter thickness $h$ [125] according to the formula

$$\lambda = \exp(-\gamma/h),$$

where $\gamma$ is a constant depending on the filter porosity, particle size, and surface velocity.

Electrostatic effects in fabric filters were investigated by Bhutra and Payatakes [126], Frederick [127], Lathrache et al. [128], and Lundgren and Whitby [129]. Frederick [127] showed that triboelectric charging is very important in the filtration process and increases filtration efficiency. Bhutra
and Payatakes [126] and Oak and Saville [130] discovered that the particles are captured in the form of long and thin dendrites on the upstream bag surface. The dust is deposited on the surface of the fabric rather than between the fibers [131]. The electric forces cause the dust to form “bridges” between the fibers, with free gaps between them [132]. In the absence of an electric field, the dendrites are shorter and multi-branched, and form a tight layer. The dendrite-like structure of the deposit reduces the pressure drop and penetration by almost an order of magnitude compared to standard fabric filters.

Lundgren and Whitby [129] noticed that particles entering the filter usually carry a low charge due to triboelectric charging, and the collection of particles in the size range from 0.1 to 1 μm results in part from this natural charging. Particles of size 1 μm were charged up to about 6 elementary charges, while 0.1 μm diameter particles were charged to 1e; however, half these particles remained uncharged. Particles larger than 1 μm are collected mainly by impact, while those smaller than 0.1 μm are collected principally by Brownian diffusion [129].

The cohesive forces between dust particles are also increased by current flowing through the dust columns. The dust cake deposited in an electrostatic field is more fragile than that on a non-electrified bag, which allows the particles to be more easily dislodged, and the filter to be better cleaned by shaking [133].

Fabric filters were also improved for more efficient removal of fine particles by using electrical forces [134,135]. Electrostatics can be added to fibrous filters in three ways:

1. **Filtration in an electric field without particle charging:** The field can be produced between a pair of electrodes (of cylindrical configuration, for example) with a fibrous filter placed between these electrodes. An example of such a filter is shown in Fig. 8a [136]. Every second wire is maintained at high potential, while the others are grounded. The best filtration results were obtained for the electrodes located at the dusty side of the filter [137]. The electrodes can also be excited by high voltage ac, but this mode has only a negligible effect on the collection efficiency [138].

2. **Filtration of charged particles without electric field:** The particles are charged in a corona discharge, in a stage before the filter, and removed in traditional bag filter with no electric field applied [139].

3. **Filtration of charged particles in an electric field:** The particles can be charged before their filtration in a corona-free electric field [86,129,140,141], or simultaneously charged and precipitated in the same stage [125,133,142,143]. An example of a device based on the first principle is shown in Fig. 8b. The concentrically arranged corona wire charges the particles in the lower part of the filter. Larger particles are collected on a metal tube, which in fact is a tubular ESP, while the particles of lower mobility flow upwards to the bag filter where they are deposited.

A two-stage, electrostatically augmented fibrous filter, which consisted of a positive corona precharger placed upstream of a polarized filter media, was constructed by Lee et al. [140] (Fig. 9a). Charging and preliminary precipitation take place in the first stage, and fine particle removal is accomplished between electrically excited fibrous filters. An example of fibrous filter with simultaneous charging and precipitation is shown in Fig. 9b [125,142]. The discharge between sharp points and the grounded filter made of sintered stainless steel fibers allows charging and precipitation of the particles in one stage. The charged particle penetration through the filter is independent of the particle size. This type of filter is particularly suitable for removal of submicron particles. The back-corona discharge was not observed in this filter. The properties of electrostatically augmented fibrous filters are summarized in Table 2.

Fibrous filters made from carbon fibers with chemically activated surfaces were proposed by Otani et al. [147] for the simultaneous removal of small particles and gaseous compounds. It was shown experimentally that penetration of charged particles decreases almost an order of magnitude for activated fibers compared to untreated ones. Otani et al. [147] also tested the process of conversion of organic gases to particles as a means for removing them by fibrous filters. Biodegradable fibrous filters were considered for production by Ciach [155]. For low resistivity dust, there is
Table 2
Electrically assisted filters

<table>
<thead>
<tr>
<th>Reference</th>
<th>Filter type (parameters)</th>
<th>Charging device (voltage)</th>
<th>Assistant electrodes geometry</th>
<th>Dust particle size and charge</th>
<th>Gas flow rate (face velocity)</th>
<th>Dust loading (particle concentration)</th>
<th>Pressure drop</th>
<th>Collection efficiency</th>
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</thead>
<tbody>
<tr>
<td>[129]</td>
<td>Fibrous filter 17.3 μm dia. wool; 10 μm dia. glass; urethane foam filter, 43 μm pores</td>
<td>Point-plane corona</td>
<td>Methylene blue + uranine dye 0.1–1 μm (6–320 e)</td>
<td>(0.22–0.4 m/s)</td>
<td>3 × 10^7–1.2 × 10^8/ m^3 (1 μm) 4 × 10^6–6 × 10^10/ m^3 (0.1 μm)</td>
<td>39–78 Pa</td>
<td>99% (1 μm), (16% for uncharged)</td>
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<td>[144,145]</td>
<td>Fluidized bed (100 × 100 mm cross section or 150 mm dia.), sand particles 0.8–2 mm or glass beads 0.5–1 mm</td>
<td>Parallel electrodes, 25 mm space (500 kV/m—rectangular); 40 mm space (375 kV/m—circular)</td>
<td>DOP 0.4–0.7 μm</td>
<td>(2 m/s)</td>
<td>980 Pa</td>
<td>&gt;99% (60%—un-electrified bed)</td>
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<tr>
<td>[137,136]</td>
<td>Bag filter, PTFE or glass fibers, 100 mm dia., 1.2 m long</td>
<td>150 μm wires on filter surface, 15 mm space (11 kV), (600 kV/m)</td>
<td>fly ash 0.01–10 μm</td>
<td>(0.03–0.06 m/s)</td>
<td>12 g/m^3</td>
<td>147–245 Pa</td>
<td>99.9% (PTFE), (99.5%—un-electrified); 99.4% (glass), (97.8%—un-electrified)</td>
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<td>[131]</td>
<td>Fabric filter (with antistatic agent)</td>
<td>Wire cylinder, 100 mm long, 50 mm dia. (+12 kV)</td>
<td>Parallel electrodes: mesh to plate, 50 mm space (−15 kV)</td>
<td>Industrial dust (1.5 × 10^−6–1.5 × 10^−5 C/m^2), (10^5 μm)</td>
<td>(0.03 m/s)</td>
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<td>[146]</td>
<td>Fabric filter PTFE-coated glass fibers, (6 bags 200 mm dia. each), 200 mm dia., 7.3 m long (21, 82, 149°C)</td>
<td>Wire cylinder, 2.4–1.2.7 mm wire, 200 mm baghouse cylinder (−23 to −50 kV)</td>
<td>Fabric with entangled yarn of 22 μm wire (500–780 kV/m)</td>
<td>Fly ash 3.3 μm (mass geometric)</td>
<td>460–520 g/h</td>
<td>(20–30% of that without electric field)</td>
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<tr>
<td>[147]</td>
<td>Fibrous filter 15 μm activated carbon fibers (surface area 1500 m^2/g)</td>
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<td></td>
<td>Cigarette smoke 0.03–0.3 μm</td>
<td>(0.1 m/s)</td>
<td>5 × 10^6/m^3</td>
<td>90% (0.1 μm)</td>
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<tr>
<td>[148]</td>
<td>Pseudo-electret filter, 23 layers (300°C)</td>
<td></td>
<td>Wire wound on a PTFE isolated core wire (500 V)</td>
<td>Mineral silt 1.24 μm</td>
<td>(0.33–0.65 m/s)</td>
<td>55 g/h</td>
<td>93–392 Pa</td>
<td>98.2% (88.2% for uncharged)</td>
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<tr>
<td>[139]</td>
<td>Fabric filter polyaramid (15 m²) (70–120°C)</td>
<td>Point-grid; dc or pulse voltage (35–45 kV/peak, 2–60 Hz)</td>
<td></td>
<td>Fly ash</td>
<td>(0.006–0.045 m/s)</td>
<td>0.25–6.1 g/m^3</td>
<td>45% of that without precharger</td>
<td>99.34%</td>
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<td>[149,150]</td>
<td>Fibrous filter, 20 μm, 3 mm thick, 5% density</td>
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<td>[151]</td>
<td>Electret filters: A: 16–18 μm, B: 17–21 μm, C: 4.6–5.4 μm, 3.8–10% density</td>
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<td>[124,141]</td>
<td>Fibrous filter 25 μm (21 g/m²) polyacrylonitrile or 25 μm (10.8 g/m²) glass fibers</td>
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<td>[146]</td>
<td>Packed-bed filter 150 mm dia., 10–40 mm height column, 180 μm sand particles</td>
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<td>[142,125]</td>
<td>Fibrous filter stainless steel fiber or metal sintered powders of 6–20 μm pores; 47 mm dia. duct</td>
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<td>[140]</td>
<td>Two-stage electrified filter-collector (610 × 610 mm cross section)</td>
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<td>[152]</td>
<td>Electret filter: polypropylene with TiO₂ and SiO₂ admixtures (1–20 μC/m²)</td>
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<td>[153]</td>
<td>Nanofiber electret filter</td>
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<td>[154]</td>
<td>Electret filter, two-stage 35 μm polyester + 10 μm polycarbonate, 0.5 mm thick</td>
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</table>

| | Stearic acid 0.46–1.4 μm; latex particles 0.13–1.13 μm NaCl 0.05–0.5 μm (1e) | (0.05–0.8 m/s) | 500 Pa (uncharged) | 45–82% |
| | A: 0.1 m/s, B: 0.1 m/s, C: 0.053 m/s | | A: 12–44 Pa, B: 3.7–27 Pa, C: 24–50 Pa | |
| | | SO₂ 0.1–10 μm (max at 0.2–0.4 μm) | (0.02–0.2 m/s) | 20 Pa | 92% (5% for uncharged) |
| | Impact charging (positive/negative polarity) | Fixed bed, parallel electrodes: 149 or 210 μm mesh | Phosphatic concentrate 0.3–10 μm (5.2 μm mean), (2730 kg/m³), (15–46 mC/kg) | (0.07–0.15 m/s) | 200 Pa (1400 Pa—uncharged) |
| | | | Metal fibers or sintered metal powder | PSL 0.05–1 μm; silica particles 0.05–0.5 μm | 0.6–3 m³/h | 6 g/cm² | 300–2000 Pa | 99.5% (10–40% uncharged) |
| | | | | | (0.15–1.25 m/s) | |
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The collection efficiency of fibrous filters can be increased by electrical energization, particularly for particles the submicron size range. The penetration of such particles can be decreased from a typical value of 90% down to about 10% or even lower. The pressure drop is also lower in this type of filter, because the structure of deposited dust changes under the action of an electric field [122]. Due to lower pressure drop, the gas flow rate can be increased without changing the collection efficiency allowing the reduction in the number of bags used for filtration. Regeneration of electrostatically assisted bag filters is simple and efficient because the particles form a cake, principally on the front surface of the filter.

4.2. Electret filters

An electret is a dielectric material that produces a permanent electric field without an externally applied voltage. Electret filters are fabricated from polymer fibers, which are permanently charged during production. Electret filters generate strong electrostatic fields close to the fiber surface and are thus able to remove very fine particles with higher efficiency compared to conventional fibrous filters [152–154]. Electret filters are now widely used in air cleaning devices requiring high-efficiency and low-pressure drop, such as indoor air filters, car-cabin filters, and respiratory filters.

Electrets are produced by either the polarization of a dielectric material in an electric field, or by charge implantation via triboelectric charging, corona charging, or during their production by the electrospinning. Ions produced during the fabrication process are frozen in the host material. Tribocharging takes place as a result of textile earthing, and it requires two different materials of dissimilar electronegativity [153]. Corona charging is suitable for charging polymer fibers, and polypropylene is usually used as electret material [153,156,157]. Direct, pulse, and pulse superimposed on dc voltages are used for corona generation. Maximum charge is attained using charging via pulse corona superimposed on a dc voltage [152]. The electrospinning process is similar to electrospraying, but it occurs for liquids of high viscosity [153,158–163]. The advantage of electrospinning is that the fiber production and charging take place within the same process step. Polycarbonate and polyurethane are particularly appropriate for the production of charged nanofibers. For example, polypropylene can be charged in a corona discharge to a value of 45 μC/m², and PTFE can be charged to 10 μC/m². Stability of the charge on an electret depends mainly on the conductivity and dielectric constant of the polymer rather than on the charging technique [153].

In electret filters, capture via Coulomb force is negligible for larger particles, greater than about 0.3 μm. Below this value, the dielectrophoretic effect become dominant. Over the size range 0.1–0.3 μm, the singly charged particles are simultaneously captured by Coulomb attraction and dielectrophoresis. For particles smaller than 0.1 μm, the Coulomb effect is dominant. Neutral particles larger than 0.1 μm are collected by combined mechanical and dielectrophoretic effects [151]. Particles form long dendrites on the electret fibers [164]. Walsh and Stenhouse [149,150] compared results using both charged and uncharged particle filtration via electrically active filters and concluded that reduction in filtration efficiency is not caused by a charge neutralization process, as earlier was supposed, but rather by a screening effect. Higher humidity causes charge depletion and makes the penetration higher. The effect is more pronounced for higher masses deposited on the filter.

Fibers made from two different materials and charged via tribocharging produce up to 1.27 higher filtration efficiency than fibers charged in a corona discharge [153]. Fibers produced by electrospinning can be of nanometer size and exhibit extremely high filtration efficiency due to the large amount of charge imparted to them. Filters produced by the electrospinning process can achieve a filtration efficiency of 99.97%. This value is characteristic of high efficiency particulate air (HEPA) filters [153]. Some additives such as SiO₂ and TiO₂ can cause an increase in the surface charge density in electrets, and also the collection efficiency of filters made from such material [152].

A pseudo-electret filter with dc energization was developed by Inculet et al. [148,165] for fine particle filtration. The pseudo-electret filter consists of an assembly of two closely located, mutually isolated thin wires (100 μm), to which a dc voltage of up to 500 V is applied. One of the wires forms a core electrode, and the other is wound outside its isolation (Fig. 10). The highly non-uniform electric field generated at the dielectric surface attracts the particles due to the dielectrophoretic force. In conventional electrets, the electric field can be neutralized by the charge deposited on the electret surface, thus reducing the collection efficiency of the filter. In pseudo-electret filters,
the polarity of the dc voltage can be reversed periodically every few minutes, and in this case the electric field can be restored at almost twice the magnitude because of the combination of the imposed voltage with the potential due to the accumulated charge.

The properties of electret filters are reviewed in Table 2. An advantage of electret filters is the additional particle collection due to electrostatic attraction. The filtration efficiency is usually higher than in a conventional filter of similar structure. Filters made of electrets can be less dense, resulting a lower pressure drop of about 1–200 Pa for an air surface velocity of 0.05 m/s. Electret filters are particularly appropriate for submicron particles. The disadvantage of electret filters is that the attraction force decreases as the fibers become covered with particles. Modern electret filters are not affected by higher temperatures and humidity, so that their operating life is sufficiently long for industrial applications [132,166].

4.3. Electrically energized granular-bed filters

Granular-bed filters are made of small granules such as sand, glass beads, or plastic balls. In non-electrified granular-bed filters, deposition by diffusion is dominant for small particles (<0.2 µm in diameter), while larger particles (>4 µm) are captured by interception or via inertial forces. Within these limits, the collection efficiency decreases to about 20% [167]. The collection efficiency of granular-bed filters can be increased by applying an external electric field to them. In electrically energized bed filters, the granules are placed in a dielectric container between two electrodes, to which an ac voltage is applied. The granules become polarized by the electric field and are then used as collection sites for smaller dust particles. The particles entering the electrified bed can be precharged to further increase the collection efficiency by additional electrostatic forces. The properties of electrically energized granular-bed filters are summarized in Table 2.

Two principal configurations of electrostatic granular-bed filters are possible, one with cross-flow, and one with co-flow of gas to the electric field [144,145,168]. Fixed bed, fluidized bed, moving bed, and dry particle scrubbers are used as electrostatically augmented granular-bed filters [122]. A fluidized bed differs from a fixed bed in that it is less densely packed, and the bed can be ‘bubbled’ by flowing gas. The moving bed is characteristic in that the granules are permanently transported through a chamber through which the gas flows. In dry particle scrubbers, the particles are precharged, then flow through a chamber to which oppositely charged granules are injected. For removing small particles from high-temperature gases, ceramic granular-bed filters seem to be more appropriate [146].

The advantage of using electrostatically augmented granular beds is that the electrostatic forces attract the particles to charged or polarized collectors, resulting in more effective cleaning of the gas. In comparison to conventional ESPs, the distance the particles must traverse to the collector is much shorter, and the collection surface area per unit volume of the bed is larger. These properties make it possible to reduce the gas residence time needed for gas cleaning. The volume of the device can also be reduced. The collection of highly resistive dust is easier using this type of filter [169]. The disadvantage of an electrically assisted granular-bed filter is the relatively high-pressure drop required; the latter depends on the electric field and ionization current [170].

5. Conclusions

The survey of ESPs presented in this paper show that it is not easy to obtain high collection efficiency for small particles in the range 0.1–1 µm. The collection efficiency of conventional cleaning devices is usually lower than 90% for such particles, hence electrical forces have been used to enhance their performance. Particle agglomerators have been proposed as a means of increasing particle aerodynamic size. This method, however, appeared to be ineffective, even if an electrostatic force is used to enhance the agglomeration process. Two- or multi-stage ESPs, in which the charging and precipitation processes are separated, have also been proposed for preventing back-corona discharge, but many experiments showed that the method of particle charging is less important than the particle collection technique. Low cohesiveness of the dust due to lack of discharge current is mainly responsible for particle re-entrainment from the collection electrode.

Various modifications to collection electrodes in ESPs have also been proposed for increasing collection efficiency, mainly in the submicron range. These designs, sometimes complex in structure, require further experimental investigation to confirm their performance. Conventional cyclones have also been modified by including the charging of particles and by imposing an electrostatic field to enhance particle collection. Electrical forces, however, are much lower in magnitude than are centrifugal forces, hence performance improvement was limited to small size cyclones only.

The performance of fibrous or granular-bed filters was improved by imposing an electric field on the filtration media. Particle penetration in such devices was sometimes lower than 1% for submicron particles. The pressure drop was also reduced in this type of filter. Electret filters can be very effective, but their collection efficiency is reduced by gaseous ions. A pseudo-electret fiber, which consists of a set of mutually isolated thin wires maintained at high voltage, was therefore invented. Such filters perform at high collection efficiency over long periods of time with negligible energy consumption.

Searching for new gas cleaning devices of higher collection efficiency for submicron particles became more important in last decades because the regulations concerning this size range of particle become more stringent with each passing year. It was shown in the paper that the
collection efficiency of hybrid systems that employ electrical forces is higher than that of conventional devices used for gas cleaning. In many cases, these systems can operate more economically than can conventional devices, especially in removing submicron particles.

References


