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Novel Self-Evacuating Electrostatic Precipitator (*SE-ESP*)

***Abstract**. In this paper, we presented a novel electrostatic precipitator (ESP) prototype. The operating mode and the components of the prototype were outlined in detail. Subsequently, three versions of the ESP were derived from the initially proposed basic model. These models were tested experimentally, and their method of procedure was validated through established simulations developed using COMSOL Multiphysics Software. Furthermore, the characteristics and efficiency of the electrostatic filtration of the three models were compared*

Streszczenie.** W tym artykule przedstawiliśmy nowy prototyp elektrofiltru (ESP). Szczegółowo nakreślono tryb pracy i komponenty prototypu. Następnie z pierwotnie proponowanego modelu podstawowego powstały trzy wersje ESP. Modele te zostały przetestowane eksperymentalnie, a ich metoda postępowania została zweryfikowana za pomocą ustalonych symulacji opracowanych przy użyciu oprogramowania COMSOL Multiphysics Software. Ponadto porównano właściwości i skuteczność filtracji elektrostatycznej trzech modeli*. (Nowatorski elektrofiltr samozasysający (SE-ESP**)*)

Keywords: electrostatic precipitator, experimental Study, numerical modelling, collection efficiency.
Słowa kluczowe: oczyszczacz elektrostatyczny, filtr samozasysający, .

Introduction

Air pollution has become a global concern and is now internationally recognized as a public health problem because people around the world breathe poor-quality air, which is filled with hazardous polluting particles and leads to premature deaths [1].

Several scientific studies supported by the World Health Organization (WHO) have reported alarming results with regard to the degree of danger posed by air pollution because poor-quality air can adversely affect health and deteriorate the balance of our environment. Therefore, air quality is critical. According to the statistical studies conducted since 2016, air pollution is a leading risk factor for death and was responsible for approximately 5 million deaths worldwide in 2017 [2].

People living in low- and middle-income countries are the most vulnerable to the hazards of air pollution. Nearly 92% of the world's population lives in places where air quality levels are close to WHO limits [3].

Air pollution, including both ambient and domestic, is the greatest environmental risk to human health. It is commonly believed that outdoor air quality is worse than indoor air quality. However, according to the Environmental Protection Agency, indoor air pollution levels are actually 2–5 times higher than outdoor pollution levels [4]. In some cases, indoor air pollution levels may be 100 times higher than pollution levels in outdoor environments [4]. These levels of indoor air pollutants are of particular concern because most people spend approximately 90% of their time indoors [4]. In other words, the air inside can sometimes be more harmful than that outside.

Annually, nearly 3.8 million people die prematurely from noncommunicable diseases attributable to the household air pollution caused by improper cooking practices, which include the use of highly polluting stoves coupled with solid fuels and kerosene [5]. Among these 3.8 million deaths, 27% are due to pneumonia, 18% are due to stroke, 27% are due to ischemic heart disease, 20% are due to chronic obstructive pulmonary disease, and 8% are due to lung cancer [5]. This continues to have a toll on the health of the most vulnerable populations such as women, children, and elderly people [6].

Approximately 75% of global dust emissions results from natural sources [7]; most of these dust-affected countries are mainly located in the northern hemisphere in an area known as the "dust belt," which stretches from the west coast of North Africa, extending to the Middle East, through Central and South Asia to China [8], where winds provoke regular and extreme dust storms [7].

Fine particles suspended in air are termed as particulate matter (PM). Dust, pollen, soot, smoke, and liquid droplets are examples of airborne PM, which contains both solid and liquid particles with a complex combination of both organic and inorganic substances [9].

The size, composition, and origin of dust particles differ considerably. Therefore, PM is divided into the following three categories:

- *Coarse particles* ($PM_{10–2.5}$) are of less concern. However, exposure to these particles can irritate a person's eyes, nose, and throat [9].
- *Fine particles* ($PM_{2.5}$) pose the greatest risk to health [9]. These fine particles can embed deep into human lungs and may even be absorbed into the bloodstream [9].
- *Ultrafine particles* ($PM_{0.1}$) can affect a person's lungs and heart. These particles essentially enter the body through the lungs [10], but they can spread to almost any organ, induce more pulmonary inflammation, and remain in the lungs longer than fine particles ($PM_{2.5}$) [10].

Furthermore, dust originated from the dust belt is spread by wind and weather to distant regions. The particles of 0.1–1 μm can stay in the atmosphere for long periods of time (several days or weeks) and can be carried over long distances of up to 1000 km [11]. Particles of >2.5 μm size can be deposited easily and travel <10 km from their place of generation [11].

Dust storms, can carry coarse mineral dust over 1000 km. Dust from the Sahara Desert is dispersed worldwide, with 12% going north to Europe, 28% going west to America, and 60% going south to the Gulf of Guinea [12]. Saharan dust results in PM levels that exceed the threshold limits established by the European Union and WHO [12]. Nearly 4 million tons of desert dust from the Sahara are transported to Mediterranean regions [13].

Pollutants present in the environment can be either anthropogenic, that is, produced by human activities, or natural, that is, created by natural processes (emissions from vegetation, soil erosion, volcanoes, oceans, etc.). All sectors of human activity, including industrial activities, transportation (road and non-road), domestic activities (heating in particular), agriculture, and forestry, are likely to lead to the release of contaminants into the atmosphere. Therefore, air pollution sources are categorized into four major types [14]:

- *Mobile sources* such as automobiles, buses, aircraft, trucks, and trains.
- *Stationary sources* such as power plants, oil refineries, industrial facilities, and factories.
- *Area sources* such as agricultural areas, towns, and wood-burning fireplaces.
- *Natural sources* such as wind-blown dust, wildfires, and volcanoes.

Therefore, numerous studies have focused on various methods of purifying air from particulates. Consequently, numerous techniques have been developed for air purification. These strategies are explained in detail in Ref. 15 &16. Among the purification methods, electrostatic precipitators (ESPs) are sustainable, reliable, energy efficient, and effective. For further guidance on the ESP see Ref. 17.

In the next section, we clarify the operation of ESPs. We presented a novel self-evacuating electrostatic precipitator developed and tested in our laboratory. A thorough description of the ESPs citing the key components, active parts, their mode of operation, and the locations suitable for their use has been provided.

Concept and Application of ESPs

ESPs are air purification and depollution systems currently used to remove suspended fine particulates, either solid or liquid, such as dust and smoke, from a gas-carrying medium in industrial plants as well as thermal power stations, cement works, among others to prevent dust contamination.

The electrostatic precipitation process occurs in two basic steps. The first step involves allowing particles to pass through two electrodes electrically insulated from each other while applying a considerable difference in electrical potential between them [18]. The high-voltage (HV) electrode normally has a small curvature section that ionizes the aerosol particles by forming ions that provide an electrical charge through a corona charging field [18]. To achieve a considerable corona discharge, a negative DC current of 15–80 kV is applied to the HV electrode [18] in the second step, thereby generating an ionizing field where the electrostatic force pushes and pulls small particles against the oppositely charged collecting electrode, which can be a large plate or cylinder with only a slight curvature [18].

The charging and precipitation of the particles may occur in one or two stages. The two discharge electrodes in a single-stage precipitator generate the corona and precipitate the charged particles. These precipitators are most widely used because a common voltage is used for both charging and precipitation, which renders its construction easy. For some applications, such as the cleaning of ambient air for air-conditioning purposes [19], the two-stage precipitators, in which charging and precipitation are performed separately, are effective. In the first stage, only a sufficient current is required for ionization, whereas in the second stage, almost no current is consumed because the second stage only requires a sufficient voltage to create a high-intensity field [19].

Because an ESP only uses energy to gather PM, it is highly efficient in terms of energy consumption. Furthermore, ESPs are highly efficient in collecting small particles. The disposal production ranges from 97% to >99% depending on the particle size [20]. However, they cannot be used in highly dusty conditions because they clog easily.

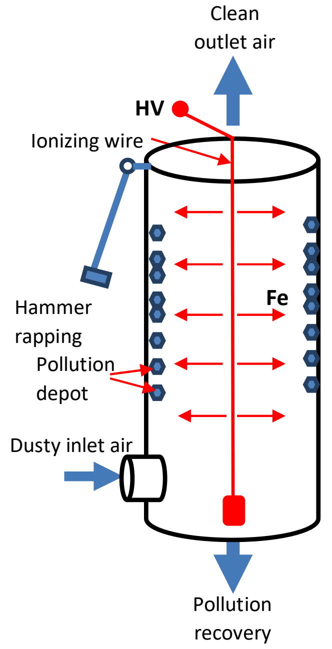

Fig.1. Schematic of a wire-cylinder electrostatic precipitator

In the aforementioned models, the pollution particles collected in the filter are extracted through scraping, vibrating, or wet fluid films (Fig. 1). However, non-industrial emission sources are critical and account for a high proportion of total air pollution, which can only be partly controlled. Furthermore, many installations, such as microelectronics, pharmaceutical, and food processing industries, require protection from dust because dust can cause severe malfunctions in such installations. The choice of purification technology depends on the pollutants to be removed, the desired purification quality, the characteristics of the polluted gas flow, and the characteristics of the place. In such situations, clean air from the contaminated exterior must be transported to a clean interior. For these situations in which the operation of classical electrostatic precipitators is difficult, we developed a novel ESP, a self-evacuation system, without pollution deposits.

Self-Evacuating ESP (SE-ESP)

1. Working principle

This system constitutes three main elements, with each element used to perform a specific function:

1.1. First component

The first component of ESP filters comprises a coaxial wire-cylinder electrodes system. The wire of a small radius functions as a discharge electrode that is held at a high negative potential of several kilovolts. The coaxial metal cylinder through which the polluted gas passes with a certain velocity V_a is connected to the ground.

The metal assembly promotes the production of very strong radial electric field intensity near the wire, which rapidly diminishes in the direction of the cylinder. Two distinct regions are formed; one region exhibits a strong field, and the other region is the drift region where the field is weak. The electric field near the wire becomes ionizing because of certain applied HV values. Electronic avalanches develop continuously, and the corona effect appears around the wire.

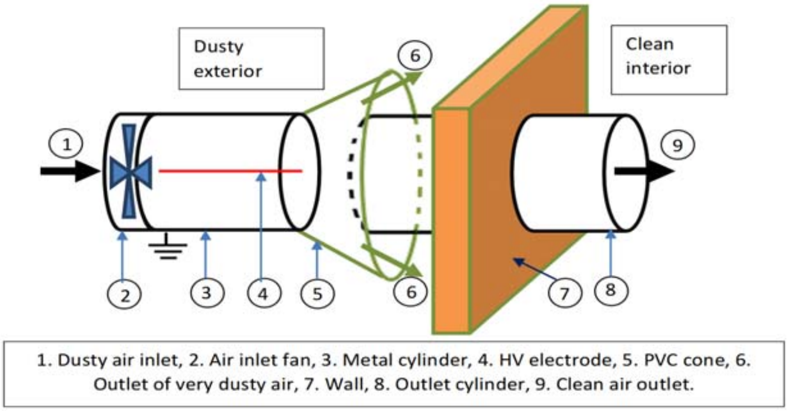

Fig.2. Schematic diagram of the experimental electrostatic precipitator without deposit (SE-ESP)

As the field becomes small, the electronic multiplication stops after a certain distance from the wire. Because electrons no longer possess sufficient energy to create new avalanches, they bind themselves to neutral atoms of the gas, forming heavy negative ions that migrate to the grounded cylinder. Going toward the cylinder, the ions charge the pollution particles by attachment. At this stage, the electric field's action on the charged particles is required, creating a radial electric force $\boldsymbol{F_e}$ proportional to the electric charge, which tends to orient the charged particles perpendicular to the system's central axis, toward the cylinder. Fig. 3 displays the electric potential distribution within the system determined by COMSOL software using the 2D axisymmetric configuration. The red arrows represent the electric forces acting on the negative ions.

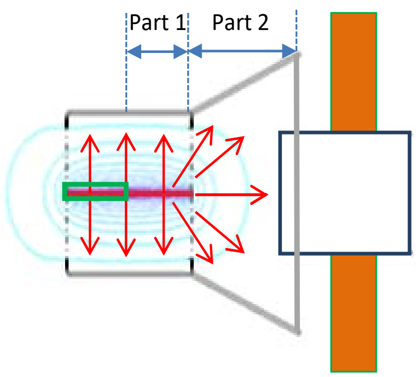

Fig.3. Electric potential distribution inside the electrostatic precipitator with the electric forces

Furthermore, the polluting particles are influenced by the drag force $\boldsymbol{F_{gaz}}$, which is caused by carrier gas movement and tends to guide the particles parallel to the central axis (Fig. 4). The resultant of these two forces determines the parabolic trajectory of the charged particles. Thus, the first part of the filter is designed to allow the dust particles to reach the second part of the filter even before dropping into the cylinder. This is possible if the position of the green insulation covering a part of the wire (Fig. 3) is correctly adjusted. Then, insulation prevents the formation of electronic avalanches, which only occurs in the vicinity of the stripped portion of the wire for a sufficient voltage.

1.2. Second component

The second component comprises a conical shape made of an insulating material and whose inclination $\boldsymbol{\alpha}$ has a major impact on the particles' orientation.

In this part, the electric force can be categorized into two components:

- A perpendicular force to the inclined plane $\boldsymbol{F_{adh}}$, which leads to the adhesion of the charged particles on the conical surface.
- A tangential force to the inclined plane $\boldsymbol{F_{mov}}$, which is used to move the charged particles toward the exit of the polluted air.

The force due to the carrier fluid's flow tends to push the particles in the direction indicated by the arrows in Fig. 4. Near the axis, the force due to gas flow pushes the gas and its remaining particles parallel to the clean gas outlet. This force in the vicinity of the inclined plane is added to the electric force $\boldsymbol{F_{mov}}$ to move the charged particles toward the polluted air outlet.

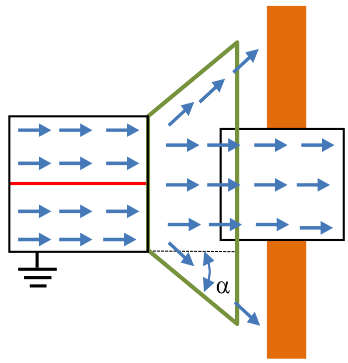

Fig.4. Schematic of wind force vectors

1.3. Third component

The third component concerns the clean air outlet; it is a PVC cylinder that crosses the wall separating the clean interior from the polluted exterior.

2. *Experimental study*

The main objective of this study was to verify the validity and effectiveness of the proposed design.

2.1. Experimental SE-ESP

The first component was a 50-mm long metal cylinder with a 20-mm radius, connected to the ground (Fig. 5a), with a wire placed in the center of the cylinder of 0.1 mm as radius, isolated on the first centimeter only. The purpose of this component is to charge the dust particles.

The second component has a 30-mm long PVC cone, which is inclined by 30° to deflect the charged particles.

The third component comprises a cylinder with a length of 50 mm and a radius of 15 mm, made of either insulating or conductive material, depending on the model. We modified these three parts by varying the length of the wire or by adding another ground or HV electrode to enhance the role of each change made in the distribution of the electrical potential lines.

2.2. Determining the minimum voltage V_C

According to F.W. Peek [21], for a cylindrical configuration, the corona effect begins on the surface of the wire with a minimum value of the electric field $\boldsymbol{E_c}$, given by the following expression:

$$E_C = E_P \cdot \delta \cdot \left(1 + \frac{k}{\sqrt{\delta \cdot R_0}}\right) \quad (1)$$

where: E_C – critical field value in (kV/cm), $E_P=31\ kV/cm$, $k=0.308$ – coefficient, R_0 – wire's radius in (cm), δ – relative air density and is expressed as [21]:

$$\delta = \left(\frac{3.92 \cdot P}{273 + T}\right) \quad (2)$$

where: P – pressure of the air in $(cmHg)$, T – ambient temperature in $(°C)$, $(\delta=1$ for $P=76\ cmHg$ and $T=25°C)$.

Under these conditions, the critical voltage required to create the critical field is given by the following equation [21]:

$$V_C = E_C \cdot R_0 \cdot \ln\left(\frac{R}{R_0}\right) \quad (3)$$

where: V_C – critical voltage, $R=2\ cm$ – cylinder's radius.

The minimum voltage found after the calculation was $V_C=6.70\ kV$.

a) Basic model

2.3. Test validity

The purpose of these tests was to ensure the design's validity and initial effectiveness. Therefore, experiments were conducted on three configurations derived from the basic form as presented in Fig. 5. Various modifications among the model were simple but considerably affected their efficiency. The main aim of these design changes was to reduce the component $\boldsymbol{F_{adh}}$ and to increase the component $\boldsymbol{F_{mov}}$ to direct the electric field toward the dusty air outlet.

The first model is identical to the basic model, with the exception that the wire is extended by 15 mm toward the conical portion (Fig. 5b). The second model is similar to the first model, except that the PVC output cylinder is replaced by a grounded metal cylinder (Fig. 5c). The third model is similar to the second model, but we added a 3-mm radius ring at the wire's end from the same wire (Fig. 5d).

b) First derived model

c) Second derived model

d) Third derived model

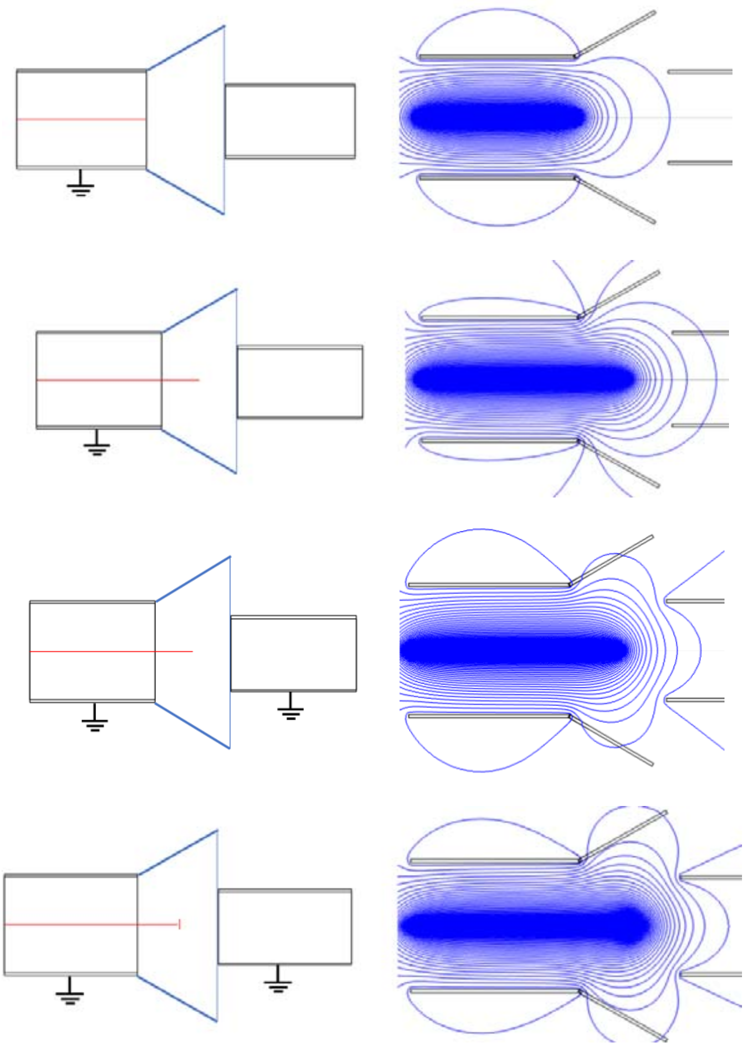

Fig.5. Electric potential lines distribution in the basic model of SE-ESP and the three other derived models

The distribution of the electric potential lines for the four cases was determined using the two-dimensional symmetric axis configuration of COMSOL Multiphysics software (Fig. 5). By applying a negative voltage of 10 kV and air polluted with flour of the order of 60–150 μm with a velocity of approximately 0.5 m/s at the entrance, we obtained encouraging results in the third model, where the quantitative efficiency exceeded 95%. For the first and the second models, we achieved highest efficiencies of 50% and 70%, respectively. The calculation of the total filtration efficiency remains the same for the three derived models from the filters. In fact, it is estimated from a weight measurement method, which is a gravimetric test on a fixed sample of polluting dust whose efficiency is the ratio of the relative weight of the particles arriving through Outlet n ° 9 of fig. 2 intended for clean air over the entire weight of the particles injected at Inlet n ° 1 of the filter. This fractional efficiency is expressed by the following formula [22]:

$$\eta_f(\%) = \left(1 - \frac{m_{out}}{m_{in}}\right) \cdot 100 \tag{4}$$

where: m_{out} and m_{in} – are respectively the masses of particles at the outlet dedicated to the pure air (9) and at the inlet of the filter (1).

Conclusions

We designed a novel model to filter air from polluting particulate. Unlike conventional electrostatic filters, the model does not require an additional removal system for polluting particles once collected and accumulated inside. Furthermore, no container is required to collect the particles. In this novel device, the evacuation is performed automatically, rendering the ESP particularly ideal for introducing clean air from a polluted environment. We made several changes to the prototype until we achieved encouraging preliminary results with a quantum efficiency of 95% for the third derivative model.

The high success of the SE-ESP model can be attributed to three main conditions. First, the electric field of the first component is perpendicular to the wire to properly charge the pollution particles. Next, the electric field component is tangential to the surface of the cone and is as large as possible. Finally, the electric field at the end of the second part must prevent charged particles from entering the dedicated clean air inlet. Therefore, we added a ring to the end of the wire. The preliminary results of this new model motivate us for further complete parametric studies.

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