MATEC Web of Conferences **55**, 05003 (2016) DOI: 10.1051/matecconf/20165505003
ACPEE 2016

Corona Performance in Wire-cylinder ESP with Particle Loading

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Abstract: This paper is aimed at investigating thoroughly the corona performance in the wire-cylinder electrostatic precipitor (ESP) with loading by suspended particles in the exhaust of a diesel engine. The onset voltage of negative corona on the discharge wire is calculated based on the criterion of self-sustained discharge. The ionized field in the ESP is mathematically modeled for calculating the spatial distribution of the space-charge density due to both the ions and the charged particles as well as the components of the electric field including the applied field and the field due to the space charge. This is in addition to the calculation of the current-voltage characteristics of the ESP with particle loading.

1 Introduction

The electrostatic precipitator is the most effective device to collect industrial particulates before escaping into the atmosphere to pollute it. This is why the researchers over the years work on modeling the processes inside the electrostatic precipitors(ESPs) including corona discharge seeking improvement of their performance.

An iterative model employed the finite element method for computing electric potential structure for an assumed charge density distribution and the doner cell method was used to compute charge density structure for an assumed electric field distribution. The model can account for particle loading of the ESP and bipolar ionic species resulting from back-ionization at the collecting electrode [1].

The Poisson's equation was solved in wire-duct ESP with particle loading using the finite difference method for a given ion density distribution. The ion charge density at the boundary of the ionization-zone was evaluated empirically and used to determine the ion-density spatial distribution. The effect of assumed uniform particle charge density on the current-voltage characteristic of the ESP was investigated, where the corona onset voltage increases with the increase of the particle charge density. Subsequently, the ion current decreases with the increase of particle charge density at the same applied voltage [2]. In wire-duct ESP, the effect of particle loading and applied voltage on the mean radius of the ionization zone around the discharge wires was investigated[3].

In wire-duct ESP, the finite element method was used to determine the electric field and current density distributions based on Kaptzov's assumption which was considered valid for each corona electrode[4]. The electric field on the corona electrode surfaces is equal to the corona onset field, given by Peek's formula[5]. Non-justified simplifying assumptions have been additionally introduced

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in the mathematical model: 1) It is supposed that the electric field on the surface of each corona electrode is virtually uninfluenced by the presence of particles. Subsequently, the corona onset voltage is not influenced by the presence of particles. 2) Ionic charge density is also virtually uninfluenced by the presence of particles.

The current-voltage formula for wire-duct ESP was derived where the particle space charge was assumed uniform over the cross-section of the precipitator. This concluded that the onset voltage of corona increases with the particle loading [6].

Simplifying assumptions commonly adopted in the ESP modeling which are justified:

1. Kaptsov' assumption which states that the field at the coronating surface remains constant at the corona onset value as determined by Peek's formula [5] irrespective of the value of the applied voltage.
2. The mobility of ions remains constant as their transit time from the discharge wire to the collecting electrode is so small for the mobility to change with the ions' life time.

Other simplifying assumptions were adopted without justification for the ESP with particle loading:

1) Some investigators [2, 3] evaluated empirically the ion charge density at the boundary of the ionization-zone surrounding the discharge wire in order to determine the ion density distribution.
2) Some investigators [4] assumed the electric field on the surface of the discharge wire is virtually uninfluenced by the presence of particles.
3) Some investigators [4] assumed the ion charge density is virtually uninfluenced by the presence of particles.
4) Some investigators [6] assumed uniform particle space charge density over the ESP cross section.
5) With particle loading, some investigators [7, 8] assumed that the charge acquired by particles is related to the field component due to the ion space charge with no justification.

This motivates the authors to investigate thoroughly the corona performance in the wire-cylinder ESP when loaded with suspended particles in the exhaust of diesel engine.

2 Method of Analysis

The equations describing the electric field and flow of charges carriers (ions and charged particles) in the ESP are the Poisson's equation for the electric field, the equation for current density and the equation of current continuity[9].

Poisson's equation for the electric field is expressed as:

$$\nabla . E = \frac{\rho}{\epsilon_0} \tag{1}$$

where E is the electric field with space charge including corona ions and charged particles, ρ is the total volume charge density of ions and particles and ϵ_o is permittivity of free space.

The total volume charge density is expressed as:

$$\rho = \rho_i + \rho_p \tag{2}$$

where ρ_i is the ion charge density and ρ_p is the particle charge density.

The electric field E is expressed as:

$$E = E_f + E_s \tag{3}$$

where E_f is the electric field without space charge i.e.; the field due to the applied voltage and E_s is the field due to space charge of ions and charged particles.

In a wire-cylinder geometry of the precipitator, the space charge affects only the magnitude but not the direction of the electric field, i.e.;

$$E = \xi E_f \tag{4}$$

where ξ is a scalar which changes over the space between the discharge wire and the collecting cylinder.

From equations (3) and (4), the field E_s due to space charge is expressed as:

$$E_s = (\xi - 1)E_f \tag{5}$$

The equation of precipitator current density is expressed as:

$$J = k_i \rho_i E + k_p \rho_p E \tag{6}$$

where k_i and k_p are the mobility of corona ions and charged particles, respectively.

Equation (6) of the current density is rewritten as:

$$J = k_i E(\rho_i + k\rho_p) \tag{7}$$

where the mobility ratio k is expressed as:

$$k = \frac{k_p}{k_i} \tag{8}$$

The particles are charged by ion-bombardment process, which is the dominant charging mechanism for particles of radii greater than 1 μm [10]. The particle charge density is expressed as:

$$\rho_p = \epsilon_o \lambda E S \tag{9}$$

where:

$$\lambda = \frac{2\epsilon_r}{\epsilon_r + 3} \tag{10}$$

where ϵ_r is the relative permittivity of the particles and S is the particle specific surface.

Assuming the particles are spherical in shape with radius r_p, so S is expressed as:

$$S = 4\pi r_p^2 N_p \tag{11}$$

where N_p is the particles concentration being assumed constant over the cross-section of the particle.

The particle concentration N_p is as expressed as follows:

$$N_p = \frac{Z}{\gamma \frac{4}{3}\pi r_p^3} \tag{12}$$

where Z is the particles weight per unit volume and γ is the specific gravity of the particles.

With the use of equation (4), the particle charge ρ_p density of eq. (9) is expressed as:

$$\rho_p = A\xi E_f \tag{13}$$

where $A = \epsilon_o \lambda$ S is a constant for particles of the same radius and permittivity.

The mobility k_p of the particle with charge q_p is determined by balancing the electric force (=q_p.E) with Stokes drag force (= $6\pi\eta r_p k_p E$) where η is the viscosity of the gas inside the precipitator.

Therefore, the particle mobility k_p is expressed as:

$$k_p = \frac{q_p}{6\pi\eta\, r_p} \tag{14}$$

The particle charge q_p is expressed as:

$$q_p = \frac{\rho_p}{N_p} \tag{15}$$

Combination of equations (1), (2), (4) and (13) results in the following differential equation, which defines the spatial distribution of the scalar ξ over the space between the discharge wire and collecting cylinder:

$$\frac{d\xi}{dr} = \frac{\rho_i + A\xi E_f}{\epsilon_0 E_f} \tag{16}$$

The continuity equation of the precipitator current density is expressed as:

$$\nabla . J = 0 \tag{17}$$

Combination of equations (4), (7) and (17) results in the following differential equation:

$$\frac{d\rho_i}{d\xi} = -\left(\frac{\rho_i + 2kA\xi E_f}{\xi}\right) \tag{18}$$

Combining of equations (16) and (18) results in the following differential equation which defines the spatial distribution of the ion charge density ρ_i over the space between the discharge wire and collecting cylinder:

$$\frac{d\rho_i}{dr} = -\left(\frac{\rho_i + 2KA\xi E_f}{\xi}\right)\left(\frac{\rho_i + A\xi E_f}{\epsilon_o E_f}\right) \tag{19}$$

The differential equations (16) and (19) are integrated along the radial direction to determine the spatial distribution of ξ and ρ_i over the space between the discharge wire and collecting cylinder. The initial conditions for such integrals are (i) ξ at discharge wire is equal to V_o/V, where V_o is the corona onset voltage determined as explained elsewhere [11] and V is the applied voltage. (ii) The electric field at the surface of the discharge electrode remains constant at the onset value, which is Kaptsov's assumption.

3 Results and Discussions

Figure (1) shows the slight increase of E_s with particle loading when compared with that for the case without particle loading [11]. The integration of E_s along the spacing between the discharge wire and collecting cylinder remains very close to zero. Subsequently, the integration of the electric field E over the spacing between the wire and cylinder is almost equal to the applied voltage which satisfies the Dirichlet condition. The onset voltage V_o' with particle loading exceeds that V_o without particle loading in agreement with eq. (A-2) of Appendix 1.

Figure (2) shows the spatial distribution of the electric field E over the space from the ionization-zone boundary to the cylinder as predicted by eq. (A-1) of Appendix 1 in comparison with that obtained using the present method of calculation. The deviation in Fig. (2) from the present calculated values is attributed to the fact that eq. (A-1) is based on assuming the same particle charge density over the cross section of the ESP.

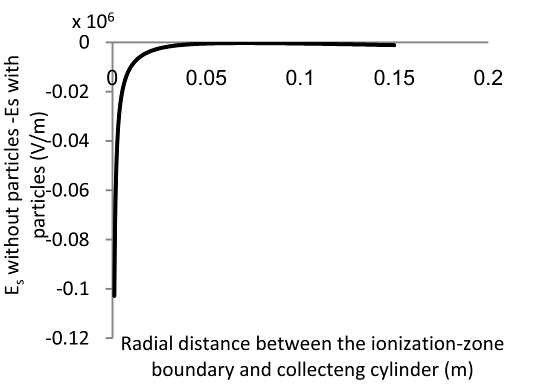

Figure 1: Excess of Es with particle loading over that without particle loading between the ionization-zone boundary and collecting cylinder. r_o = 1 mm, R = 15 cm, V_o' = 30.659 kV and V = 60 kV.

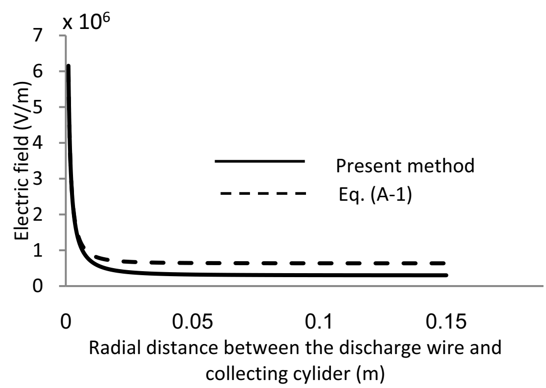

Figure 2: Calculated spatial distribution of the electric field E between the discharge wire and collecting cylinder compared with that obtained by eq. (A-1) for the ESP with particle loading. r_o = 1 mm, R = 15 cm, V_o' = 30.659 kV and V = 60 kV.

Figure (3) shows the spatial distribution of the ion charge density over the spacing between the wire and cylinder with and without particle loading [11]. The spatial distribution of the ρ_p in Fig. (3) follows that of the electric field which charges the particle. This does not support one of the assumptions proposed before [4] which consider no effect of particle loading on the ion charge density. With particle loading, it is worthy to notice in Fig. (3) that (i) ρ_p assumes values almost one order smaller in magnitude than those of ρ_i with particle loading in agreement with previous findings [1] and (ii) the sum $\rho_p + \rho_i$ with particle loading is almost equal to ρ_i without particle loading over the spacing between wire and cylinder. This is because the particles are charged at the expense of ions.

Figure (4) shows how the corona current increases with the applied voltage with and without particle loading. The figure shows a slight increase of the corona current value without particle loading over that with particle loading at the same voltage.

The decrease of the electric field within the ionization zone due to charged-particles field-shielding results in an increase of the onset voltage V_o' with the increase of particle radius r_p as given in Table (1). The corona I-V characteristics of the ESP at varying r_p for the same particle density N_p showed an increase of the corona current with the decrease of r_p due to decrease of V_o'. Such increase of the corona current reaches up to 10 % at applied voltage of about three times the corona onset voltage V_o'.

The decrease of the electric field within the ionization zone due to increase of N_p because of the above-mentioned field-shielding results in increase of the corona onset voltage V_o' as given in Table (2). The corona I-V characteristic of the ESP at varying particle concentration N_p for the same particle radius r_p showed a decrease of the corona current with the increase of the N_p because of the increase of V_o'.

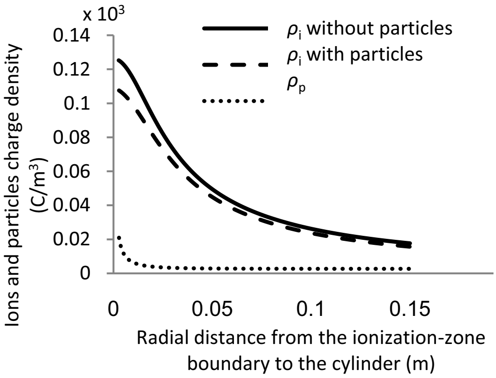

Figure 3: Calculated spatial distribution of the ion and particle charge density values between the discharge wire and collecting cylinder. r_o = 1 mm, R = 15 cm, V_o = 30.659 kV and V_o' = 31.0271 kV and V = 60 kV.

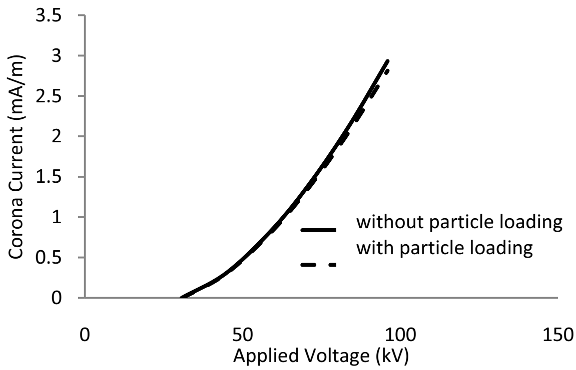

Figure 4: Calculated corona I-V characteristics of the ESP with and without particle loading. r_o = 1 mm, R = 15 cm, r_p = 30 μm, $N_p = 0.094*10^9$, V_o = 30.659 kV and V_o' = 31.0271 kV

Table 1: Calculated increase of the corona onset voltage V_0' with the increase of particle radius r_p at the same particle concentration N_p (=$0.2*0.094*10^9$).

r_p (μm)	10	30	50
V_o (kV)	30.6898	31.57891	33.72505

Table 2: Calculated increase of the corona onset voltage V_0' with the increase of particle concentration N_p at the same particle radius r_p (=30 μm).

r_p (μm)	10	30	50
V_o (kV)	30.6898	31.57891	33.72505

4 Conclusions

1. The ionized field in the ESP is mathematically modeled for calculating the spatial distribution of space charge density due to both the ions and charged particles as well as the components of electric field including the applied field and the field due to space charge.
2. The calculated spatial distribution of space charge density due to charged particles between the discharge wire and cylinder of the ESP with particle loading is one order higher than that due to ions.
3. The current-voltage characteristics are calculated for the ESP with particle loading at varying particle radius for the same particle concentration. The smaller the particle radius, the higher is the corona current at the same applied voltage.
4. The current-voltage characteristics are calculated for the ESP with particle loading at varying particle concentration for the same particle radius. The higher the particle concentration, the smaller is the corona current at the same applied voltage.
5. The calculated onset voltage of corona on the discharge wire of the ESP with particle loading increases with the increase of either the particle radius or the particle concentration.

Acknowledgment

This paper is extracted from a research project sponsored through joint innovative projects fund STDF (Egypt) – IRD (France), project STDF ID-5457. The authors acknowledge such sponsorship.

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Appendices

Appendix 1: Analytical expressions defining wire-cylinder ESP performance with particle loading:

1. Spatial distribution of electric field E:

It has been reported [7]that the spatial distribution of the electric field with space charge E (r) in wire-cylinder ESP is expressed as:

$$E(r) = \sqrt{\left[\left(\frac{r_o}{R}\right)^2\left(E_o^2 - \frac{I}{2\pi\epsilon_o K_i}\right) + \frac{I}{4\pi\epsilon_o K_i(\lambda Sr)^2}\right]e^{2\lambda Sr} - \frac{I}{4\pi\epsilon_o K_i}\left[\frac{2}{\lambda Sr} + \frac{1}{(\lambda Sr)^2}\right]} \quad \text{(A-1)}$$

2. Onset voltage of corona:

It has been reported [6, 7] that the corona onset voltage in wire-cylinder ESP increases with the presence of dust as expressed by:

$$V_o' = V_o + \frac{\rho_p}{4\epsilon_o}R^2 \quad \text{(A-2)}$$

where V_o and V_o' are the corona onset voltage values with and without particle loading.

The expressions (A-1) and (A-2) are based on assuming both particle ρ_p and ion ρ_i space charge density values are independent of position over the ESP cross-section which is not justified. This makes the formulation of these expressions are questionable [6, 7].