The Optimum Operation Conditions for Electrostatic Precipitator in Particulate Emitter Industries

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Abstract–**The performance of the electrostatic precipitator (ESP) is studied theoretically using an advanced simulation model. The theory of the operation of the ESP was presented in the concepts of electric potential and the electric field and their role in creating the corona onset, which initiates the charging of the dust particles through the process of ionizations. The effective design and operative parameters are the main keys which play an important role to achieve good performances with demanded efficiencies. The ESPVI 4.0W computer code which owned and employed by the environmental protection agency of USA is used in this work to examine the effects of all operating parameters on the performance of an assumed ESP example. These calculations show the significance and usefulness of the computer simulations in designing ESPs, testing their operations, and predicting the reasons of the defaults. Discharge electrode spacing, wire-plate spacing, number of electrodes, number of sections, resistivity of dust particles, and particle distribution were studied versus the efficiency of the device. The particle size distribution may lower the performance of the ESP, especially, when it lies in the region where the two-charging method field and diffusion charge are not efficient. However, we conclude that not only good designing parameters are enough to achieve successful electrostatic precipitation process. Such an achievement requires a correlative optimization to be performed between these parameters and the operating conditions.**

Index Terms–**Current density, Electrostatic precipitator, Electrostatic precipitator VI 4.0, Optimum operation, Wire plate geometry.**

I. Introduction

A necessary tool for the electrostatic precipitator (ESP) owners or operators is a means to understand how the unit works; when it is, or is not, functioning properly; how to identify and correct problems; and what options are available to improve its performance.

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The fundamental principle of operation of an ESP is that the particles are passed through an electrical field where they receive an electrical charge. Charged particles are then deflected across the field and collected on a grounded plate. Most industrial ESPs are based on a single-stage approach in which both charging and migration across the field take place within the same set of electrodes [1].

The understanding of electrostatic precipitation has, in recent years, reached a high level. The physics of the electric fields, the charging of particles within the field, their migration velocity and collection, and the effect of the charged particles have become well understood. The mathematics that describes the physics has evolved. The solutions for the ESP mathematical physics have become readily available [2]. However, the process is combined of several activates: Production of an electric field to create corona and ions, charging of the particles by the ions, the space charge effect, migration of the charged particles through the field, and collection and removal of the charged particles [3] (Fig. 1).

The ESPVI 4.0W has been developed to allow the user to accurately predict ESP performance. This model is the result of many separate research efforts that have been drawn together into a close-knit working relationship. It runs on Windows compatible computers.

The ESPVI 4.0W controls the data entry with a menu-structured interface and makes the results of intermediate calculations available to appropriate parts as input data. The outputs are presented in a variety of forms, both tabular and graphical [4]. The ESPVI 4.0W is the latest in a long series of model development activities under the sponsorship of the U.S. environmental protection agency that started in the 1970s [5].

The performance of an ESP can be determined by the voltage–current (V–I) characteristics. The V–I curves under clean air conditions help in diagnosing the electrical problems that occur under various load conditions in an existing precipitator. The electrostatic field in the inter-electrode region is governed by Poisson's and current continuity equations [6]. Several numerical techniques are being employed today, either individually or in combination, for predicting the DC V–I characteristics. It seems a tradition to start with McDonald, *et al.* [7] since they developed the first ever numerical technique based on finite difference method (FDM) but the method proved to be highly time- consuming for larger grid sizes and a simple numerical technique, to solve the governing equations.

FDM was used to solve, both Poisson's and current continuity equations simultaneously with suitable boundary conditions. The electrical conditions, predicted under dust-free conditions, give a reasonable agreement with experimental data. However, this method is less accurate and takes a more number of iterations when compared to other methods [7].

Kallio and Stock [8] developed their approach, which employed finite element method with quadratic interpolation in solving Poisson's equation to yield the electric potential solution and a backward difference method to compute the space charge density from the continuity equation. Furthermore, this method shows better accuracy and faster computation than the pure FDM approach of McDonald *et al.* [7], and the total number of iterations required by FE-FDM was much less than that required for pure FDM.

Adamiak [6] simulated the electrical conditions using a combined boundary element method and method of characteristics (BEM-MOC). The electric potential was computed using BEM, while the charge distribution was found out using MOC. Recently, Rajanikanth [9] introduced what they called a quasi-analytical method, based on solving the current continuity equation by FDM and Poisson's equation by variation principle with the help of Rvachev functions (R-functions).

In further step, Rajanikanth and Thirumaran [10] combined BEM and FDM to do simultaneous solution for governing Poisson's and current continuity equations over a one-quarter section of precipitator, and only a quarter sections in the present BE-FDM [5] because of the symmetry of the wire-plate geometry facilitates.

Kim, *et al.* [11] proposed a theoretical model to predict the collection performance of ESP by considering simultaneously the convection force, the electrostatic force, and the turbulent diffusion process. However, they employed the mass balance equation which contains all the fundamental forces; furthermore, this equation can be solved by the separation of variables method. Al-Daamy [12], in his study, employed an approach close to McDonald and FDM approach and gave a review for these methods.

Experimental studies also were conducted in different levels. Kim and Lee [13] designed and built a laboratory scale single-stage ESP. The problem of the experimental research in the laboratory scale is the dimensions of the studied models. Sometimes, the length and height of these models are not more than one meter, by which researchers unable to produce a good simulation to the real industrial electrostatic precipitators. In Ohio University, an intensive work was going on, namely, MSC research thesis to achieve an optimum design of the discharge electrodes and optimum efficiency [1-3].

The simulated ESP software will help not only to predict the performance and the efficiency of the device but also to troubleshoot the problems. Building and creating this software are intended by companies and agencies who are working in this industry.

II. Theoretical Aspects

The heart of the modern ESP model is the well-known Deutsch equation, which in its rigorous form computes the probability that a particle traveling in the turbulent interior of an ESP will enter the laminar layer at the collecting surface. If the particle entering the laminar layer is charged and an electric field exists at the collecting surface, then its migration velocity assures its collection. This differs from the Deutsch equation used in its non-rigorous form, in which a single pseudo migration velocity, sometimes called a rate parameter, is used to represent all the particles in the gas stream regardless of their size [4].

$$\eta = 1 - \exp(A\omega_e/Q) \tag{1}$$

Where *h* is the efficiency, ω_e is the effective migration velocity, A is the area of grounded collecting electrode, and Q is the actual gas volumetric flow rate.

In the modern computerized model, the Deutsch equation is used in its rigorous form. It requires that all the particles included in the performed calculation should have the same migration velocity. Here, the true migration velocity is required instead of a rate parameter. To handle this requirement, the particle size distribution is divided into a number of narrow size increments, for each of which the migration velocity is computed. Before computation of the migration velocity, the charge of the particles in each size increment is determined. Depending on the particle size, the model uses diffusion, field charging, or some combination of both. In addition, the computation is divided into a number of ESP length increments, usually one for each electrode element. For each of the length increments, the particle charge corrected for charging time and migration velocity are recomputed. The changing electrical conditions from one increment to the next are accommodated in the calculations. Finally, a double summation, for both the particle size and length increments, is performed to give the overall ESP collection efficiency.

A. Production of an Electric Field

In practice, with a negatively energized system, as the electrons rapidly move across the field area, they collide with, and attach themselves to, gaseous molecules to produce negative ions. Any positive ions are attracted toward the discharge element and on reaching the element. There is an abundance of free electrons adjacent to the discharge element. However, the number of free electrons decreases as the distance from the element increases, and there is a corresponding increase in the number of negative ions. Within a relatively short (compared to the distance to the collector electrode) distance from the corona discharge electrode, the free electrons disappear and are completely replaced by the ions. Negative corona is a feature of gases that exhibit appreciable electron attachment and is, therefore, sensitive to gas composition and temperature.

B. Charging of the Particles by the Ions

For industrial ESPs, in which negative ionization is used because of its lower corona initiation voltage and higher

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breakdown potential, particle charging occurs in the area between the active plasma region and the passive electrode surface. As the gas-borne particles enter the space charge region of the field, two charging mechanisms occur: By ion attachment, i.e., field charging and by diffusion charging. Field or impact charging predominates for particles greater than about 0.8–1 μm. Diffusion charging is essential for particles <0.2 μm diameter. Both processes occur in the intermediate size range but neither dominates (Fig. 2). Classical charging theory provides the saturation charge, *q*, for field charging as follows [4]:

$$q=3\pi\varepsilon_0 d2E \tag{2}$$

Where *d* is the particle diameter, ε_o is the permittivity of free space, and *E* is the electric field. Diffusion charging, *Q*, is given by Equation 3:

$$Q=(1/2)dKT/e^2 \tag{2}$$

Where *d* is the diameter, *K* is Boltzmann constant (1.38054×10^{-23}J/K), *T* is the absolute temperature, and *e* is the electron charge. The level of this charge is proportional to the electric field. The presence of back corona gives rise to positive ions in the gas stream, which, in turn, modifies the charge on the particles.

The ESPVI 4.0W computes both the amount of diffusion charge and field charge that each particle size acquires. Bipolar charging is also included to allow ESPVI 4.0W to consider the effects of back ionization when necessary.

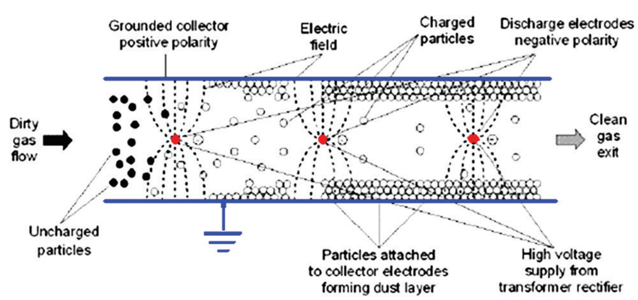

Fig. 1. Basic parallel plate electrostatic precipitator arrangement [3].

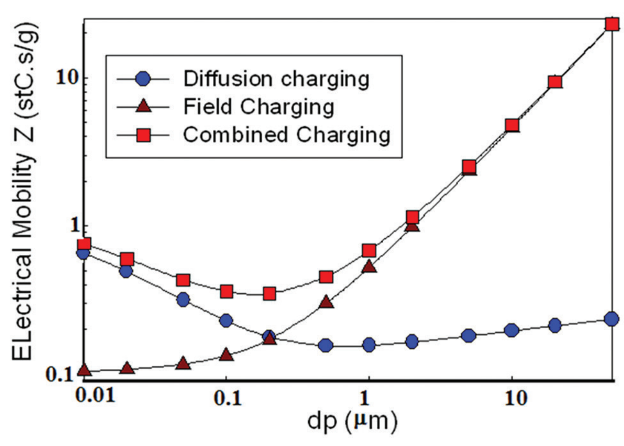

Fig. 2. The field, diffusion, and combined charging as a function of the particle diameters [4].

ESPVI 4.0W divides the particle size spectrum for an ESP (0.07−70.0 μm), which is in the form of a log-normal distribution, into 27 discrete size fractions. For each size fraction, ESPVI 4.0W computes both the diffusion and the field charge levels. As time is a factor for both charging mechanisms, ESPVI 4.0W considers it, as it relates to the velocity of the gases through the ESP, in computing the level of charge. This means that, further, the particle travels into the ESP, and the higher is the level of charge that it acquires, up to its maximum level.

It can be shown that, with good electrical conditions, most field-charged particles reach around 90 percent of their full saturation charge in <0.1 s; the diffusion charging of the particles can take longer depending on the abundance of negative ions that are present. Hence, it can be assumed that, on entering a precipitation field having a typical exposure/treatment time of 3 to 5 s, the particles achieve their maximum charge.

C. Effect of the Charged Particles on the Electric Field

Charged particles entering the electric field within an ESP have the effect of modifying the electric field. For this discussion, the term charged particles, includes electrons, ions and actual particles that have an electric charge on them. Each charged particle has its own electric field. A volume containing a cloud of charged particles, which is called the space charge, has an electric field that is contributed to by the individual particles. The electron component makes only a very small contribution to the space charge because they either travel very rapidly out of the cloud or, more likely, give up their charge to a gas molecule to form an ion. The majority of the ions travel quite rapidly out of the charged particle cloud to the collecting surface, thereby making a small but significant contribution to the space charge. The effect of space charge is to weaken the electric field near the corona discharge electrodes, thereby suppressing some of the corona and its generation of ions. It effectively accomplishes this by raising the corona onset voltage, V_C, as follows [4]:

$$Vc=V+\psi(\rho) \tag{4}$$

Where $\psi(\rho)$ is a function of the space charge, ρ, that elevates the corona onset voltage, *V*, to a new voltage level, V_C. If it increases the corona onset up to the level of the applied voltage, it can effectively shut down the corona. The ESPVI 4.0W does, from first principles, find solutions for Poisson's equation for different ESP configurations and operating conditions. It accurately computes the space charge and the resultant corona suppression from inlet to outlet as the particles are charged and collected.

D. Migration of Charged Particles through the Electric Field

Migration velocity, ω, is the velocity that a charged particle achieves in a quiescent gas. It is a balance between the coulomb (or electrical), viscous, and inertial forces, which leads to Equation 5:

$$\omega=(QE)/(3\pi d\mu)[1-\exp(-3\pi d\mu t)/m] \tag{5}$$

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Where Q is particle charge, E is an electric field, d is the particle diameter, μ is the viscosity, t is the time, and m is the particle mass. The numerator QE is the electrical force acting on the particle. Its denominator, $3\pi d\mu$, is the resisting viscous force. The exponential, time-dependent inertial force is generally of short duration, which does eventually go to zero, leaving the migration velocity in its steady-state form, which is the terminal velocity. However, until it goes to zero, it must be considered since it does affect collection. Once it does go to zero, Equation 5 becomes the terminal velocity that the particle ultimately achieves.

ESPVI 4.0W does explicitly determine the migration velocity, taking into consideration the decrease of the inertial force with time, and apply the correct particle size-dependent Cunningham slip factor. From Equations 2 and 5, once it has achieved its steady-state form, Equation 6 can be derived as follows:

$$\omega=(\varepsilon_0 dE^2)/\mu \quad (6)$$

The significance of this equation is to demonstrate the behavior of particles dominated by field charging. Accordingly, the amount of charge on the particle is proportional to the square of its radius and migration velocity of the particle is increased with the increase of its size. Furthermore, the migration velocity is proportional to the square of the applied voltage. The particles of those sizes, about 0.2–0.8 µm, for which neither diffusion or field charging dominate, will have the lowest migration velocity which is most difficult to collect in an ESP. This is due to the penetration by particle size for an actual ESP. It should be noted that penetration is:

Penetration = 1 - *Efficiency*

For a fundamental determination of ESP performance, such as that embodied in ESPVI 4.0W, the Deutsch equation is used in more scientifically rigorous form. This is done in conjunction with the particle charging migration velocity means discussed earlier.

E. Collection of the Charged Particles

Deutsch's derivation of this equation for the collection of particles in an ESP was done on a rigorous basis [4]. The equation for the efficiency η is given by Equation 7:

$$\eta=1-\exp[-(A_0/Vf)\omega \quad (7)$$

Where A_0 is the area, V_f is the volumetric flow rate of the gas, and w is the migration velocity of the particles. The collection of the particles by the Deutsch relationship does involve the ESP geometry, especially the collector electrode area. Deutsch also considers the gas flow through the ESP.

III. The Input Parameters of the Tested ESP

For ESP modeling with ESPVI 4.0W, the particle size distribution is divided into 27 narrow size segments which are sufficiently narrow to be treated as one specific size for calculating the total charge and migration velocity. The ESP length is divided into a number of short segments, one for each corona discharge electrode. For each of the length segments, the electrical conditions are computed taking into consideration the electrode size and the space charge caused by all of the particles in its portion of the gas stream.

In spite of the communications which we made with technical management in Tasloga factory of cement, in Sulaymaniyah, and with their entire offer to help, we found that the provided information is not enough to perform a complete simulation and reliable calculations. Under these circumstances, we oblige to use set of data from the database of the USA (EPA) to conduct this work. The most important parameters of Gannon factory (plant 6 in SORI database) a have unit of precipitation with gas conditioning system, which is reducing the resistivity of the dust and increasing the efficiency of device. The input data are arranged in Tables I.

TABLE I The Design Parameters of The ESP

Data for ESP			Data for section		
Parameter	Unit	Value	Item	Units	Value
SCA	$m^2/m^3/sec$	65.37	SCA	$(m^2/m^3/s)$	8.171
Plate area	m^2	40973.7	Plate area	m^2	5117.07
Gas velocity	m/s	1.463	Length	M	1.372
Number of sections		8	Wire-plate spacing	m	0.1143
Plate length	M	10.97			
Plate height	M	9.14			
ESP width	M	46.63	Stack diameter	m	6.10

ESP: Electrostatic precipitator

TABLE II Gas Properties in the Assumed ESP

Parameter	Unit	Data value	Parameter	Unit	Data value
N_2	%	70.7	Gas Temperature	(K)	450
O_2	%	7.0	Gas Volume	m^3/sec	626
CO_2	%	14.3	Gas Pressure	(kPa)	1.02E02
H_2O	%	7.9	Gas Viscosity	(kg/ms)	2.40E-05
SO_2	ppm	7.660E-02	Gas mobility	(m^2/Vs)	9.73E-05
SO_3	ppm	3.100E-04			

ESP: Electrostatic precipitator

TABLE III
The Operating Voltages And Electrical Parameters For Assumed ESP

Section	1	2	3	4	5	6
Voltage	40800	40000	40400	42200	38500	39000
Current density A/cm^2	2.38E-4	2.85E-4	2.78E-4	2.85E-4	3.56E-4	3.75E-4
Current *A*	1.218	1.458	1.423	1.458	1.822	1.919
Starting voltage *V*	0	0	0	0	0	0
Peak to average voltage	1.319	1.374	1.326	1.270	1.522	1.530
Maximum voltage V	45000	45000	45000	45000	45000	45000
Maximum peak voltage V	63000	63000	63000	63000	63000	63000
Maximum current A	1.5	1.5	1.5	2.0	2.0	2.0
Resistivity Ohm-m	2.8E+8	2.8E+8	2.8E+8	2.8E+8	2.8E+8	2.8E+8

ESP: Electrostatic precipitator

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In Table I, we include the designing parameters, such as the specific collection area (SCA), which can define the collecting plate area which is required to for each 1 m^3/sec of the flow, the dimensions of the unit, (length, width, and height), the total area of the plates and the diameter of the chimney (stack), gas velocity, and the number of sections. The sectionalization has advantages to improve the performance and prevent the total shut down of the device. Gannon constructed with eight sections. The data of each section (field) are also included in Table I.

A. Gas Property Data

Gas composition and properties are affecting the whole production process in many aspects, such as the explosion hazard (if the ratio of O_2 and CO is higher than the safety level), the contribution of H_2O and SOx in the corrosion of the structure of the device and its components. Also, there are environmental restrictions on the emission concentration of NOx and SOx to the environment. The physical properties of gas such as volume, pressure, and temperature have direct involvement in the design of the unit and its performances. These parameters are arranged in Table III.

B. Voltage and Current Settings

The electrical operating parameters such as applied voltages (HV) on the discharge electrodes (wires), maximum voltage allowed, maximum peak voltage, maximum current, current, and current density at each section (field) in the ESP are tabled in Table IV. Further parameters have to be included in the simulation such as dust resistivity. However, in ESP, a huge and dusty macroscopic system, employing physics with microscopic phenomena, demands an efficient mathematical model, very good design, and first class expensive technology. Its master key is the experience which makes all these advantages worth their offers.

IV. RESULTS

ESPVI 4.0W has been used for obtaining results related to space charge, current densities, particle size through migration velocity, and efficiency. This model is a full simulation to the ESP, treats the whole process, and predicts the overall performance to indicate the limitations and faults if occurred.

A. Current Density and Space Charge Through High Voltage

The relation of current density with the applied high voltage obeys the sequence of the charging operation, starting with the corona onset limit, as a minimum voltage could start the emission of electrons, then the ionization, and the particle charging. These processes begin at voltage higher than the V_C. Fig. 3 show the results for six sections. First section starts with a higher voltage than others. On the other hand, the second section starts with a voltage which is lower than that of the first section but higher than that of the third section. This sequence applies to the third field, fourth field, and so on. For the same voltage, the current densities grow in the direction to the last section. Space charge starts low in the low applied voltage (greater than V_c,) and grows till reaching maximum value and then slowly will drop when the voltage increases. Fig. 4 demonstrates this description for the first section. An interesting image can be noticed in the other sections, and this is different in many aspects such as the line does not have maximum as in the first section and it is lower in value. As we move to the outlet, the level of space charges gets lower and lower. More details are presented in Smail [14].

B. The Migration Velocity of Charged Particles

In Fig. 5a, the migration velocity of the charged dust particles is shown for different spacing of discharge electrodes. It is readable that these velocities increase as the distance between two electrodes is increased, which can be explained by the profile of electric field distribution in the path of the particles. The current density as a function of the discharge electrodes spacing is presented in Fig. 5b. In both cases, linear relation is present. The relationship between the migration velocity and the spacing of wire- plate is shown in Fig. 6. It is quite clear that these velocities are decreased as the spacing between wires and

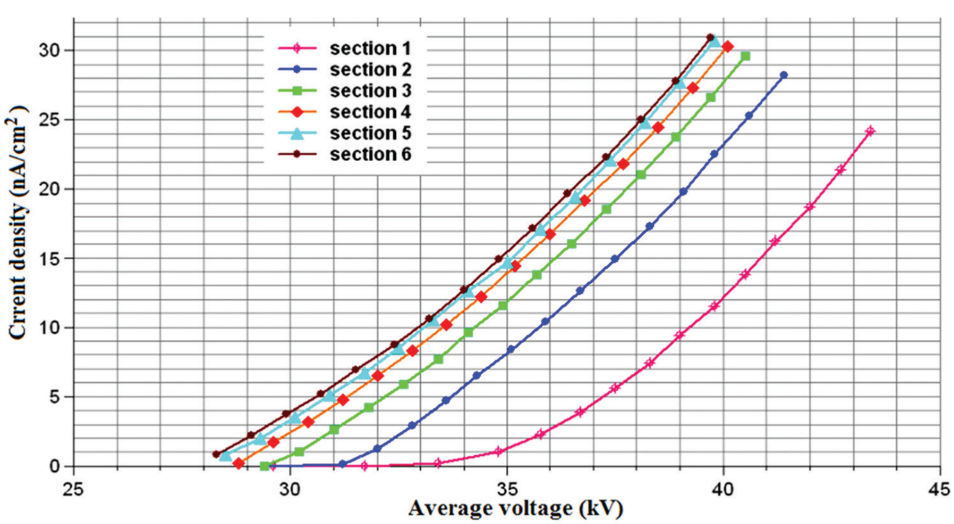

Fig. 3. Current density versus applied high voltage in electrostatic precipitator with six sections.

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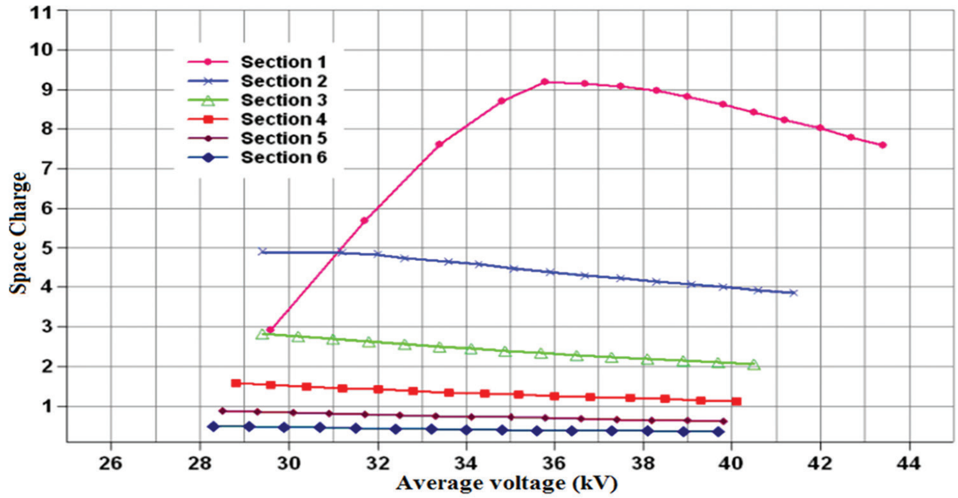

Fig. 4. The space charge versus high voltage in electrostatic precipitator with six sections.

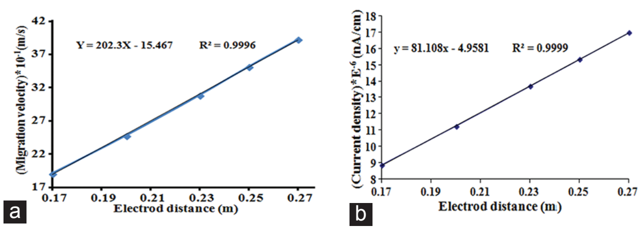

Fig. 5. The migration velocity (a) and current density (b) as a function of the electrodes distance.

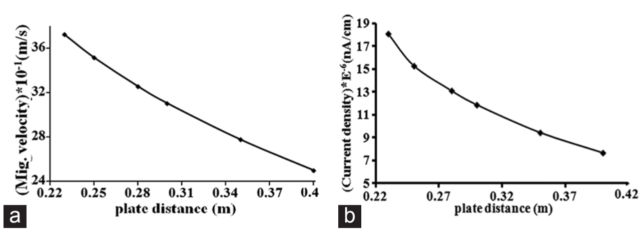

Fig. 6. (a) The migration velocity of charged particles as a function of the wire-plate distance (b) The current density as a function of plate distance.

TABLE IV The Report of ESPVI 4.0w Overall Results For Gannon1 Precipitator

Criteria	Rappers on	Rappers off
Efficiency	99.94%	99.98%
Penetration	0.06%	0.02%
Emissions	2.64 mg/m^3	0.83 mg/m^3
	4.39 mg/m^3	1.38 mg/m^3
PM10	1.83 mg/m^3	0.67 mg/m^3
PM2.5	0.64 mg/m^3	0.55 mg/m^3
Opacity	1.4%	0.9%

Rapping contribution=68.7% of total emissions

the collecting plate increased. However, this can be overcomed by increasing the high voltage on the discharge electrodes.

C. SCA

It has been noted from the designing parameters that the SCA (the area of collected plate required for each m^3/s of the gas flow) is affecting the efficiency of the ESP; therefore, any increase in the collecting plate area will enhance the efficiency (Fig. 7). This problem has to be carefully considered since that will influence the cost of process economically.

D. Sectionalizing

Sectionalizing in ESP devices is one of the important designing parameters since it represents two effecting parameters, the total collecting area and the number of power supplies, if each section is fed independently. These two parameters are increasing the overall efficiency in one hand and preventing the system from being out of service, if one of the power supplies is off. The effect of the sectionalizing is presented in Fig. 8.

E. ESP Height and Length

The ESP height and length are directly affecting the specific collection area (SCA). However, increasing the height of the ESP will increase the efficiency of the device by a reasonable margin when an improvement is needed. Fig. 9 shows the efficiency versus the plat height. The improvement in efficiency will reach its saturation at height around 10 m.

The effect of ESP length causes a fast change in efficiency till reaching the steady state. The length of plate or ESP means the treatment time at which the dust particles are subjected to the influence of the electric field, practicing the charging, and the collecting processes (Fig. 10).

F. The Particle Size Role on Efficiency

Fig. 11 shows the ESP efficiency (rapper off and rapper on) as a function of the particle mean diameter, which in fact reflects the suitability of particle charging methods (field and diffusion charging). Therefore, we can notice that efficiency is high in the diameter range where the diffusion charging process is efficient (small particle size). The same thing can be said about the region of the field charging method domination (large particle size). In the region where both methods are not efficient, the efficiency is low. More details are presented in Smail [14].

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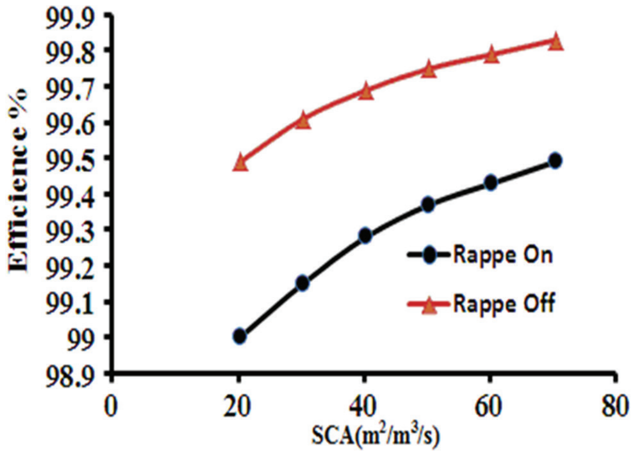

Fig. 7. The efficiency of the electrostatic precipitator in particulate as a function of the specific section area.

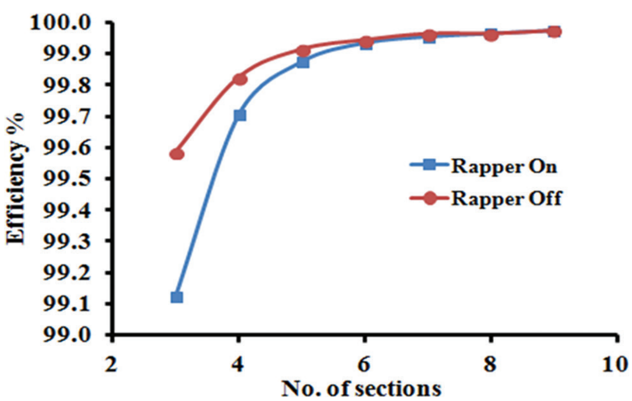

Fig. 8. The efficiency of the electrostatic precipitator in particulate as a function.

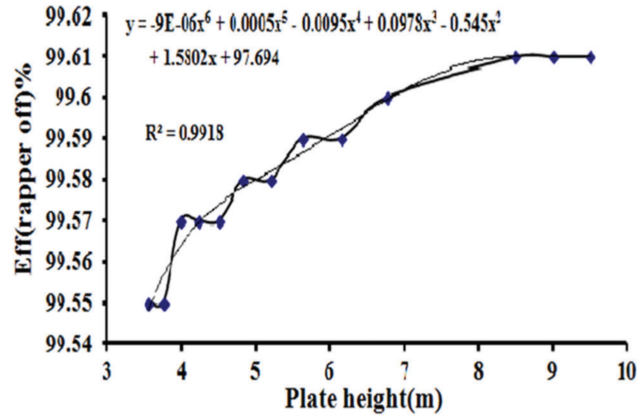

Fig. 9. The efficiency of the electrostatic precipitator in particulate (ESP) (rapper on) as a function of the height of the ESP.

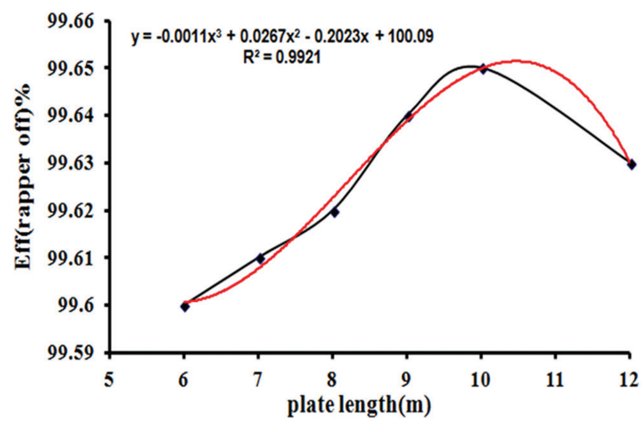

Fig. 10. The efficiency of the electrostatic precipitator in particulate (ESP) (rapper on) as a function of the length of the ESP.

G. The Particle Size through the Migration Velocity

The relationship between the particle size and the migration velocity of charged particles to the collection plates is shown in Fig. 12. The behavior of migration velocity is analogous to the behavior of the efficiency since their values are decreased with the increase of particles size. For instance, whenever the radius of the particles is around 0.5 µm, which is the range where the charging process is very weak, the migration velocity, has attains a minimum value. As the particles become larger than 0.5 µm, the field charging becomes effective and the migration velocity starts to increase again to reach a high value in largest size because of that the larger particles accommodate larger electric charge.

H. The Penetration

As a sequence of the role of particle size on efficiency of the ESP and its overall performances, the penetration reflects the badness of particle charging methods (field and diffusion charging) and the weakness of the efficiency of the device. Therefore, we see that penetration is low in the diameter range where the diffusion charging process is efficient (small particle size). The same thing can be said about the region of the field charging method domination (large particle size). However, in the region where both methods are not efficient, the penetration is high (Fig. 13).

VI. Overall Results

The overall results contain mainly the efficiency of the system under investigation, the penetration, opacity, and PM10 and PM25 limits in both situations where rapping system is on and off. In Table IV, these results are shown. The data show that the efficiency, penetration, emission, and opacity are better when the rapping system is off. However, this price has to be paid in short-term performance, but the advantages of the rapping system are greater than its disadvantages; furthermore, no ESP device can function probably without rappers (more details can be found in Smail [14]).

VII. Conclusions

To observe the mathematical model, performance in presenting full-scale ESP operation is a goal to be achieved, since the testing of ESP operation in practical manner even on the laboratory scale is not simple task for many reasons; Some of these reasons are: The cost of implementing

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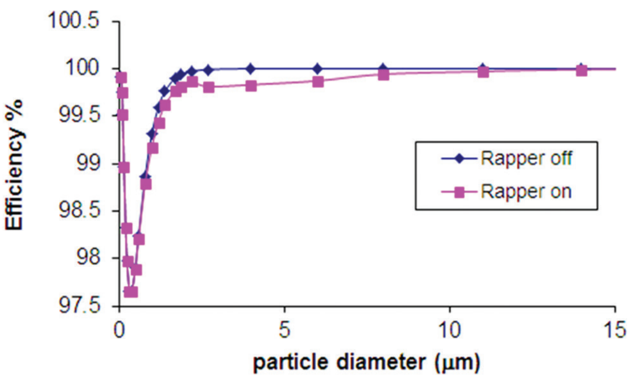

Fig. 11. The collection efficiency (rapper off and on) as a function of particle mean diameter.

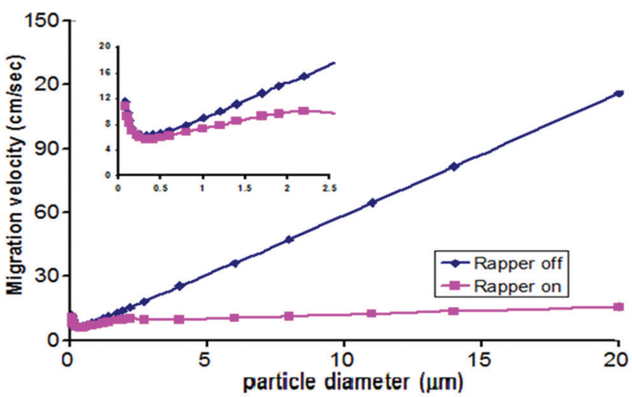

Fig. 12. The migration velocity as a function of the particle diameters.

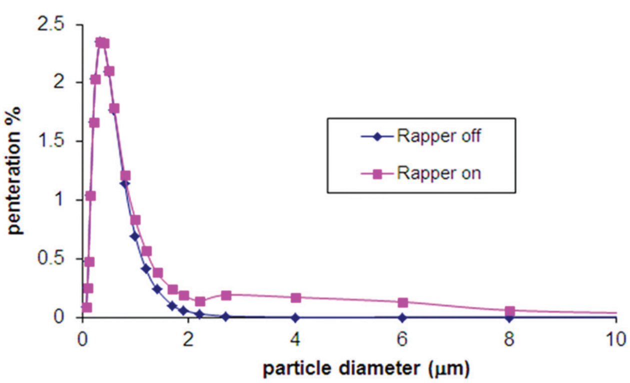

Fig. 13. The penetration as a function of the particle diameters.

such investigation. The ESP system cannot be watched or monitored closely for every single parameter involved in the process, especially during the operation. This is because of the dusty environment, the high temperature and the high voltage danger. Several effective parameters have to be measured or tested outside the site such as the composition of gases, the row materials and the electrical resistivity of the dust. For many other reasons, it seems that the need for software, which may take in account all the designing and operating parameters, is crucial. Therefore, the ESPVI 4.0W software was employed, and to observe its performances, an example of wire-plate type ESP is analyzed. It may be concluded that, with a rich database of the ESP, a full calculation can be made concerning the electrical properties, operation conditions, fault existence, and performance. Combining the computer simulation technique with a wise experienced judgment to its output can give a successful and economical tool for designing and testing the performance of the new electrostatic precipitators. This can also provide continues investigations on the preventive maintenance in the running precipitators. However, from this overall conclusion, several specific derivations related closely to the conditions of operation may be pointed out:

1. The increase of high voltage will increase the current density and the total secondary current which results in increasing the efficiency, unless that the spark rate or the arc crossover violates the operation. In many cases, the increase in current density or the total secondary current is not combined with good efficiency due to what so called the intermittent in the device or to the existence of back corona in the ESP.
2. To produce a given current, higher operating voltage is required in the first section than in the other sections. This is because of the high space charge density in this section, which is due to the high level of dust particles concentration in the gases at the inlet of the ESP. Space charge will produce electric field imposing the original field and persist the generation of corona. Increasing the high voltage may overcome this problem and enforce the charges to be driven to the collecting plate.
3. The particle size distribution is an important contributor to the efficiency of the device, accordingly, as example if the most of particles are in the range of 0.5 µm, then high efficiency cannot be achieved, since the charging of these particles is not sufficient neither in field charging method nor in diffusion charging method. The migration velocity also has lower values for particles with diameter around 0.5 µm and has higher values for particles with higher diameter.

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References

[1] B. Liao, "The Membrane Vibration and the Dust Removal Efficiency of the Membrane Based Electrostatic Precipitator," M.Sc. Thesis, Ohio University, 2003.

[2] W. Khan, "Moving-Membrane-Based Electrostatic Precipitator," M.Sc. Thesis, Ohio University, 2001.

[3] C. Junhong, "Direct Current Corona-Enhanced Chemical Reactions," Ph.D. Thesis, Minnesota University, 2002.

[4] K. Parker and N. Plaks, "U. S. Environmental Protection Agency," Electrostatic Precipitators (ESP) Training Manual. EPA-600/R-04-072, Jul, 2004.

[5] U. S. Environmental Protection Agency, "Operation and Maintenance Manual for Electrostatic Precipitators," EPA 625/1-85/017, 1985.

[6] K. Adamiak, “Simulation of corona in wire-duct electrostatic precipitator by means of the boundary element method,” *IEEE IAS Annual Meeting,* vol. 66, pp. 610-615, 1991.

[7] J. R. McDonald, W. B. Smith, H. W. IIIrd Spencer and L. E. Sparks, “A mathematical model for calculating electrical conditions in wire-duct electrostatic precipitator devices,” *Journal of Applied Physics,* vol. 48, pp. 2231-2243, 1977.

[8] G. A. Kallio and D. E. Stock, “Computation of electrical conditions inside wire-duct electrostatic precipitators using a combined finite-element, finite-difference technique,” *Journal of Applied Physics,* vol. 59, pp. 1799-1806, 1986.

[9] B. S. Rajanikanth, “Studies on the Voltage-Current Characteristics of Plate-Type Precipitator Geometry under Combined dc/pulse Energizations,” USA: Proceedings of IEEE IAS Annual Meeting Michigan, pp. 725-729, 1991.

[10] B. S. Rajanikanth and N. Thirumarah, predication of pre-breakdown V-I characteristics of an electrostatic precipitator using a combined boundary element-finite difference approach, *Fuel Processing Technology*, vol. 76, pp. 159-186, 2002.

[11] S. H. Kim, H. S. Park and K. W. Lee, “Theoretical model of electrostatic precipitator performance for collecting polydisperse particles,” *Journal of Electrostatics*, vol. 50, pp. 177-190, 2001.

[12] F. K. Al-Daamy, “Mathematical Model for Prediction of Pre-Breakdown V-I Characteristics of An Electrostatic Precipitator,” PhD Thesis Baghdad University, 2007.

[13] S. H. Kim and K. W. Lee, “Experimental study of electrostatic precipitator performance and comparison with existing theoretical prediction models,” *Journal of Electrostatics*, vol. 48, pp. 3-25, 1999.

[14] J. M. Smail, “Optimum Operating Conditions for Electrostatic Precipitator (ESP) in Particulate Emitter Industries,” MSc Dissertation Koya University, 2008.

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