Journal of Kerbala University , Vol. 6 No.2 Scientific. 2008

High Temperature-High Pressure Effect on Performance of an Electrostatic precipitator

تأثير درجة الحرارة و الضغط على كفاءة المرسب الكهروستاتيكي

Fadhil.K.Fulyful

Abstract:

This paper presents a finite difference numerical model to calculate the effect of high temperature-high pressure on V-I curves for negative corona discharge of an electrostatic precipitator . The simultaneous solution for the governing Poisson's and current continuity equations helps in predicting the voltage –current characteristics of precipitator ,the results at atmospheric conditions are considered as a reference. Electrical characteristics were evaluated for an operating of (1,2,3and 4bar)pressures and temperatures (293,400,500,600 and 700 K).The numerical results are compared with experimental data from the literature, and the agreement is excellent.

الخلاصة:

يعرض هدا البحث نموذجا رياضيا لحساب تأثير درجة الحرارة و الضغط على منحنيات الفولتية- التيار للمرسب الكهروستاتيكي بالاعتماد على التفريغ الهالي السالب ، تم حل معادلة بواسون ومعادلة استمرارية التيار سوية للتنبؤ بخصائص الفولتية- التيار للمرسب ،وتم اعتماد النتائج عند الظروف القياسية كمصدر للمقارنة.في هذا البحث تم حساب الخصائص الكهربائية للمرسب في درجات الحرارة (293,400,500,600 & 700 K) والضغط (1,2 ,3& 4 bar) أيضا تم مقارنة النتائج الحسابية مع النتائج العملية وكانت المقارنة مقبولة إلى حد ما.

1-Introduction

Electrostatic precipitator (ESP) is the most widely used device for particulate emission control .ESP is a physical process by which particles suspended in gas stream are charged electrically ,and under the influence of electric field are separated from the gas stream .The precipitation system consists of appositively charged collecting surfaces and a high voltage discharge electrode wire are placed centrally between the plates. A corona discharge, occurs close the negative electrode, ,setting up an electric field between the emitter and the charged surface. The voltage-current (V-I) characteristics are one of the major diagnostic tools being frequently used to monitor an ESP's performance. Typical new equipment design efficiencies are between 99and 99.9%[1].But several factories determine ESP collection efficiency, ESP size, maximizing electric field strength ,dust resistively, gas temperature ,chemical composition and particle size distribution[2].The most economical design and operation of particles fall within certain desired limits. If the resistivity is low, particles give up their charge too easily and become re-entrained in the gas flowing past the collecting electrode .On the other hand ,high resistivity particles cannot lose their charge upon reaching the collector electrode because of low conducting of the material deposited earlier. As
a result , the effective field strength is reduced and the efficiency falls.

Particle resistivity can be controlled in many cases by selecting the proper operating temperature or by injecting water to reduce the resistivity. The disadvantage of injecting water is the increased complexity of the wash and the fact that the collected slurry must be handled more carefully than a dry product ,adding to the expensive .

Thomas and Wong [3] studied the effects of temperature and pressure on electrical characteristics of ESP using stainless and platinum wires . They commented that the corona is affected by electrode material but did not quantify the effect.

The variation in resistivity with changing gas temperature for six different industrial dusts was discussed in (U.S.Environmental Protection Agency 1985) [4] For most dusts, resistivity will decrease as the gas temperature increase.

George Rinard *et al*. [5] measured the electrical operating characteristics and collection efficiencies for an operating pressure of (6.4 bar) and temperature near 870 ° C with both negative and positive corona of tube type ESP. In positive corona the curves were spark-limited and with negative corona the maximum voltage was limited by the power supply.

Operating gas temperature of the dust is key factor influencing dust resistivity and must be carefully considered in the design of an ESP Awma [6].

Junhong Chen *et al*. [7] developed a numerical model of the negative DC corona plasma in a dry air.A parametric study is conducted to examine the effects of linear current density (0.1-100 μA per cm of wire length), wire radius (10-1000 μm), and air temperatures (293- 800K) on the distribution of electrons and the Townsend second ionization coefficient, in the negative corona ,energetic electrons are beyond the ionization boundary and the number of the electron is greater than in the positive corona .The number of electrons increases with increasing temperature.

A numerical model developed by Biskos *et al*. [8] to describe the performance of the ESP is used to predict the behavior of the charger when some operating conditions are changed, the numerical model show better agreement with the experimental results at sub-atmospheric pressure. It is shown that greater ion concentrations are achieved at lower pressure.

2-Description of the Negative DC Corona Discharge

Several things happen very rapidly (in a matter of a millisecond) in the small area around the discharge electrode. Figure (1) illustrates the negative polarity.High negative voltage is applied to the small radius wire and the plate or cylinder is grounded. A high negative voltage is applied to the small radius wire and the plate or cylindrical is grounded. The corona discharge is initiated when the electric field near the wire is sufficient to ionize the gaseous species .The minimum electric field in a dry air is a function of the wire radius,the surface roughness of the wire, air temperature and pressure[9].The corona discharge is normally used at atmospheric pressure. Negative corona is only possible in electronegative gases,such as oxygen, water vapor and carbon dioxide. It dose not occur in the pure gases such as nitrogen ,hydrogen,helium and argon that have no affinity for electrons.

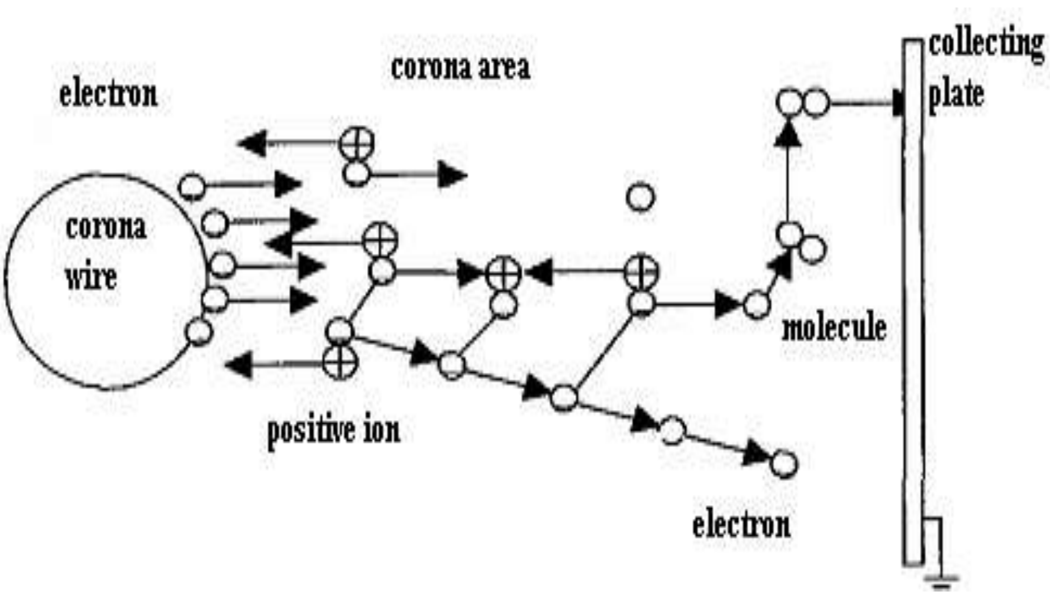


Figure (1) Corona Generation[7]

In contrast to the uniform positive corona discharge ,negative corona discharge appear as discrete points or tufts along the wire .At voltages near the corona onset voltage , only a few tufts appear .They are irregularly spaced along the wire and preferentially appear at imperfections on the surface .As the voltage is increases and the distribution of tufts becomes more uniform[10] .

Seed electrons to initiate the ionization process are produced by naturally occurring ionization events . The free electrons produced in the initial ionization process are accelerated away from the wire in the imposed electric field .Inelastic collisions of electron and neutral gas molecules produce more electron –positive ion pairs in a self-sustained process referred to as the electron avalanche[11]. Secondary electrons to sustain the discharge may be produced by photoemission from the discharge electrode ,bombardment of the discharge surface by positive ions or photo ionization in the gas[12] .The mean kinetic energy of ions in the corona plasma is on the order of (0.01- 0.1ev). These ions are not energetic enough to knock out electrons from the electrode .On the other hand ,short –wavelength photons emitted in the corona discharge are energetic enough to either ionize the gaseous species or to extract electrons from the electrode surface . Since the work needed to remove electrons from the electrode surface (approximately 4 to 5 eV [13] for metals most likely to be used in corona discharge devices) is considerably less than the ionization energy of oxygen and nitrogen molecules (12.06 eV for O_2 and 15.6 eV for N_2[13]) the yield of photoelectrons from the electrode surface is mach higher than that from the gas .As a result ,the most significant mechanism for the generation of the secondary electrons is photoemission from the discharge electrode surface[14].The yield of photoelectrons depends on the wavelength of photons as well as the work function of the discharge electrode material.

3-Mathematical Model

The mathematical analysis is perform by solving simultaneously Poisson's and current continuity equations ,by Finite Difference Method.

The equations describing the potential distribution and charge density are obtained from the following [15].

$$\nabla^2 V = -\frac{\rho}{\varepsilon_\circ} \quad (1)$$

$$\nabla \cdot J = 0 \quad (2)$$

$$E = -\nabla V \quad (3)$$

$$J = \rho b E \quad (4)$$

where

V= applied voltage (kV)

$\rho =$ space charge density (Coul./m^3)

$\varepsilon_\circ =$ permittivity of air (F/m)

J = current density (A/ m^2)

E= electric field (V/m)

$b =$ ion mobility(m^2/V.s)

Equations (1) & (2) can be simplified as

$$\nabla(\varepsilon_\circ \nabla V) = -\rho \qquad (5)$$

$$\nabla(\rho b \nabla V) = 0 \qquad (6)$$

Alternatively Equations(5) & (6) can be combined to produce an integral expression for the charge density between two positions on the grid

$$\rho_2 = \left[\frac{1}{\rho_1} + \frac{1}{\varepsilon_\circ} \int_1^2 \frac{ds}{E} \right]^{-1} \qquad (7)$$

the electric field can also be calculated from eq. (5)

The three boundary conditions needed for the solution of the above system are the value of the potential (V) on the emitter electrode ,the zero potential on the collector surface ,and the corona onset gradient on the emitter electrode ,E_{on} as given by Peek's formul [7].

$$E_{on} = A\delta + B(\delta / a)^{0.5} \qquad (8)$$

where a is the wire radius (m) , δ the air relative density and A,B empirically determined coefficient

The following general assumptions are adopted in addition to Peek's formula : steady state conditions, negligible ion diffusion and zero thickness of the ionization zone.

The simplified governing Equations in the steady-state plasma region are conservation of charge for positive ion, negative ion and electrons given by Eqs. (9-11), respectively and the simplified Maxwell's Equation (12), which relate the electric field to the charge carrier number densities .

$$\frac{d(n_p \mu_p E)}{dx} = -\chi n_e \mu_e E \qquad (9)$$

$$\frac{d(n_n \mu_n E)}{dx} = \beta n_e \mu_e E \qquad (10)$$

$$\frac{d(n_e \mu_e E)}{dx} = (\chi - \beta) n_e \mu_e E \qquad (11)$$

$$\nabla \cdot E = -\frac{e(n_p - n_e - n_n)}{\varepsilon_\circ} \qquad (12)$$

where

n_p, μ_p = number density and mobility of positive ions

n_n, μ_n = number density and mobility of negative ions

n_e, μ_e = number density and mobility of electrons

$\chi, \beta =$ the ionization coefficient and the attachment coefficient of electrons.

In the continuity Eqs.(9)&(11) recombination and diffusion are neglected because the gradient in the electron number density distribution is small . The ionization coefficient(χ) ,attachment coefficient (β) and the mobility (μ_e) of electrons depend on the magnitude of the reduced electric field. Empirical correlation for (χ) are obtained by modifying the expressions provided by Ryzko [13] to incorporate the dependence on neutral density (N)

$$\frac{\chi}{N} = 3.63\times10^5 \exp\left(-1.68\times10^7 \frac{N}{E}\right) 1/m \quad for E \le 45.6\times10^5 \, V/m \qquad (13\ a)$$

$$\frac{\chi}{N} = 7.36\times10^5 \exp\left(-2.01\times10^7 \frac{N}{E}\right) 1/m \quad for E > 45.6\times10^5 \, V/m \qquad (13\ b)$$

This modification allows us to in corporate the effects of gas temperature on the transport properties.Only one boundary condition is required for each of Eqs.(7, 9-11).The boundary condition for Eq (7) is specified at the outside boundary of the corona plasma, where the density of positive ions is negligible . In this paper a zero density ions is assumed

$$n_p(r_0) = 0 \qquad (14)$$

Where r_0 = radius of the outside edge of the corona plasma(m)

The number density distribution of electron is not sensitive to specification of this boundary condition . The distribution of electron number density did not change when the positive ion density at the plasma boundary was varied from (0 to 10^{10} m^{-3}) [7] .

The boundary condition for the negative ion density distribution.Equation (9) is specified at the wire surface where the density of the negative is assumed to be zero

$$n_n(\alpha) = 0 \qquad (15)$$

where (α) = wire radius (m)

This boundary condition is justified by the fact that the secondary electrons emitted from the discharge electrode surface do not have sufficient time to form negative ions near the surface .Specification of a boundary condition for Equation(10) requires knowledge of the number of electrons at the wire surface .This value is not known and may be a function of electrode material and surface condition .Then the number of electron based on a specified current .At the outside edge of the corona plasma ,current is carried by electrons and negative ions .Thus, the number density of electrons can be determined as

$$n_e(r_0) = \frac{J(r_0) - e n_n(r_0)\mu_n E(r_0)}{e\mu_e(r_0)E(r_0)} \qquad (16)$$

where $J(r_0)$ the surface current density of the plasma

Eqs. (1-7) together with boundary conditions (8) and (9-12 ,14-16) are solved using the Finite Difference Scheme.

4- Result and Discussion

The predictions were made based on the parameters values were given by[17] .The V-I characteristics are determined for five gas temperature (293,400,500,600 and 700K) ,gas pressures(1,2,3 and 4 bar).These values are the ranges commonly used in DC corona [7] .In addition ,the distribution of ion number density is evaluated for the same values of temperature and pressure ,the effect of temperature and pressure on the charging time of particle are also calculated at number density 1.5×10^{12} (ion m^{-3}) and the ion mobility of 2.0×10^{-4} m^2/V.s for all cases.

4.1Effect of temperature on the V-I curves

The electrical operating point at an ESP is the value of voltage and current at which the ESP operates .Because of the importance of temperature in the characterization of electrical characteristics ,V-I curves is plotted in Fig.(2) for different value of temperature , the plot illustrates that the current density level increase at the same applied voltage , the corona onset voltage is decreased as temperature increase due to the fact that the mean free path of ions increases with temperature . The figure shows the comparison between V-I curves in case of different temperature and the case of dust free condition (T=293K) ,also the spark over is a function of temperature.

4-2 Effect of pressure on the V-I curve

Fig.(3) shows the effect of pressure on V-I curves. It is shown that lower current density obtained at greater pressures .The corona wire –voltage remains unchanged ,the electrical mobility increases with decreasing pressure. Spark over voltages for higher pressure could not reached.

4-3 Effect of temperature on the resistivity

Resistivity of dust is an important phenomenon in the inter-electrode region where most particles charging takes place .Resistivty of dust is found to be minimum in the temperatures (400 to 700 K) as shown in the fig(4),and maximum in the temperatures (293-400K).It is well known that high resistivity dust causes a phenomenon called back corona which reduces collecting efficiency.

4-4 Effect of temperature on the ion number density

The dependence of the ion number density on temperature is evaluated , results are from (293 to700 K) plotted in fig(5) ,the ion number density decrease as the temperature increase due to the fact that the mean free path of ion depends on temperature. The high temperature determine the rapidity of charging ,as shown in the fig(6) .The rise in temperature creates reduction in charging time ,the effect of pressure on the time charging is plotted in fig (7),for applied voltage (25kV) the charging time increases with increasing pressure

4-5 Distribution of potential along the wire - plate line

Fig.(8) shows the variation of the potential from wire to plate for Kallio's [14] ESP geometry.The curves show different value of voltages (25,30,35,40,45and 50 kV) .Higher the potential ,higher will be the magnitudes of current densities . It is also seen that there is no change in the shape of these profiles .

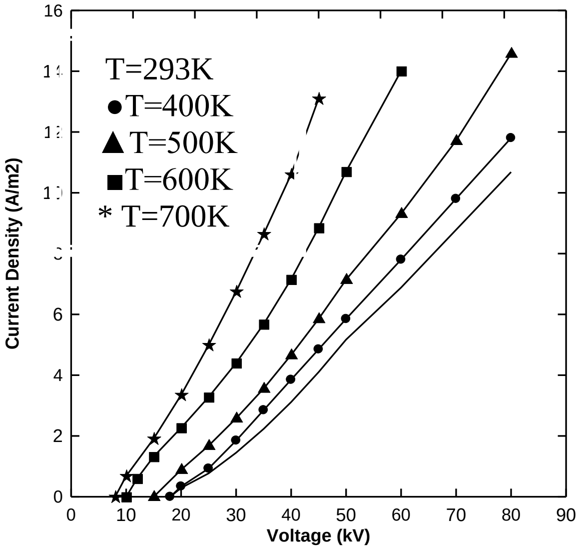


Fig.(2)effect of temperature on V-I curves

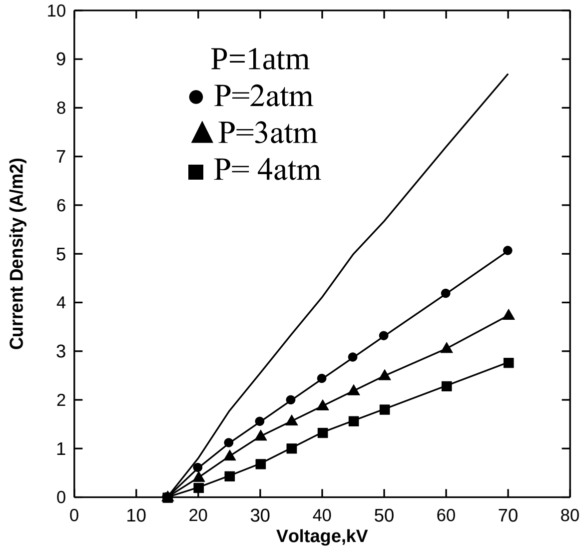


Fig.(3) effect of pressure on V-I curves

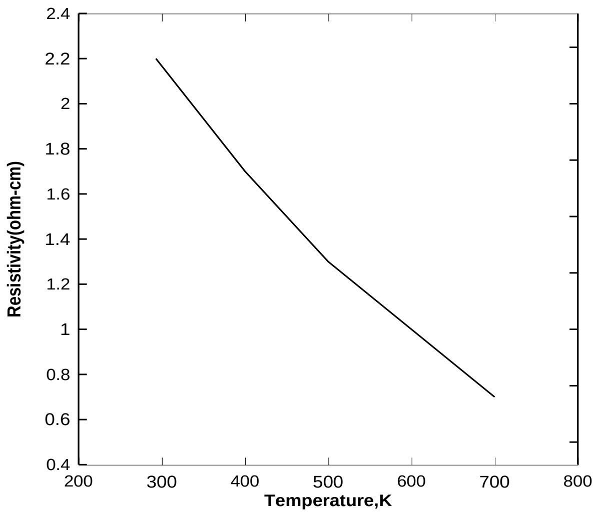
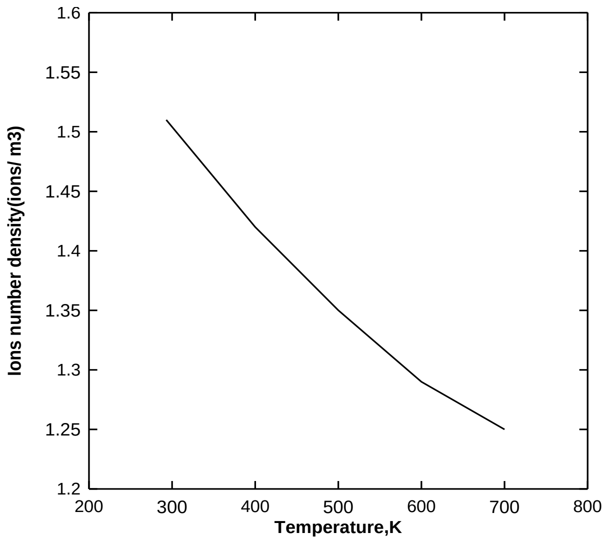


Figure (4) effect of temperature on resistivity



Figure(5) effect of temperature on the ion number density

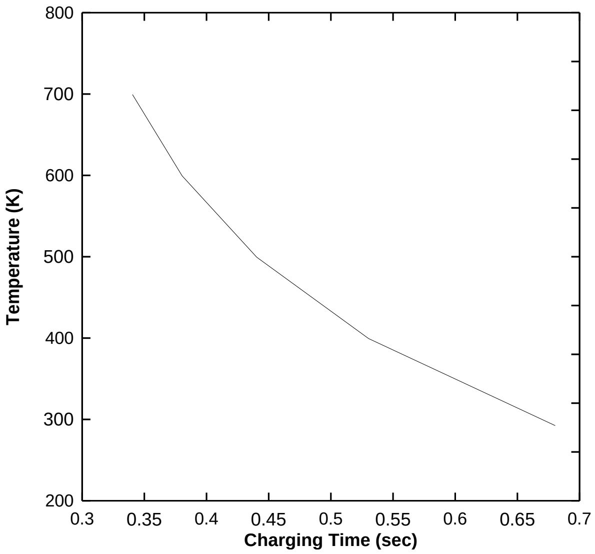


Fig.(6) Figure (6) effect of temperature on charging time

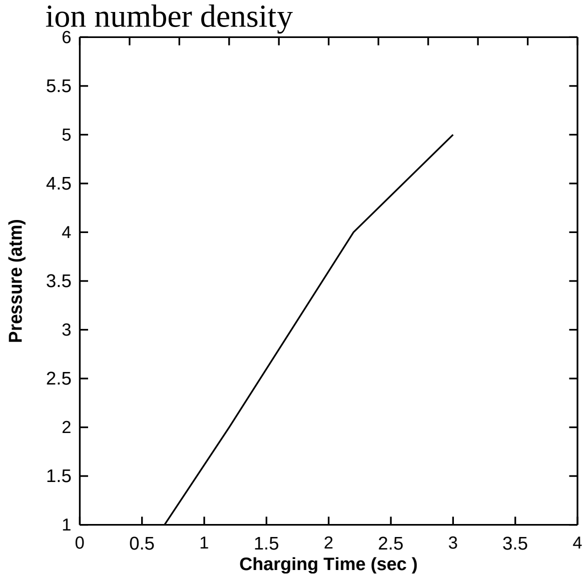


Figure (7) effect of pressure on charging time

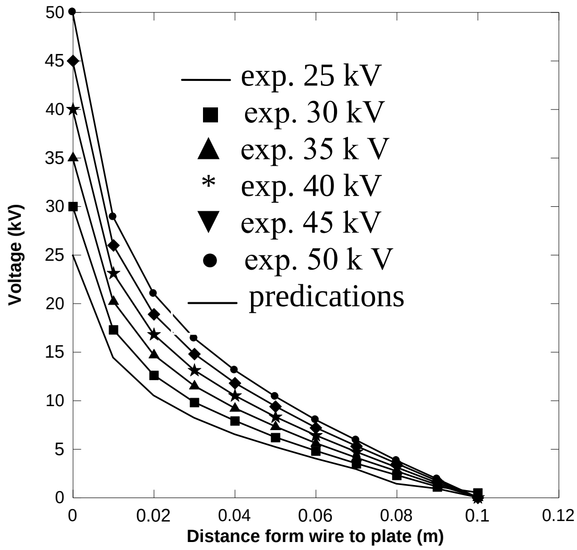


Fig. (8) comparison of the predicted potential with the measurements[17] of along wire-pate line

5-Conclusions

In this work , we have presented a mathematical model of the negative DC corona to predict the V-I characteristics of an electrostatic precipitator in case of high temperature high pressure .The current density increases with increasing temperature, but it decreases at high pressure .In addition, the temperature as a functions of charging time , resistivity , and ion number density .In addition ,the distribution of applied potential at the wire is determined along the distance from wire to plate, the results show good agreement with published analytical results[17]. Finally ,from the comparison between the V-I curves at atmospheric conditions and the case of high temperature high pressure of electrostatic precipitator ,it observed the shifted of the curves from the atmospheric condition, this deviation can indicate ESP performance at high temperature high pressure .

References:

[1]J.K. Lee et al. , An experimental study of electrostatic precipitator plate rapping and re-entrainment. Proceedings of Seventh International Conference on Electrostatic Precipitation,Kyongju,Korea,PP.155-162,1998.

[2]H. Elayyan, Computation of pulsed corona space charge in electrostatic precipitator configurations ,ABHATH AL-YARMOUK: Basic Sci. & Eng. Vol.10,No.2B,pp.469-487,2001.

[3] J.B. Thomas and E. Wong , J.Appl.Phys.29,1226-1230,1956.

[4] U.S. Environmental Protection Agency. Operation and Maintenance Manual for Electrostatic precipitators .EPA 625/1-85 /017.1985.

[5] George Rinard ,Donald E.Rugg , and Toshiaki Yamamoto ,High –Temperature High pressure Electrostatic precipitator Electrical characterization and collection Efficiency,IEEE,Vol.IA-23,No. 1, 114-120,1987.

[6] Awma, Air &Waste Management Association, Air Pollution Engineering Manual , Van No strand Reinhold , New York,1992.

[7] Junhong Chen and H.Davidson , Model of Negative DC Corona Plasma : Comparison to the Positive DC Corona Plasma, Plasma chemistry and Plasma Processing ,Vol. 23, No.1, 83-102,2003.

[8]G.Biskos, K.Reavell, N. Collings, Electrostatic Characterization of Corona –Wire Aerosol Chargers, Journal of Electrostatics 63 ,69-82 , 2005.

[9]F. W. Peek, Dielectric Phenomena in High –Voltage Engineering, 3rd ed., McGraw-Hill ,New York, 1929.

[10] P. A. Lawless, K. J. McLean, L. E. Sparks, and G. H. Ramsey, J. Electrostatic 18, 199–217,1986.
[11] J. H. Davidson and E. J. Shaughnessy , Experiments in Fluids **4**, 17–26 1986.
[13] L. B. Loeb, Electrical Coronas: Their Basic Physical Mechanisms,
Berkeley, University of California Press, 1965.
[14] Y. P. Raizer, Gas Discharge Physics, Springer, New York, 1997.
[15] K. J. McLean, P. A. Lawless, L. E. Sparks, and G. H. Ramsey, J. Electrostatics **18**, 219–231 ,1986.
[16]B.S. Rajanikanth, N. Thirumarah ,Predication of Pre- breakdown V-I Characteristics of an Electrostatic Precipitator Using A combined Boundary Element –Finite Difference Approach ,Fuel Processing Technology 76,PP.159-186,2002.
[17] H. Ryzko , Proc.Phys.Soc.85,1283-1295,1965.
[18]G.A. Kallio, Interaction of electrostatic and fluid dynamic fields in wire-plate precipitators , Ph .D .Thesis, Washington State University ,1987.