

Prediction of the Effect of Electrostatic Charging on Spray Characteristics

M. M. Elkotb¹, H. El-Ghazaly², H. El-Salmawy³,
and H. Abdel-Hameed⁴

1. Professor of heat engines, Mechanical power department, Cairo university
2. Associate professor, Electrical power & machines department, Cairo university
3. Assistant professor, Mechanical power department, Zagazig university
4. Assistant lecturer, Mechanical power department, Zagazig university
Cairo, Egypt

Email : Salmawy@FRCU.EUN.EG, Fax : (202) 572-8811

ABSTRACT

The effect of electrostatic charging on spray characteristics has been numerically investigated. The governing equations for mass, momentum, and energy have been solved numerically using an Arbitrary Lagrangian Eulerian (ALE) grid. The turbulence has been solved using the $k-\epsilon$ model for turbulence. A term for pseudo viscosity is added to the momentum equations to include the effect of the spray droplets on both turbulence generation and destruction. The effect of droplets interaction on the drag coefficient has been considered. Both the droplets collision and breakup are considered. Regarding the electrostatic charging, it has been expressed in the equations through its impact on the droplet effective surface tension and the repulsion forces between droplets. The effective surface tension is considered in the droplet breakup model, originally developed to account the effect of aerodynamic forces. The liquid was assumed to be conductive and charged by conduction. The results showed that charging the spray droplets enhances the droplet breakup with an increase in spray volume due to the repulsion forces between the spray droplets. Increasing the charging voltage up to 2.5 kV resulted in increasing both the spray half cone angle and the penetration time by about 6 times and 20 percent respectively. Also, the spray droplet size distribution showed a shift toward smaller droplet sizes as the electrostatic charging voltage increases.

KEY WORDS: SPRAY, ELECTROSTATIC, MODELING

INTRODUCTION

Charged liquid drops have been used in many applications such as painting, agricultural pesticide spraying, ink jet printing, electrostatic dispersal of liquids and air cleaners [1]. Charging of liquid fuels is limited to low capacity atomizers and it has not been used on large scale industrial level. It is expected that charging a liquid spray will improve the mixing between air and fuel due to better atomization and increase in spray volume [2]. This will be very helpful specially when heavy fuels such as residuals and synthetic fuels are considered. It will lead to a reduction in the harmful emissions and better combustion efficiency.

Bailey and Balachandran [3] experimentally studied the effect of electrostatically charging liquid hydrocarbons with various values of electrical conductivity, permittivity and viscosity by means of a capillary tube system raised to a high potential with respect to earth. They found that the most important liquid parameter, which influences the formation and breakup of liquid ligaments by electrostatic forces, was the electrical resistivity. It was much more significant than the permittivity. They also found that, as the liquid viscosity was increased, the propagating waves, which normally induce jet breakup, were attenuated allowing jets to exist. Regarding the liquid resistivity, the lower its value, the higher was the surface charge. For relatively low values of electrification, droplets were approximately equisized. Increased electrification resulted in smaller droplets. Smith [4] studied experimentally the effect of several parameters of a liquid on its electrohydrodynamic atomization. He concluded that as liquid conductivity increases, the filament width, length, droplet size and flow rate all decrease markedly. The main effect of increasing viscosity was an increase in the droplet size.

Kelly [2] characterized electrostatic atomization of fuel as: narrow droplet size distribution, droplets in the micron size range, auto-dispersal of spray droplets, and absence of droplet agglomeration. These are ideal factors for improving mixing of air and fuel in the combustion systems. However, no electrostatic fuel atomizer has been commercially adopted due to the low electrical conductivity of liquid hydrocarbon fuels. Attempts to increase flow rate by enhancing the electrical conductivity through the use of additives or by operating at higher voltages and higher currents have not been fruitful. Several electrostatic fuel atomizers have been patented [5-7], but none have been introduced into practice. The two factors that have contributed to this situation are: the lack (until recently) of economic incentives to pursue research on alternate and unconventional atomizer systems, and the absence of a useful theoretical model of the electrostatic spray process. In his paper, Kelly [2] introduced a statistical equilibrium model to get the state of the spray cloud downstream from its origin.

The scope of this study is that the liquid does not rely solely on electrostatic charging for atomization, but the liquid is considered to be atomized under the action of the aerodynamic forces. The charging of the spray droplets will be superimposed on the droplets already atomized. Accordingly, this paper investigates the improvements in the spray characteristics as a result of the superimposed electrostatic charging. This will be studied numerically by solving the governing equations for both the air and droplets. The turbulence will be modeled using the k-ε model. Both the effects of the droplets on the turbulence and the effect of their interaction on the drag coefficient will be considered. The superimposed charge will be considered from the perspective of its impact on both the effective liquid surface tension and the created repulsion forces between the charged droplets of the same polarity. Both will be used to modify the collision and the breakup patterns of the droplets inside the spray. The produced mathematical model will be used to predict the changes in the spray characteristics as a result of electrostatic charging.

GOVERNING EQUATIONS AND SOLUTION ALGORITHM

Two groups of governing equations for both the flow and droplets are used. Two-way momentum coupling exists between the two phases. The fluid governing equations are expressed as

i) Continuity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{u}) = 0 \quad (1)$$

ii) Momentum:

$$\frac{\partial (\rho \bar{u})}{\partial t} + \nabla \cdot (\rho \bar{u} \bar{u}) = -\nabla p - \nabla \left(\frac{2}{3} \rho k \right) + \nabla \cdot \underline{\underline{\tau}} + \bar{D}^s \quad (2)$$

iii) Internal energy equation:

$$\frac{\partial (\rho I)}{\partial t} + \nabla \cdot (\rho \bar{u} I) = -p \nabla \cdot \bar{u} - \nabla \cdot \bar{J} + \rho \epsilon \quad (3)$$

iv) Turbulence model: k-ε model is used. The turbulent kinetic energy and dissipation rate equations are given as:

$$\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho \bar{u} k) = -\frac{2}{3} \rho k (\nabla \cdot \bar{u}) + \underline{\underline{\tau}} : \nabla \bar{u} + \nabla \cdot \left(\frac{\mu}{Pr_k} \nabla k \right) - \rho \epsilon + \dot{W}^s \quad (4)$$

$$\frac{\partial (\rho \epsilon)}{\partial t} + \nabla \cdot (\rho \bar{u} \epsilon) = -\left(\frac{2}{3} C_{\epsilon 1} - C_{\epsilon 3} \right) \rho \epsilon (\nabla \cdot \bar{u}) + \nabla \cdot \left(\frac{\mu}{Pr_\epsilon} \nabla \epsilon \right) +$$

$$\frac{\epsilon}{k} \left[C_{\epsilon 1} \underline{\underline{\tau}} : \nabla \bar{u} - C_{\epsilon 2} \rho \epsilon + C_{so} \dot{W}^s \right] \quad (5)$$

where \bar{D}^s is a source term which accounts for the spray. It takes the following form:

$$\bar{D}^s = - \int f \rho_d (4/3) \pi r^3 \bar{F}_D d\bar{u}_d dr dT_d dy dy \quad (6)$$

and \dot{W}^S accounts for turbulence destruction due to presence of the drop. Consequently it has a negative sign and it is given as

$$\dot{W}^S = - \int f \rho_d \frac{4}{3} \pi r^3 \vec{F}_D \cdot \vec{u}' d\vec{u}_d dr dT_d dy d\dot{y} \quad (7)$$

where f is the probability density function and it is defined as follows

$$f(\vec{x}, \vec{u}_d, r, T_d, y, \dot{y}, t) d\vec{u}_d dr dT_d dy d\dot{y}$$

represents the probable number of droplets per unit volume at position \vec{x} and time t with velocities in the interval $(\vec{u}_d, \vec{u}_d + d\vec{u}_d)$, radii in the interval $(r, r+dr)$, temperatures in the interval (T_d, T_d+dT_d) , and displacement parameters in the intervals $(y, y+dy)$ and $(\dot{y}, \dot{y}+d\dot{y})$. It is assumed that each turbulent component of u' follows a Gaussian distribution with mean square deviation $2/3 k$.

\vec{F}_D is the drag force per unit mass of the droplet and can be expressed as follows:

$$\vec{F}_D = \frac{3}{8} \frac{\rho}{\rho_d} \frac{|\vec{u} + \vec{u}' - \vec{u}_d|}{r} (\vec{u} + \vec{u}' - \vec{u}_d) C_D \quad (8)$$

The quantities $C_{\epsilon 1}$, $C_{\epsilon 2}$, $C_{\epsilon 3}$, C_μ , C_{s0} , Pr_k , and Pr_ϵ are taken as follows [8]:

$C_{\epsilon 1}$	$C_{\epsilon 2}$	$C_{\epsilon 3}$	C_μ	C_{s0}	Pr_k	Pr_ϵ
1.44	1.92	-0.333	0.09	1.5	1.0	1.3

Regarding the droplet momentum equation, it can be expressed as follows:

$$\frac{d\vec{u}_d}{dt} = \vec{F}_D + \vec{b} \quad (9)$$

where \vec{b} is the body force per unit mass due to the repulsion between droplets. This will be described later. The drag coefficient used for the droplet is given as [9]:

$$C_D = \frac{24}{Re} \left[1 - \frac{2.54 - (1.7041 / e^{0.00227 * Re})}{e^{0.8 * l}} \right] \quad (10)$$

where l is the inter-drop distance/drop diameter.

AUXILIARY EQUATIONS

The equation of state of air is

$$p = R T \left(\frac{\rho}{M} \right) \quad (11)$$

The dynamic viscosity for turbulent flow is

$$\mu = \mu_{air} + C_\mu k^2 / \epsilon + \mu_s \quad (12)$$

where

$$\mu_{air} = \frac{A_1 T^{3/2}}{T + A_2}, \quad \text{and} \quad \mu_s = \text{const.} * \phi_d \rho r |\vec{u} - \vec{u}_d|$$

where μ_s is the pseudo turbulence [10], which represents the turbulence generated due to the droplets.

ELECTROSTATIC CHARGING OF THE DROPLETS

In this study, the liquid is assumed to be conductive and to be charged by conduction. These assumptions imply that during the breakup, the charges redistribute themselves over the droplets' surfaces on a time scale less than

that required to mechanically form the droplets. The spray droplets and the liquid body will have the same potential as the drop is separated. Therefore, each of the spray droplets carries a net charge (q) so that:

$$V = \frac{q}{4 \pi \epsilon_0 r} \quad (13)$$

where V is the liquid potential and ϵ_0 is the permittivity of free space.

The work required to spray the droplets comes mainly from the aerodynamic forces used to atomize the liquid. The charges on the droplets are used only to improve the atomization characteristics of the spray.

As the spray is formed, a repulsion force between each drop and all the nearby droplets forming the spray is established. This force is proportional to the droplets' charges and inversely proportional to the square of the distance separating them, i.e., the force between a drop (i) and all the nearby droplets is given by

$$\vec{F}_i = \left(\frac{4}{3} \pi r^3 \rho_d \right) \vec{b}_i = \frac{1}{4\pi\epsilon_0} \sum_{\substack{j=1 \\ j \neq i}}^n \frac{q_i q_j}{r_{ij}^2} \hat{r}_{ij} \quad (14)$$

This force is expected to increase the cone angle of the spray and to ensure better mixing between the fuel and the surrounding air. Another force of repulsion is exerted on the drop surface due to the charges on the drop itself. This force is radial and opposing the surface tension force. Since this electrical force F_e is expressed as:

$$F_e = \frac{-q^2}{8\pi\epsilon_0 r^2} \quad (15)$$

and the surface tension force F_s is expressed as:

$$F_s = 8\pi \sigma r \quad (16)$$

Then the net force holding the drop is:

$$F_t = 8\pi \sigma r - \frac{q^2}{8\pi\epsilon_0 r^2} \quad (17)$$

This can be looked at as if the liquid has a net effective surface tension:

$$\sigma_{\text{eff}} = \sigma - \frac{q^2}{64\pi^2 \epsilon_0 r^3} \quad (18)$$

where the second term represents the effect of the charge forces on the surface tension. When σ_{eff} equals zero, the drop will breakup due to the electrostatic charges only. The charge under this conditions is the maximum charge the drop can acquire and it is called Rayleigh limit.

In this study, the effect of the droplets' charges was taken into account by incorporating the above set of equations into the governing equations and the equations of the droplet breakup [8]. As a result, the droplet size distribution is modified due to the consecutive breakups resulting from the reduced effective surface tension. The total forces acting on the drop were also modified in the momentum equations to take into account the repulsion forces between the droplets which in turn change the drop velocity.

BOUNDARY AND INITIAL CONDITIONS

The temperature of the domain was maintained at 300 °K. The calculations were performed using the two-dimensional mesh shown in Fig.(1). The computational region was 12 cm in the axial direction, which was resolved with 20 cells, and 3 cm in the radial direction, which was resolved with 18 cells. The cell dimensions were expanded with both axial and radial distance from the injector, where the smallest cell had radial cell size $\delta r = 0.0538$ cm and axial cell size $\delta z = 0.262$ cm. The left boundary was the axis of symmetry while the bottom boundary was a rigid free-slip wall, and the right and top boundaries were open constant pressure boundaries that allowed the flow to either enter or exit the mesh. The drops were injected with SMD of 0.3 mm, equal to the nozzle exit diameter. These were injected at the lower left corner of the mesh in the axial direction without initial

frequency. The probability density function for the injected droplets was taken as $f(r) = (3/\bar{r}) \text{EXP}(-3r/\bar{r})$, where \bar{r} is the Sauter mean radius. This distribution is modified according to the charging voltage, where the injected drop which has a charge above the Rayleigh limit is subsequently disintegrated under the action of the electrostatic forces. Two types of breakup are considered to satisfy the minimum energy condition [1]. These types are: equisized droplets and different sized droplets. The selection between these two types of breakup depends on how far the charge is above the Rayleigh limit (more than 1 % above the Rayleigh limit produces equisized droplets). When the charge is at Rayleigh limit, the droplet disintegrates to two siblings having a mass ratio equal to 0.25 and 0.75 and a charge ratio equal to 0.4 and 0.6 of the original droplet respectively [1]. The velocity of the injected drops was calculated according to the difference between the injected pressure and the back pressure. The injected pressure is taken to be 10 atm., and the back pressure is 1 atm. The discharge coefficient is taken as a function of the injection pressure and the back pressure ($C_{dis} = 1 - 0.09155 \ln(p_{inj}/p_{back})$) [11]. Number of injected computational drops each second of problem time was 1.8×10^5 .

RESULTS AND DISCUSSIONS

The results are obtained for six different applied voltages on the injector. These voltages include the state of no charging and other five states with increasing step of 0.5 kV for the case under concern over the preceding one. The penetration time of the spray with respect to the axial distance is investigated. The axial distance is computed as that contains 99 % of the total spray mass in the domain. Figure (2) shows that the penetration time increases slightly for increasing the applied voltage. This is due to lowering the axial momentum of the spray which is added to its radial momentum. The gain in radial momentum is mainly due to the repulsion forces of the droplets. Also, this can be attributed to the enhancement of the droplet breakup which leads to smaller droplet sizes with less momentum. Figure (3) shows the spray shape in the domain for six different charging voltages. The cone half angle which includes 99 % of the total spray mass increases considerably with increasing the applied voltage. Moreover, the droplets penetrate more uniformly in the air. As the charging voltage increases a reduction in the increasing rate of the cone half angle is noticed, as shown in Fig.(4).

Regarding the effect of charging on the drop size, Fig.(5) represents the spray droplet size distributions at different charged voltages. As shown in the figure, increasing the charge tends to shift the distribution towards smaller diameters and make the size distribution more uniform. This can be explained in the light of the enhancement of the droplet breakup due to the applied charging voltage. Also the absence of droplets agglomeration due to the repulsive force between them prevents the formation of larger droplets. The accumulative curve in Fig.(6) which is the integration of the previous probability curve assures the aforementioned two properties. Figure (7) presents SMD versus the axial distance of the spray. For no charging condition, breakup dominates in the region just after the injector, then agglomeration due to collision dominates so that the SMD increases slightly along the axial distance. For charging condition, breakup also dominates first with higher rate than the no charge case. The higher the droplet charge, the more rapid is the breakup. After the breakup region, SMD remains nearly constant until the end of the domain. This comes from the repulsion forces which prevent the droplets from agglomeration. Increasing the droplet charge decreases the final SMD. This is because of the decrease in the effective surface tension due to the repulsion effect of the charges on the droplet surface.

CONCLUSION

A numerical model is developed to investigate the effect of electrostatic charging on the spray characteristics. The charging process enhances the breakup of the droplets, widens the spray cone, prevents droplets agglomeration, and makes the droplets size more uniform. These factors are of great importance in atomization and combustion processes and are the result of two important effects accompanying the droplets charging. These effects are the repulsion forces between all droplets and the reduction in effective surface tension of the droplet as a result of the repulsion forces on its surface that is directed radially outward. Experimental study is being conducted to verify the previous results.

REFERENCES

1. H. M. El-Ghazaly, "Theoretical and Experimental Studies on the Instability of Charged Liquid Drops," Ph. D. Thesis, Ontario, London, 1986.

2. A. J. Kelly, "The Electrostatic Atomization of Hydrocarbons," ICLASS-82, Wisconsin, U. S. A., 1982.
3. G. Bailey and W. Balachandran, "The Disruption of Electrically Charged Jets of Viscous Liquid," J. Electrostatics, 10, 1981, pp. 99-105.
4. D. P. H. Smith, "The Electrohydrodynamic Atomization of Liquids," IEEE, 1984, pp. 1080-1088.
5. A. Wobig, "Burner for Liquid and Gaseous Fuels," U. S. Patent 3, 167, 109, Jan. 26, 1965.
6. F. E. Luther, "Electrostatic Atomization of Liquid Fuels," U. S. Patent 3, 269, 446, Aug. 30, 1966.
7. W. Simm, "Electrostatic Atomization of Liquids," U. S. Patent 3, 608, 821, Sept. 28, 1967.
8. A. A. Amsden, P. J. O'Rourke, and T. D. Butler, "KIVA-II: A Computer Program for Chemically Reactive Flows with Sprays," Los Alamos National Laboratory Report LA-11560-MS, UC-96, May 1989.
9. H. A. El-Salmawy, "Evaporation and Drag Characteristics of Multi-Component Hydrocarbon Droplets," M. Sc. Thesis, Cairo University, 1986.
10. H. S. Abdel-Hameed, "Erosion due to Particulate Flow in Pipe Bends," M. Sc. Thesis, Zagazig University, 1994.
11. S. Abdel-Meguid, "Theoretical and Experimental Investigation of Fuel Spray in Open Combustion Chamber of Diesel Engines," Ph. D. Thesis, Cairo University, 1986.

NOMENCLATURE

A_1, A_2 : constants for molecular viscosity of the air

CA: cone half angle

I : specific internal energy

\vec{J} : heat flux

k : specific turbulent kinetic energy

M : molecular weight

p : pressure

q : drop charge

r : droplet radius

r_{ij} : the distance between drop i and j

R : universal gas constant

Re : droplet Reynolds number

SMD : Sauter mean diameter

t : time

T : temperature

\vec{u} : fluid velocity

\vec{u}' : turbulent (fluctuating) fluid velocity

V : liquid potential

y : displacement of the droplet's surface from its equilibrium position divided by the droplet radius

\dot{y} : the time derivative of y

Subscripts

d : droplet phase

Greek symbols

ε : dissipation rate of turbulent kinetic energy

ρ : fluid density

σ : surface tension

$\underline{\tau}$: viscous stress tensor

Φ_d : volume fraction of the droplet phase

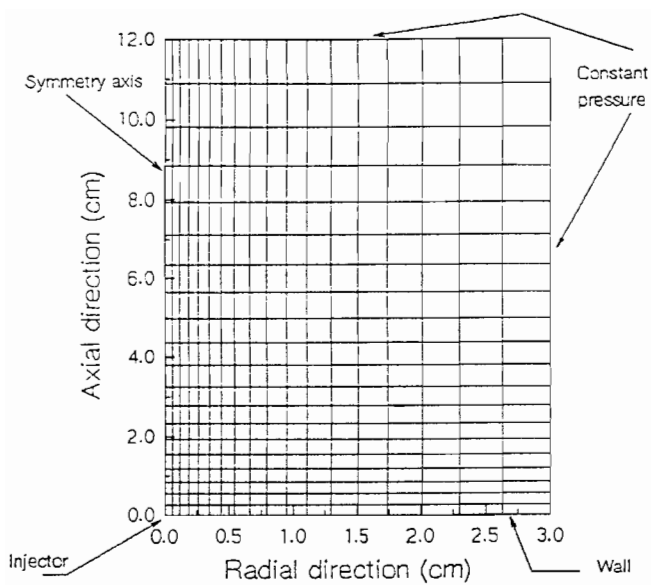


Fig.(1) Axi-symmetry grid.

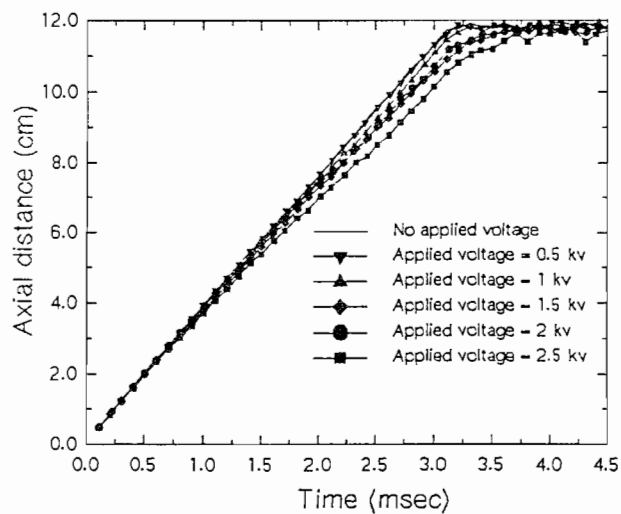


Fig.(2) Spray penetration at different applied voltages to the injector.

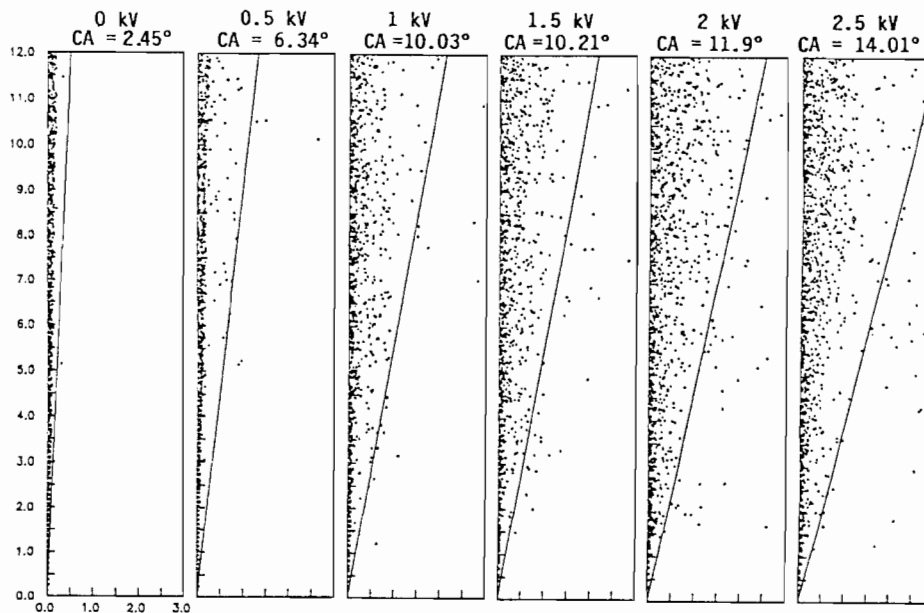


Fig.(3) Impact of applied voltages on the spray dispersion.

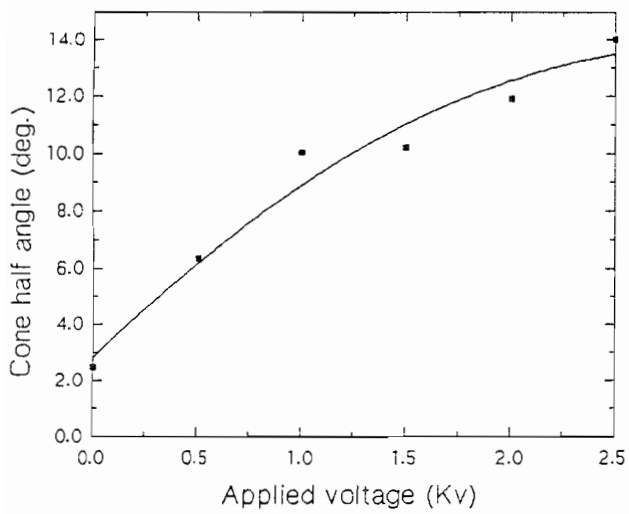


Fig.(4) Effect of applied voltage to the injector on the spray cone half angle.

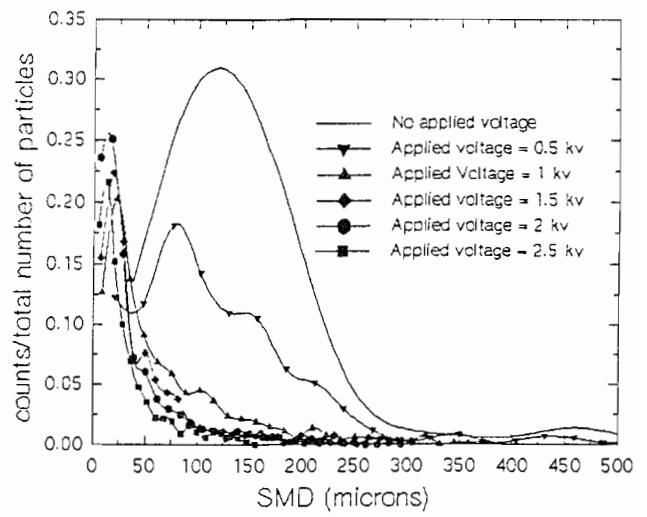


Fig.(5) Spray droplet size distributions at different charging voltages.

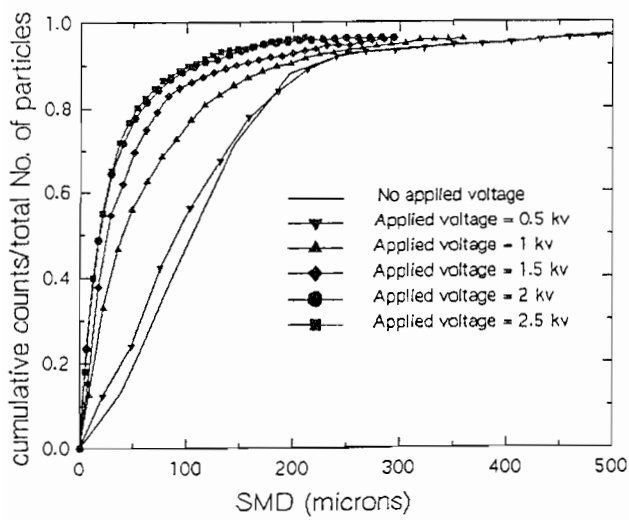


Fig.(6) Spray cumulative distribution curves at different charging voltages.

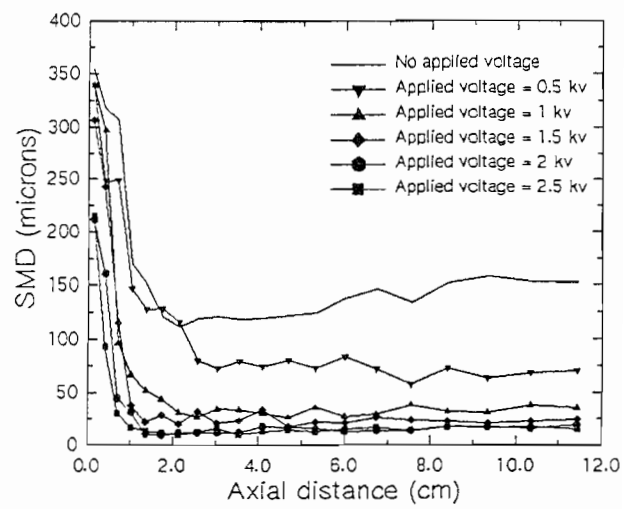


Fig.(7) Effect of charging voltage on Sauter mean diameter at different axial distances from the injector.