Investigation of the Electrostatic Charge Injection Method at High Hydrodynamic Pressures

E. L. Ergene*,1,2, A. Kourmatzis3, J. Komperda1, R. J. Schick2, J. S. Shrimpton3 and F. Mashayek1

1Department of Mechanical and Industrial Engineering
University of Illinois at Chicago
Chicago, IL 60607 USA

2Spray Analysis and Research Services
Spraying Systems Co.
Wheaton, IL 60187 USA

3Energy Technology Research Group, School of Engineering Sciences
University of Southampton
Southampton, SO171BJ UK

Abstract
The electrostatic charge injection method is applied at high hydrodynamic pressures, up to 40 bar, to evaluate the electrical and atomization performance of a point-plane type charge injection atomizer using Diesel fuel. The main focus of this paper is to investigate the effect of electrostatic charging on higher pressure injection systems in order to form finer sprays. Laser Diffraction Spectrometry (LDS) measurements and imaging studies are performed to investigate the effect of the electrostatic charge injection technique on drop size distribution as a function of orifice size, applied electrode voltage, inter-electrode positioning, hydraulic pressure and corresponding axial tip velocity at high Reynolds numbers. It is observed that spray dispersion is enhanced and drop size is reduced with the increase in specific charge. The various stages experienced by the electrostatic spray as the electrode voltage is increased from zero are described in detail on the basis of an imaging study. LDS measurements are conducted to show how drop size profiles vary as a function of downstream position from the nozzle tip. These measurements are used to understand the aerodynamic effects of the surrounding air on the secondary break-up of the dense spray in virtue of more air entrainment to fuel spray. Finally, these findings are discussed and several advantages of the electrostatic charge injection method for modern diesel engines are outlined.

*Corresponding author
Introduction

The strong effect of spray atomization on the combustion of Diesel fuel has long been known. Better atomized fuel will result in less production of soot, which is formed in the fuel-rich regions of the spray. In order to further improve spray atomization, several methods have been proposed. The electrostatic charge injection method is one of many novel approaches that have been investigated in the past three decades and this method has several advantages such as smaller droplets, narrow droplet size distribution and a lower power requirement to generate the spray.

Several electrostatic charge injection atomizers have been designed [1-2] and tested extensively to understand the effect of the nozzle geometry, electrode location, orifice size and liquid viscosity on the specific charge of the resulting spray. The common way of applying this technique is by having a dielectric liquid flowing between two electrodes a distance L apart, where one electrode is at high negative voltage, and the other electrode is grounded. When charge is present in the liquid jet, the binding force due to surface tension that holds the jet together is reduced by Coulombic repulsion. If the surface charge density reaches a critical value and the electrostatic force dominates the surface tension, jet atomization and dispersion is observed.

Primary break-up is the initiation of the atomization process due to inherent perturbations that cause the liquid jet to form individual droplets. In secondary break-up, air resistance is sufficient to further reduce droplet diameter with the inviscid effects of the surrounding air. The former is directly governed by the atomizer geometry and Reynolds number (Re); the latter is observed in high pressure, dense sprays and is a function of the Weber (We) and Ohnesorge (Oh) numbers defined respectively as [3]:

\[
We = \frac{\rho u^2 d}{\alpha}, \quad Oh = \frac{\mu}{\sqrt{\rho ad}}
\]

(1)

where \(d\) is the orifice diameter, \(\rho\) is the density, \(u\) is the mean nozzle orifice velocity, \(\alpha\) is surface tension and \(\mu\) is the dynamic viscosity of the working fluid. The Weber number is a measure of the liquid’s momentum relative to its surface tension and the Ohnesorge number is the ratio of viscous force to surface tension force. For low \(Oh\), an increase in the \(We\) will increase the contribution of the secondary break-up to form a finer spray [3].

The electrical performance of an electrostatic atomizer is quantified with the mean specific charge (SC), which is defined as the spray charge per unit volume. It’s known that the specific charge should be at least on the order of 1 C/m³ to form a fully developed Diesel fuel spray [4]. The dispersion rate increases and droplet sizes further decrease as the specific charge increases. A simple relation between mean droplet size as a function of mean droplet specific charge, independent of fluid properties and hydrodynamic effects, was given by Kelly [5] as:

\[
(SC)^{1/2} D_{\alpha 0.5} = \text{constant}, \quad SC = \frac{I}{dQ}
\]

(2)

where SC is the specific charge in C/m³ and \(D_{\alpha 0.5}\) is the mean volume diameter in µm that will be explained in detail. \(I\) is the spray current in amperes and \(Q\) is the flow rate in m³/s. The value of the constant is dependent on the geometrical parameters of the atomizer. According to relation (2), mean droplet size is inversely proportional with the square root of specific charge. Therefore, it can be concluded that droplet size change is negligible when the specific charge reaches its practical limit of \(\sim 5 \text{ C/m}^3\) measured in these experiments. The maximum limit of the SC is strongly dependent on the orifice size. If the orifice disk channel is considered as a charged cylinder, the surface electric field \((E_0)\) of the exiting fluid stream can be approximated as follows:

\[
E_0 = \frac{(SC)d}{4\kappa}
\]

(3)

where \(\kappa\) is the dielectric constant of the working fluid. The magnitude of the surface electric field is limited by the corona onset value of the surrounding atmosphere. Therefore, in order to further increase the SC limit, smaller orifice disks should be used.

The governing equations of electrohydrodynamics based on the electroquasistatic assumption relevant to dielectric fluids are derived by Castellanos [6]. These equations are the simplified version of the Maxwell equations using the assumption of the dominance of the electric energy over the magnetic energy. The reader should note that these equations are only valid for a quiescent liquid between two electrodes [7]. However, from these equations important non-dimensional parameters were derived, shown as:

\[
T = \frac{eV}{\kappa \mu}, \quad M = \frac{\epsilon \varepsilon}{\kappa}, \quad C = \frac{(SC)^2}{eV}
\]

(4)

where \(\epsilon\) and \(\kappa\) are the permittivity and ionic mobility, respectively. The first nondimensional parameter, \(T\), is derived from an analogy to the Rayleigh-Benard problem. Comparing the viscous effects with the Coulombic forces provides an insight into the stability of the system. The transition from stable to an unstable state is
denoted by the critical stability parameter, \( T_c \), for which it has been shown [8] that electroconvection starts at a value of \( T_c \approx 100 \). This critical value corresponds to -90V for Diesel fuel in the injector used in this study. At around -10kV, the value of the stability parameter is \( T = 11,840 \), which is indicative of electroconvective instability where large scale roll structures will be produced. The second non-dimensional parameter, \( M \), is defined as the ratio of the hydrodynamic mobility to the ion mobility. \( M \) is known [8] to have values in the range of \( 4 \leq M \leq 400 \). The higher the non-dimensional number \( M \) is, the lower the drift velocity is. The atomizer used in this study has \( M = 15.8 \) for Diesel fuel. The last non-dimensional parameter, \( C \), is the measure of the injection strength given as the time-scale ratio of the ionic drift to the Coulombic relaxation of charge. For \( C \ll 1 \), the charge injection is termed as weak injection and indicates that the electric field is determined by the power supply connected to the charge injector electrode. On the other hand, for high values of \( C (>1) \), the injection regime is strong and the electric field mainly depends on the injected specific charge.

The main objective of this study is to show that the electrostatic charge injection technique is a viable method of producing fine sprays at hydrodynamic pressures of up to 40 bar. An enhancement in the atomization performance is expected as compared to the previous results [9-10] at lower pressures. In order to analyze the high-pressure effects on spray dispersion, the break-up mechanisms are evaluated by means of a Malvern Laser Diffraction Spectrometry (LDS) droplet size measurement system, digital camera imaging techniques and electrical measurements. Using the results of these measurements, it is investigated how electric charge improves the aerodynamically driven atomization of the dielectric liquid jet. A further objective of this work is the observation of the stages of the spray development at increasing electrode voltage.

This paper is organized as follows: In section 2, the major characteristics of the design and the experimental rig are described and the necessary experimental information is provided. In section 3, charge injection characteristics for the broad range of test conditions are presented. In Section 4, changes in the spray profile are visually investigated by studying spray images for various operating voltages and different testing conditions. LDS droplet size testing results are presented in section 5. Finally, some concluding remarks are provided in section 6.

**Experimental Setup**

The purpose of the atomizer is to introduce an electrostatic charge to the liquid and to inject fluid through the nozzle orifice creating a charged spray downstream from the orifice. Figure 1 illustrates the experimental rig. A stainless steel needle with a tip radius of 100 μm was used as the charging electrode. The needle tip radius was measured using the PS3 Clemex microscope with 200x magnification and software system within 0.1 μm. A micrometer was mounted on the atomizer body to adjust the charging electrode distance from the grounded nozzle orifice inlet within 5% accuracy. The electrode gap is non-dimensionalized (\( L/d \)) by taking the ratio of the electrode gap (\( L \)) to the orifice size (\( d \)). The portion of the total electric current (\( I_T \)) from the needle electrode tip carried away by the sprayed liquid is called “spray current” and denoted by \( I_s \). Images were taken using a Canon EOS 7D digital SLR camera system assisted with a strobe light featuring 10 μs flash duration.

![Figure 1. Schematic of high pressure flow setup utilized for electrical and spray characterization.](image)

The test liquid was the Diesel fuel that is sold commercially. It has a typical viscosity of 2.4 mPa.s, density 840 kg/m³, and surface tension 0.025 N/m at laboratory conditions [11]. Test fuel was driven from the reservoir to the high pressure pump by means of a pressurized vessel. Rubber reinforced hoses and PTFE fittings were used in the hydraulic circuit to ensure electrical isolation of the nozzle.

The high voltage power supply (HVPS) unit used in the experiment was the Spellman LS30PN operated with negative polarity, and rated for an amplified voltage range from 0 to -25kV in 0.01kV intervals and 30 watts of output power at 24 VDC nominal inputs. Negative polarity of the high voltage supply was used over the positive polarity because it is found to be more stable and requires lower field intensities in order to inject the same amount of charge.

A Zenith HPB series gear pump is used to achieve a steady high pressure flow. This pump is specially designed to provide a precise, pulseless, repeatable flow. Although this system was capable of delivering a discharge pressure of up to approximately 275 bar at a
maximum flow rate of 0.526 L/min, measurements were done at a maximum 40 bar due to limitations of the atomizer design.

Droplet size measurements were taken with a Malvern 2600 LDS particle analyzer. The Malvern analyzer is a laser diffraction instrument that measures drop size based on the energy of the diffracted light caused by drops passing through the analyzer’s sampling area. The scattered light intensity is measured using a series of semicircular photo diodes housed in the receiver unit. Malvern 2600 particle analyzer falls into the category of non-imaging optical systems due to the fact that sizing is performed without creating an image of the particle on the detector. The computer software reads the detector signals over a period of time and sums this data. The Rosin-Rammler distribution function is used to convert the light intensity distribution into a drop size distribution function (5). One of the main advantages of using this distribution is that it allows data to be extrapolated into the range of very fine drops, where measurements are more difficult and thus less accurate. The exact size for every volume fraction, F(D), in the spray can be calculated using the $D_{0.632}$ and q parameters that are generated from the actual data. $D_{0.632}$ is the drop diameter such that 63.2% of the total volume of liquid sprayed is made up of drops with diameters smaller or equal to this value. q is the measure of the drop size spread. The lower value of q indicates a wider droplet size distribution.

$$F(D) = 1 - \exp\left[ -\left( \frac{D}{D_{0.632}} \right)^q \right]$$

(5)

The analyzer has a 2mW He-Ne laser beam with 9 mm diameter at a light wavelength of 632.8 nm. The 300 mm focal length receiver lens configuration allows a measurement range of 5.8 µm and 564 µm for the Malvern 2600 instrument at a maximum working distance of 400 mm from the receiver. Although it was expected that there would be some drops smaller than 5 µm, these were missed from the distribution because the instrument was set to ensure that drops larger than 200 µm could be measured.

The $D_{50.5}$, $D_{32}$, $D_{10}$ and $D_{80}$ diameters were used to evaluate the droplet sizes. $D_{50.5}$, volume median diameter (VMD), is the value where 50% of the total liquid volume (or mass) is in drops with smaller (or larger) diameter. This diameter is used to compare the change in drop size on average between test conditions. $D_{32}$, Sauter mean diameter (SMD) is the diameter of a drop having the same volume to surface area ratio as the total volume of all the drops to the total surface area of all the drops. $D_{10}$ and $D_{80}$ are the values where respectively 10% and 90% of the total volume (or mass) of liquid sprayed is made up of drops with diameters smaller or equal to these values.

**Electrical Performance**

<table>
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<th>d (µm)</th>
<th>Flow rate (ml/min)</th>
<th>u (m/s)</th>
<th>We</th>
<th>Oh</th>
<th>Re</th>
<th>SCmax (C/m³)</th>
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<td>6048</td>
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<td>30</td>
<td>7560</td>
<td>0.033</td>
<td>3125</td>
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</table>

Table 1. Variables and relevant non-dimensional numbers for all experimental cases.

Testing conditions are summarized in Table 1. Experiments were performed using 3 different orifice sizes of 100 µm, 200 µm and 250 µm. The range of the operating system pressure was between 7 to 40 bar to maintain the same velocity range for different size orifice disks. The electrode gap ratio (L/d) was set at 3 for 100 µm and 200 µm and 2 for 250 µm orifice disks as these gap ratios were observed to be the optimum point to provide a more uniform spray pattern within our high voltage power supply limit. Spray currents, $I_s$, were recorded with a HP 3458A digital pico-amp multimeter and corresponding specific charge values were calculated.

**Figure 2.** Spray current profiles as a function of orifice size (d), applied voltage (V) and average axial orifice velocity (u).

The variation of $I_s$ as a function of the applied electrode voltage is shown in Figure 2 for different testing conditions up to the partial breakdown point where spray current starts to decline as the applied voltage is increased. As seen from Figure 2, a greater amount of
electric charge could be injected into the liquid at a higher axial orifice velocity, as observed in literature [12-13]. This may be explained due to higher injection velocity allowing for charge to be carried away from the inter-electrode gap prior to leaking to the ground through the atomizer body. In addition to injection velocity, electrode voltage is an important parameter in the initiation and development of charge injection. The threshold voltage \( V_{th} \) is the magnitude of the applied voltage at which the energy barrier around the charger tip is overcome by the injected charge. After surpassing this critical value, charges appear in the liquid. The amount of electric charge in the liquid per unit time is proportional to the strength of the local electric field above the threshold value. Injection of the charge starts around -5 kV at these testing conditions.

One of the main concerns in electrostatic atomization is to maximize the spray charge per unit volume to maintain spray quality. In contemplation of noticeably improving the diesel fuel atomization by means of electric force to sustain stable combustion, the charge-volume ratio, i.e. specific charge, should be at least at the order of 1 C/m\(^3\). Figure 3 shows the corresponding specific charge for various diameters at two testing velocities. A slight decrease in SC is observed at elevated injection velocities. As seen from Figure 3, the maximum level of specific charge with a 100 µm orifice disk equating to 5 C/m\(^3\) is significantly larger than the specific charge obtained in low pressure studies [14], showing the potential of high pressure electrostatic charge injection systems.

**Spray Visualization**

After confirmation that the high pressure system can achieve high amounts of spray specific charge (SC) for a good spray pattern, an imaging study was carried out to study the stages of atomization at high pressure. The development of the spray pattern has several stages as the applied voltage is increased. These stages can be summarized as solid stream, distorted stream, deflection of smaller droplets from the core, and fine atomization.

Figure 4 shows the spray development with increasing voltage. The solid stream stage is the uniform integrity of the working fluid observed between zero and the threshold voltage as shown in Figure 4(a). The stream narrows when moving away from the orifice due to the effects of the surface tension force which causes a fluid to tend to minimize its surface area. At a certain distance from the orifice, the emerging stream of liquid breaks up into droplets. This break-up can be explained with the inevitable small perturbations present. Above the threshold voltage, jet instability is observed as a distorted cylindrical stream as the jet is pinched into smaller segments with the effective decrease in liquid surface tension. This instability is shown in Figure 4(b) and (c). As the specific charge increases proportionally

![Figure 3](image1.png)

*Figure 3. Specific charge profiles as a function of orifice size \( (d) \), applied voltage \( (V) \) and average axial orifice velocity \( (u) \).*

![Figure 4](image2.png)

*Figure 4. Stages of spray with increasing voltage at 250 micron disk and \( u=30 \text{ m/s} \) (a) \( V=0 \text{ kV} \) (b) \( V=-6 \text{ kV} \), \( SC=0.15 \text{ C/m}^3 \) (c) \( V=-9 \text{ kV} \), \( SC=0.45 \text{ C/m}^3 \) (d) \( V=-12 \text{ kV} \), \( SC=0.8 \text{ C/m}^3 \) (e) \( V=-16 \text{ kV} \), \( SC=1.5 \text{ C/m}^3 \).*
with voltage, finer droplets are formed and deflected away from the core of the spray, as if they repel each other. Smaller droplets carry more specific charge and so are repelled further from the center. At this stage, a heavier centerline pattern is observed as in Figure 4(d). As the applied voltage is increased further the radial droplet size distribution becomes more uniform. Figure 4(e) shows the maximum specific charge case at this condition around -16 kV. This pattern continues until the spray collapses at higher applied voltages.

Figure 5 is the spray development of the same orifice disk but at a higher axial orifice velocity. The images are brighter than the lower velocity case due to the higher strobe light intensity perceived by the digital camera. This may be explained by the development of mist around the spray which causes light from the strobe to be deflected into the camera lens, thereby increasing perceived intensity. As seen in Figure 5(a), there was no spray at zero voltage, indicative that this test condition was still under the critical velocity, defined as the case where the spray forms hydrodynamically without charge in the spray. At voltages just above the threshold voltage, the distorted stream stage was observed with a noticeably heavier core (Figure 5(b) and (c)) as a result of the higher flow rate. When a greater amount of specific charge is reached by further increasing the voltage, lateral electric forces stretch the liquid jet as shown in Figure 5(d). The main difference with the aforementioned case (Figure 4(d)) is the noticeably wider angle of the spray resulting from the increase in flow rate. Figure 5(e) shows the condition of the widest spray angle achieved at the maximum specific charge level when applied voltage was approximately -17 kV. In this regime, the atomized spray appears to be almost perfectly mixing with the surrounding air as it moves a short distance from the orifice, resulting in a fairly uniform spray pattern.

**Drop Size Testing**

Volume median diameter (VMD) comparison for different testing conditions obtained via LDS droplet size analysis is presented in Figure 6. Note that the measurements could not be conducted at very low specific charge levels (SC<0.3 C/m^3) due to the drop size analyzer’s range limit of the corresponding receiver lens. Furthermore, no fluid break-up was observed at zero applied voltage as shown in the imaging section. Measurements were conducted at a spray distance of 15 cm (x=15 cm) downstream from the orifice. All data presented was measured at the sustainable stable operating conditions.

Major factors in the fuel spray dispersion are known to be aerodynamic forces and disruptive electric forces [15]. From Figure 6, VMD decreases with the increase of specific charge for all cases. Spray dispersion increases proportionally to electric potential applied and hence drop size reduces in agreement with the images of the previous section. In addition to the enhanced dispersion, increase in the spray angle contributes to smaller droplet sizes. It may be expected that the higher injected amount of fuel tends to increase the fuel-rich heavy spray core region. In contrast, in this study, smaller VMD values can be achieved with the same orifice size at higher Reynolds number with the help of the hydrodynamic pressure effects. Therefore, it can be concluded that the combination of both higher aerodynamic and electric forces improves atomization and spray performance at higher flow rates.

For the smallest orifice size tested, d=100 µm, the value of the VMD was slightly larger than the orifice diameter measured at the lowest testing pressure and the lowest measured specific charge setting. For this configuration, the VMD value decreased down to approximately half the orifice diameter as the specific charge was raised until a uniform spray pattern was
formed. For larger orifice sizes, the largest VMD values that could be measured within the acceptable obscuration rates were approximately 120-125 µm (0.5-0.6d). A wider spray pattern was observed indicating greater dispersion of smaller drops. Increasing the system pressure further led to lower VMD values of 0.22d for 100 µm and 0.16d for larger orifice disks. It can be concluded that the higher aerodynamic shear improves atomization performance significantly as the flow rate is increased. The spray pattern radius is smaller and thus less dispersed than lower pressure cases that offer significantly wider angles; however, high hydrodynamic pressure technology allows for fairly small droplet diameters over a smaller area at a higher flow rate.

Figure 6. VMD Profiles as a function of orifice size (d), specific charge (SC) and average axial orifice velocity (u).

Larger orifice diameters lead to larger droplets for the same system pressure in pure hydraulic nozzles that are not electrostatically assisted. However, in electrostatic atomizers, atomization rate at the corresponding specific charge level becomes the major factor in drop size profiles at constant system pressure. In the tested electrostatic atomizer, the 250 µm orifice disk produced a fully developed spray in the range of ~1.5 C/m³ with VMD of 65 µm at the lowest pressure setting. At this SC range, for the d=100 µm orifice diameter, irregular large drops were still observed to persist in the spray central core region with a VMD of 83 µm. These large drops especially skew the VMD and Dv0.9 volumetric curves towards the larger drop size range, as large drops contain a majority of the spray volume.

Figure 7 illustrates the shift in the volumetric percentage distribution curves versus the droplet size for 100 µm and 250 µm disks at the lowest testing pressure setting corresponding to an average axial nozzle tip velocity of u=30 m/s. The increase in specific charge results in hundreds of microns shift in Dv0.9 whereas the change in Dv0.1 is negligibly small comparatively. Therefore, it can be concluded that primary break-up of larger drops into several small drops occurs significantly more often than the secondary break-up of small drops into further smaller droplets. Note that some drops for low specific charge cases were beyond the drop size measuring range limit of the analyzer as seen from Figure 7.

Figure 7. Volumetric percentages as a function of specific charge (SC) for d=100 µm and d=250 µm at u=30 m/s

Figure 8 shows the drop size distribution at two different downstream positions from the nozzle tip using d=200 µm orifice disk at u=40 m/s. As seen from Figure 8, there is a small variation between drop size profile curves moving from x=15 cm to x=25 cm downstream. This can be explained with the decrease in break-up tip length and as a result, a uniform spray pattern is already formed at the measured downstream positions. The decrease in Dv0.9 curves further downstream indicates the decrease in maximum drop size with more air entrainment to the fuel spray. In contrast, the Dv0.1 curve shows a slight increase which can be a result of evaporation while moving downstream. In addition, smaller droplets that have small momentum can easily drift away from the measurement volume because of the turbulence created inside the charge collector cage. The VMD and SMD curves show minimal variation which implies an identical combustion performance for both cases.

Figure 8. Drop size distribution at two different downstream positions from the nozzle tip using d=200 µm orifice disk at u=40 m/s.
Conclusions

The ultimate goal of this research is to show that the electrostatic charge atomization technique is a viable method to obtain finer sprays at up to 40 bar by means of electrical measurements, spray imaging and LDS droplet size testing. High hydrodynamic pressure allows for a higher amount of charge injection to the liquid. A specific charge level of approximately 5 C/m³ could be reached with the 100 µm orifice disk. This aids in increasing the atomization quality at a higher flow rates by forming fairly small droplet diameters down to a VMD of 0.16d. The shifts in the droplet size parameter curves to lower droplet size region are shown as a function of the specific charge of the fuel spray. Statistical drop size data parameters are compared at two different downstream positions from the orifice. A small decrease in maximum drop size is noticed; however, the change in VMD is found to be negligible. Break-up mechanisms for high pressure Diesel fuel are studied in conjunction with electrostatic atomization. The stages in the spray development as a function of applied voltage are shown by means of an imaging technique.

In the future, this study will be extended to higher hydrodynamic pressures to analyze the effect of turbulent flow inside the orifice channel on the spray pattern and the drop size profile. In order to analyze number density and velocity of the droplets as a function of the spray radius, phase doppler anemometry (PDPA) measurements will be conducted.

References


Figure 8. Drop size distribution data as a function of specific charge (SC) for d=200 µm, u=40 m/s at x= 15 cm (case #1) and x=25 cm (case #2)