Characterization of an Electrostatically Charged Gasoline Fuel Injector Spray

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Abstract
A gasoline fuel injector was modified to allow the addition of electrostatic charging to the spray as an additional means of controlling fuel dispersion. An electrode with a sharp orifice was placed over the tip of the injector to inject charge into the low conductivity liquid. The spray was characterized with images obtained using a MIE scattering technique, droplet sizes were measured with Fraunhoffer diffraction, and velocity fields were obtained with Particle Imaging Velocimetry. Results showed that the charged sprays exhibited greater penetration and repeatability of droplet size. The velocity fields revealed increased vorticity and axial droplet velocity.

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Introduction

One of the inherent challenges in designing a pressure-driven liquid fuel injector is the fact that the fuel momentum, which determines the way fuel is dispersed in the combustion chamber, is dependent on mass of fuel injected, which is determined by engine load. The result is that injector design is a compromise that is not optimal under all engine operating conditions. A second shortcoming of conventional pressure driven fuel injectors is their relatively poor fuel atomization during the initial phase of injection, before the injector is fully open. This results in the presence of large fuel droplets in the leading edge of the spray which often cannot fully vaporize before combustion.

The experiments reported here investigate the possibility of altering the sprays from a commercially available fuel injector through the use of electrostatic charging. While systems employing electrostatic effects as a sole means of atomizing liquids, defined as “electrosprays”, are not new, having been observed by Zeleny in 1917 [1], little research has been devoted to the combination of electrostatic charging with pressure-driven sprays for power generation applications, where high flow rates of low conductivity fuels are often required. Traditionally, electrostatic charging has been used at liquid flow rates on the order of ml/hr [2, 3], for applications including mass-spectrometry of large liquid molecules [4], ink jet printers, and targeted drug inhalation [5].

To our knowledge, the only demonstrated application of electrostatic charging in the field of combustion has been in “micro-combustion”. A micro-burner design utilizing electrosprays was proposed by Gomez and co-workers in Refs. [6-8]. Outside of the combustion field, Law [9] showed that applying a strong electric field near the orifice of a pesticide nozzle can increase the percentage of pesticide delivered to target plants.

Recent publications by Shrimpton [10] described numerical simulations of electrostatically charged pulsed sprays typical of GDI fuel injectors. Results suggested that the electric charge could cause spray expansion in an engine combustion chamber. The experiments described here are aimed at determining the effects that can be observed with modest charging of the fuel emerging from a fuel injector. The modifications to the injector are intended to be simple and the injection pressures are kept low compared to normal GDI practice, to make electrostatic effects easier to observe.

Experimental Apparatus and Techniques

A schematic of the experimental apparatus used in spray visualization experiments is shown in Fig. 1. Similar setups were used for PIV and Fraunhofer dif-

![Figure 1. Experimental apparatus.](image-url)
Synopsis of Electrostatic Effects

Measurable effects on the structure of the velocity field in the sprays and the repeatability of droplet sizes were detected. It is important to note, however, that these results were obtained with relatively weak charging of the fuel. Specifically, preliminary measurements showed that the amount of charge injected to the fuel was on the order of 1 nC/g. This is approximately two orders of magnitude smaller than the charge densities reported in [2,8,9]. So, before discussing spray structure effects some details on the spray charging scheme are necessary.

1. Effectiveness of Charge Transfer to the Fuel

The effectiveness of charge transfer is effected both by the strength of the electric field in the vicinity of the spray and the conductivity of the fuel. Local electric field strength is strongly influenced by the electrode geometry and generally, sharp electrode features enhance the field strength. As Fig. 3 shows, simply increasing the angle of the conical feature on the injector cap used as the electrode increases electric field strength by nearly 50%. Moreover, one could in principle conceive more elaborate modifications of the injector tip, e.g. insertion of extractor rings in the vicinity of the injector tip that would significantly enhance the strength of the local electric field. However, such radical modifications to the electrode may constitute a formidable departure from current automotive practice.

An alternative, less intrusive way to enhance electrostatic effects is to increase fuel conductivity with the addition of conductivity enhancing additives, which is exactly what was used for smaller flow rates in [2,8,9]. Figure 4 shows the effect of adding 0.05% by weight DuPont Stadis 450 additive on charge transfer to the fuel. The ratio of charge transferred by the gasoline with Stadis additive to charge transferred by gasoline without Stadis is shown on the left ordinate axis. The mass of liquid injected by a single injector pulse is plotted on the right ordinate axis. The Stadis additive in-creased the charge carried by the sprays by 20 to 50 fold. As injection pressure was increased, the effect of Stadis appears to decrease. However, since the mass of fuel injected increases with injection pressure, the increase in charge caused by the antistatic additive is approximately constant for constant mass of injected fuel.
A detailed study of the change of spray properties caused by antistatic additives is beyond our scope here; the possibility of fuels of enhanced conductivity is simply provided as an avenue for future research. For the rest of the paper, we are focusing on the electrostatic effects observed without additives.

2. Structure of the Velocity Field

The effect of electrostatic fields on spray structure are highlighted in Fig. 5. There, two sets of data are superimposed for the purpose of comparison. In the background, Mie scattering images are shown that visualize the overall appearance of the spray cone. Two sprays are presented 1.6 ms after the start of injection at 2.8 bar injection pressure. The spray on the left took place without electric charging, while a voltage of 3 kV was applied to the spray that appears on the right. Superimposed on each image is the PIV velocity field captured under the same conditions.

A very interesting finding emerges: While the Mie scattering images show very little difference between the charged and non-charged sprays, the velocity fields indicate that there are significant differences in the velocity of the droplets and also in the distribution of fuel droplets in the spray.

Notably, charged and non-charged sprays seem to
differ little in terms of overall penetration and spray angle, a point that is discussed in detail in [11]. For the same injection pressure and the same time after injector actuation, the sprays have developed to two cones that appear to be very similar when illuminated with laser light. The PIV measurement of the velocity field, however, shows the following striking difference. The velocity field of the uncharged spray has a coherent appearance of droplets moving with almost parallel velocities, practically parallel to the injector axis, except perhaps for a few droplets that interact with the initially stagnant ambient air at the periphery of the spray.

This is to be compared with the disordered velocity field of the charged spray in which no apparent structure can be observed. Evidently the Coulombic repulsion between droplets destroys the coherence of the uncharged spray. It should be noted that this is in principle a desirable effect, since it facilitates fuel-air mixing. Additionally, this disordered velocity field was observed for uncharged sprays at higher injection pressures. This leads to the conclusion that electrostatic phenomena can assist injection in the sense of inducing at lower injection pressures phenomena that would normally be observed at elevated pressures. This can potentially be a very important feature for efficient injector design, since the advantages of high injection pressures may be achievable without the massive hardware necessary to generate high fuel pressures.

It is also observed that the velocity field of the uncharged spray is nearly symmetric and extends approximately to the middle of the field of view. The charged spray velocity field, on the other hand, extends nearly over the entire field of view, indicating that the PIV instrument was able to resolve fuel droplets farther from the injector. Additionally, the velocity field of the charged spray exhibited more off-axis pockets of fuel in the lower region of the image. The charged spray occupied a greater portion of the image area.

The electrostatic charging also appears to affect the direction in which the droplets are traveling. Whereas the majority of the velocity vectors in the 0 kV spray are nearly parallel to the injector axis, the droplets in the 3 kV spray appear to be moving with significant radial velocity components.

Quantitative measurements of velocity along the injector axis are presented in Fig. 6. The non-charged spray exhibits a greater velocity near the injector tip, spikes approximately 8 mm below the tip, and then decreases. The zero velocities recorded from 16 to 21 mm indicate that no droplets could be resolved by the PIV system this distance from the injector. It is emphatically stressed that these points do not indicate stationary droplets. Notably, for the charged spray, a nearly monotonic increase in droplet velocity with distance from the injector tip was observed (with the exception of zero velocities indicating that the velocity could not be resolved).

3. Droplet Size Effects

The effect of electrostatic fields on droplet size are shown in summary in Fig. 7. There, results of Fraunhofer light diffraction (Malvern) measurements of droplet size as a function of time during spray evolution are presented. The data were taken at a distance of 9 mm from the injector tip, for an injection pressure of 2.8 bar. It should be noted that because of the way the Malvern technique operates, the data are integrated in the radial direction in the spray, i.e. the measurements provide an average size across the radial direction in the spray. At each time after injector actuation ten measurements were taken for both the charged (3 kV) and the non-charged spray and the mean value and the stan-
The fuel droplet is about $1.3 \times 10^{-12}$ g. Assuming a charge density of 2 nC/g results in a charge per droplet of $2.62 \times 10^{-15}$ C. Figure 3 suggests an electric field strength of approximately 350,000 V/m. Multiplying the field strength by the charge carried by a droplet gives a force due to the electric field of $1.2 \times 10^{-8}$ N.

A first observation that can be made is that there is, especially in the non-charged case, a slight increase of droplet size with time during the injection. This is in agreement with the theory proposed in [13], which predicts significant coalescence during transient injection. The suggestion that coalescence should be happening in the sprays under consideration is further supported by the fact that the temporal variation of size is significantly less for the charged spray. Evidently, in the non-charged spray coalescence causes a gradual increase in size in the non-charged spray. However, in the charged spray, droplet coalescence is hindered by Coulombic repulsion, and the related effect is much weaker. It is also noted that the non-charged sprays took significantly longer to pass through the particular axial location.

The droplets of the charged sprays are almost always finer than the those of the non-charged ones, but most notably, the standard deviation of the droplet sizes is smaller in the charged spray case by a factor of 4 (for approximately equal droplet size). This means that injections of charged sprays were much more repeatable than injections of non-charged sprays. From Fig. 7, it can be seen that the relative variation in the charged spray (i.e. the ratio of standard deviation to mean diameter) drops from approximately 15% to approximately 3% with the application of the electric field. This can be a potentially powerful design feature given the importance of precise control of droplet size for emission control.

**Forces on Charged Droplets**

Combining the results of the measurements described in the preceding sections, it is possible to estimate the forces exerted on a fuel droplet by the presence of the electric field, Coulombic repulsion with another fuel droplet, gravity, and viscous drag.

From the results of Fig. 7, it can be seen that a typical droplet diameter in a 2.8 bar spray is 150 µm. Using this value for diameter and assuming a spherical gasoline droplet with density 0.74 g/cm³, the mass of the fuel droplet is about $1.3 \times 10^{-6}$ g. Assuming a charge density of 2 nC/g results in a charge per droplet of $2.62 \times 10^{-15}$ C. Figure 3 suggests an electric field strength of approximately 350,000 V/m. Multiplying the field strength by the charge carried by a droplet gives a force due to the electric field of $1.2 \times 10^{-8}$ N.

The force due to Coulombic repulsion between two 150 µm diameter droplets at one diameter separation distance can be calculated knowing the charge on each droplet, $(2.62 \times 10^{-15}$ C) and the droplet diameter. The result is a force of approximately $2.7 \times 10^{-12}$ N.

For the purposes of comparison, the force due to gravity for our $1.3 \times 10^{-6}$ g droplet is $1.2 \times 10^{-8}$ N. The drag force can be calculated by using the well-established dependence of drag coefficient on Reynolds number. The result is a force due to drag equal to $4.3 \times 10^{-8}$ N.

The above calculations show that, without the use of conductivity enhancing additives, the force due to Coulombic repulsion is much smaller than the force due to the electric field. The force due to the electric field is, in turn, much smaller than the force due to gravity which is itself much smaller than the force due to viscous drag.

**Conclusions**

A commercially available fuel injector was modified with the addition of a simple electrode to allow electrostatic charging of the fuel spray. PIV measurements to characterize the sprays of the modified injector both with and without charge applied have shown that electrostatic charging results in increased vortical motion of the fuel droplets and that the charged spray occupies a greater portion of the PIV measurement plane. These enhanced vortical motions could be achieved equivalently by increasing the injection pressure. Electrostatic fields can therefore be used to induce fluid motions that are characteristic of elevated injection pressures at low pressure, thus avoiding the cost of the hardware necessary to run high injection pressure. Fraunhofer light diffraction measurements of droplet size showed a significant increase in repeatability of droplet size with electrostatic charging. Increased size repeatability could mean reduced unburnt hydrocarbon emissions from practical engines. The distribution of droplets, droplet velocities, and diameters of the charged sprays were similar to those of non-charged sprays at higher injection pressures. These results were obtained with only a modest fuel charge density, which could be increased with improved electrode geometry or the use of conductivity enhancing additives.

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**References**


