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# Electrical and transient atomization characteristics of a pulsed charge injection atomizer using electrically insulating liquids

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Charge injection atomizers are energy efficient devices that can be used in order to promote the atomization of dielectric liquids, and a potential application of such devices is fine spray delivery in small internal combustion engines. The operation of a pulsed charge injection atomization system operating at practical engine frequencies under a high voltage pulse train has not been well recorded in the literature. This initial investigation defines the electrical and transient global atomization performance of a charge injection atomizer operating under a steady flow regime, but with a typical high voltage pulse train. Results show that voltage-current characteristics follow similar trends to that of a steady flow, steady voltage system, and observation of the data also reveals that output current waveforms depend on the input pulse train frequency. No degradation in charging efficiency was observed at higher frequencies, which suggests that a charge injection atomizer can operate efficiently at practical engine speeds. Photographs also confirmed the high voltage pulse train injects charge that produces sections of primary atomization on the continuous liquid jet.



## 1. Introduction

A charge injection atomizer is a device that promotes the atomization of a dielectric liquid via the injection of charge into the liquid volume. The introduced charge promotes the atomization and dispersion of the ejected liquid jet [1–7]. The development of such devices is driven by the need to introduce more energy efficient methods for fuel atomization, and the most pressing need is to develop fuel spray combustion systems where precise control of the combustion mixture is possible. Two combustion systems that would potentially benefit are HCCI (homogeneous charge compression ignition) mode internal combustion engines and pulse detonation engines. In both these cases, a highly homogeneous fuel-air mixture is required in order to reduce harmful emissions such as unburnt hydrocarbons [8]. Preliminary work examining the turbulent mixing of charged particles shows this seems feasible [9]. Here, the target application is a small internal combustion engine (50–250 cc), where maximum injection pressure is limited to approximately 2 bar. In such small engines, use of conventional high pressure fuel injection systems consumes too much of the engine power output. Therefore, an electrostatic atomizing device is a very attractive option as it is electrically efficient and is not power intensive [4,5,10–12]. A further application of this atomization device is in the food processing industry, where controlled coating of products with edible oils is required, e.g. the coating of bread tins on a production line.

Fig. 1 shows a schematic of a steady flow charge injection atomizer where a negative high voltage Spellman model LS30PN power supply is connected to the central electrode forming an electric field between the electrode and the grounded orifice plate. As the dielectric liquid passes over the electrode, charge is injected and upon exiting the orifice of diameter $d$, the charge present within the bulk of the liquid acts to promote the atomization of the emerging jet. The current carried away from the atomizer body by the liquid jet is termed the spray current, $I_S$, and the current that passes through the liquid to the atomizer orifice plate and then to earth, is known as the leakage current, $I_L$, where the total current $I_T = I_L + I_S$. The dominant electrical force present within the liquid in the atomization zone is a radial coulomb force dependent on the applied electric field and charge density within the liquid. The operation of such steady flow, constant DC voltage atomizers is well documented [1–7,11]. Spray characterisation has been carried out in the past using photography and phase Doppler anemometry [7,11,13,14], and electrical measurements have also been acquired [1–4,6,7,11].

The reader should note that constant DC current-voltage, or $I_T$-V characteristics, are independent of a number of parameters.

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**List of symbols**

| | | | |
|---|---|---|---|
| $A_d$ | Drop x-sectional area, $m^2$ | $r$ | Radial position, m |
| $C_D$ | Drag Coefficient, N/A | $t$ | Time, s |
| $D$ | Diffusion Coefficient, $m^2/s$ | $T$ | Temperature, K |
| $d$ | Diameter, m | $u$ | Velocity, m/s |
| $E$ | Electric field, V/m | $V$ | Electric potential, V |
| $e$ | Elementary charge, C | $\varepsilon$ | Electric permittivity, F/m |
| $I$ (rms) | Current, A (rms) | $\kappa$ | Ionic mobility, $m^2/Vs$ |
| $k_B$ | Boltzmann constant, $m^2kgs^{-2}K^{-1}$ | $\lambda_d$ | Debye length, m |
| $l$ | length scale, m | $\Lambda$ | Nozzle to spray can distance, m |
| $m$ | mass, kg | $\mu$ | Dynamic viscosity, Pa s |
| $n$ | Volume number density of charged ions, $-/m^3$ | $\rho$ | Density, $kg/m^3$ |
| $Q$ | Mass charge density, $C/kg$ | $\sigma$ | Electric conductivity, $1/\Omega m$ |
| | | $\tau$ | Time scale, s |

Specifically, a linear or ohmic regime, followed by a parabolic or charge injection regime [4,15] is observed. This characteristic is independent of the internal atomizer geometry L/d, injection velocity, fuel type and orifice hole size [4,6,11,16]. Further work examining multiple orifices also shows that the $I_T$-V characteristic is independent of the number of holes as well as the pattern of the holes [6,7,17] showing that the injection of charge into the liquid is determined by the emitter surface. This type of I–V characteristic, i.e., the linear followed by a parabolic regime is also observed in quiescent liquids, where charge injection in to point-plane and plane–plane geometries has yielded very similar relationships [15,18].

Constant DC voltage operation of this technology is well documented, however in order to apply this technology to a pulsed system such as an engine, research into the use of pulsed charge injection atomizers is required, and this has not been widely reported in the literature. A first attempt at developing a pulsed charge injection atomizer was made by [19] in collaboration with Robert Bosch GmbH. Some data was published regarding the electrical and spray characteristics of the atomizer [19], however detailed studies investigating the effect of different frequencies and internal geometry were not documented. A patent for a pulsed voltage pulsed flow electrostatic atomizer was brought forth by [20]; however data from a working prototype is not available.

The optimal use of pulsed charge injection atomizers requires the understanding of the transient nature of charge injection. Extensive research regarding transient unipolar injection has been carried out by [18] where the application of a voltage step in to a quiescent dielectric liquid was investigated, and important timescales were revealed. Timescales defining how long it takes for an instability to appear in a dielectric after first application of voltage were determined [18]. However, the analysis was restricted to quiescent liquids and to single voltage steps. Qureshi [21] examined the effect of applying repeated voltage pulse trains in to dielectrics, however once more, the research was restricted to quiescent liquids, and in this case concentrated on discharge phenomena rather than maximizing the injected current. Furthermore, his experiments were not at frequencies and duty cycles typical of small engine applications.

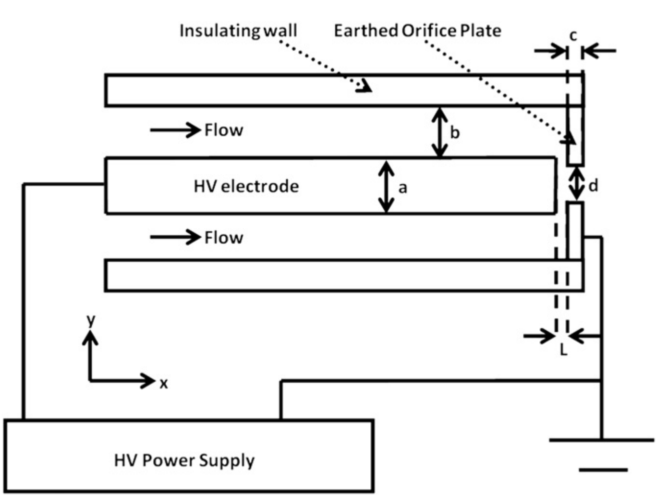


**Fig. 1.** Schematic of steady flow charge injection atomizer.

Other previous work in pulsed voltage operation has been carried out by [22] where a qualitative analysis of atomization was carried out for liquid hydrocarbons as a function of voltage repetition frequency, flow rate and voltage level. The investigation revealed a dependence of atomization quality on frequency, voltage and flow rate, however no quantitative data was provided regarding electrical performance. The effect of voltage pulses on the operation of ESPs (electrostatic precipitators) has also been reported. A paper by [23] examines what effect a pulsed voltage superimposed on to a DC voltage has on the roll structures attained, using PIV (particle image velocimetry). The research revealed that a voltage pulse train aids in the creation of roll structures, which is a desired phenomenon for an ESP [24,25]. The reader should note however that in ESPs, air is the driven fluid, which has a larger charge mobility value than the dielectric liquid we consider here. The larger charge mobility of a dielectric the more the electrically induced motion is decoupled from the fluid dynamics, as the convection of charged air is mainly driven by the presence of an electric field rather than a bulk flow. With low mobility dielectrics, such as hydrocarbon fuels, both the electric field and the bulk flow play a significant role in the convection of the liquid leading to strongly coupled and chaotic fluid motion for sufficiently strong charge injection.

In summary, the transient voltage, current, and fluid-flow operation of pulsed charge injection atomizers is not well documented in the literature. This paper serves to provide and analyse data which examines the electrical and spray performance of a pulsed square wave voltage, but steady flow charge injection atomizer. The reader should note that for use in internal combustion engines, both the flow and voltage would have to be pulsed in order to supply the combustion chamber with dispersed and atomized fuel intermittently. However, examination of the simpler pulsed voltage-steady flow case is a necessary step towards developing a fully pulsed flow and pulsed voltage electrostatic atomization device. The reason being that such a study will isolate the effect of transient charge injection on electrical and atomization performance as opposed to adding a level of complication resulting from pulsing the flow also, which would lead to fluid acceleration and deceleration within the electrode gap.