Experimental Investigation of Electrical Characteristics of Electrodynamic Atomization

Shehzaib Yousuf Khan[1], Muhammad Uzair[2,*], and Assaad Masri[1]

ARTICLE INFO

Article history:
Received: 26 April 2020
Revised: 15 January 2021
Accepted: 7 March 2021

Keywords:
Electrohydrodynamic
Electrical characterization
Atomization
Biodiesel
Spray current
Specific charge
Leakage current

ABSTRACT

The study presents the electrical characterization of charge injection atomization of an electrohydrodynamic spray of different biodiesel blends comparing with the conventional and commercial diesel fuels. The electrohydrodynamic atomization is not commercially available due to limited knowledge. So, in this study, experimental work was performed using an electrohydrodynamic atomizer on diesel fuel and different biodiesels. The selected biodiesels (B1 to B4) are all saturated fatty acid esters (FAMEs) with shorter to larger carbon chain lengths and different unsaturation degrees. The electrical characteristics of diesel and biodiesel fuels such as spray current, specific charge, and leakage current have been investigated and compared.

1. INTRODUCTION

The electrohydrodynamic (EHD) atomization of liquid fuel has always been an interesting research area since the work of Kim and Turnbull [1]. Kim & Turnbull used a chemically etched tip needle in a glass capillary with very low flow rates and current to produce electrostatic spraying in insulators. The EHD atomization works on a similar mechanism of fuel injection in small internal combustion engines however the EHD atomizer or electrostatically charged fuel injection system consumes much lower electrical power less than 2 m-Watt to generate sprays of fuel. EHD atomization is promised to provide for thermally efficient fuelled small engines less than 50-100cc and micro-combustors. However, due to limited knowledge and research EHD atomizers are not commercially available for combustion applications.

The limitation of the flow rate of 10^{-3} mL/s was surpassed by Kelly [2] who proposed a 'Spray Triode', a modified atomizer orifice contraction design with an additional grounded electrode. The EHD atomizer was predominantly upgraded in three stages on modifying the nozzle design by introducing compact 'Spray Triode' by Kelly [2]. The first version of the nozzle design was a simple electrode, charge emitter needle, and orifice design for a large diameter ~500 μm based on the work of Jido [3,4]. However, the first version of the EHD atomizer was not only limited to 10^{-3} mL/s flow rate and 10^{-9} A total current but also the performance is decreased since needle tip become blunt due to high electric flux causing Joule heating at the tip. The second improved version of Kelly's [2] Spray Triode design allowed the atomizer to operate at volumetric flow rates of 1 mL/s which was much greater than that of Kim & Turnbull [1]. The issue with the lower amount of current was also solved by placing grounded orifice plate as anode near to the specialized cathode charge emitting needle which is also similar to the work by Denat et. al and other co-workers [6,7,8]. The tip radius of the charge emitting electrode was later increased to ~50-60 μm which was highlighted the fact by Shrimpton [5,9,10] that the atomizer work with the same performance for a radius greater than 1 μm a specialized emitter tip material of Kelly [2] was not required. The stainless-steel sewing needle was used by Yule et. al [11] of tip radius 60 μm which corrected the wrong assumption of Kelly [2] based on the field emission mechanism of Kim & Turnbull [1], that Spray Triode required emitter tip radius of fewer than 1 μm so that the surface electric field intensity is increased. Shrimpton [9,10] preferred to use negative polarity over positive. The charge emitting electrode requires lower electric field intensities $E \sim 5 \times 10^{9}$ V/m for negative polarity or field emission, whereas positive polarity or field ionization typically requires $E \sim 5 \times 10^{10}$ V/m, greater in the magnitude of 10, which was proposed by Robinson et al [12]. Crowley [13] suggested that the electric breakdown

[1]*School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Australia.*
[2]*Department of Mechanical Engineering, NED University of Engineering and Technology, Pakistan.*
**Corresponding author:* Muhammad Uzair; Email: uzair@neduet.edu.pk.

strength in most of the commercial fuels is found to be E ~ 20 x 10^6 V/m.

The main focus of this paper is to find out the electrical characteristics of EHD atomization using primary atomization. The electrical characteristics are observed for higher spray specific charge and electrical field with current and voltage measurements. The electrical characteristics of the EHD atomizer are quantified with some electrical properties such as electric field, applied voltage, spray specific charge, spray current, leakage current, and total current. The spray current I_S is the current carried throughout the spray from the needle electrode tip whereas the leakage current I_L is the current that is leaked in the atomizer through the fluid to the atomizer body. The sum of spray current I_S and leakage I_L current defines the total injected current $I_T = I_S + I_L$. The most desirable condition to operate an EHD atomizer is that the spray current should be higher while reducing the leakage current. The specific charge and spray current are related and can be found by dividing spray current by the volumetric flow rate.

Singh et al [14] used a similar device to investigate the near-field characteristics of charge injection atomizer sprays and observed the reduction in specific charge due to an increase in temperature. The reason for the reduction is due to a decrease in viscosity at higher temperatures resulting in increased ionic drift. It was suggested that preheating high viscosity fuel improves the spray atomization and relatively smaller droplet sizes are produced.

Ahmed et al [15] investigated the effect of specific charge on the droplet and ligament size of a hybrid atomizer diesel sprays which was air-assisted as well as electrostatically injected. It was suggested that the effect of the charge depends on the aerodynamic Weber number. Weber number [16] is an important dimensionless number studied for the formation of droplets which is the ratio of inertial forces to surface tension force.

Li et al [17] reported the effect of additive Al nanoparticles in ethanol which reduces the droplet diameter of charge injection atomizer sprays. The atomization performance significantly improves on increasing the nano-Al concentration which was observed from the breakup of a jet under a strong electrical field. The electrostatic breakup in high nano-Al concentration was found to be influenced by effective surface tension reduction as proposed by Shrimpton et al. [18].

2. EXPERIMENTAL SETUP

Figure 1 [19] shows the schematics of an electrohydrodynamic (EHD) atomizer or pulsed charge injection atomizer designed and manufactured at The University of Sydney. The design consists of the following main components: atomizer housing, electrode housing, electrode, orifice base disk, micrometer. The housing is made of Perspex while the negatively charged electrode and the orifice disk both are made of copper. The orifice disk is also called a grounded electrode which has a central nozzle of diameter (D) equal to 250 μm. The inter-electrode gap (L) from the electrode tip to the orifice disk can be controlled with the micrometer. The micrometer used is a Starrett 262RL Micrometer Head which has a non-rotating spindle and ranges from 0 to 1 inch with 0.001-inch graduation. The round intervals are noted for setting up the inter-electrode gap with 25 intervals each consisting 4th part of 0.1 inches. The intervals are taken as 8, 10, 12, 15, 17, 19, 21, and 23 to determine the important geometric dimensionless parameter known as normalized electrode gap which is the ratio of electrode gap to the diameter of the nozzle (L/D). An electrostatic charge is injected with this atomizer through the nozzle orifice which creates jet breakup and sprays downstream the nozzle. This atomizer design is similar to the third generation point-to-plane atomizer. The electrical circuit is completed by connecting the electrode through the housing by inserting an insulated copper wire.

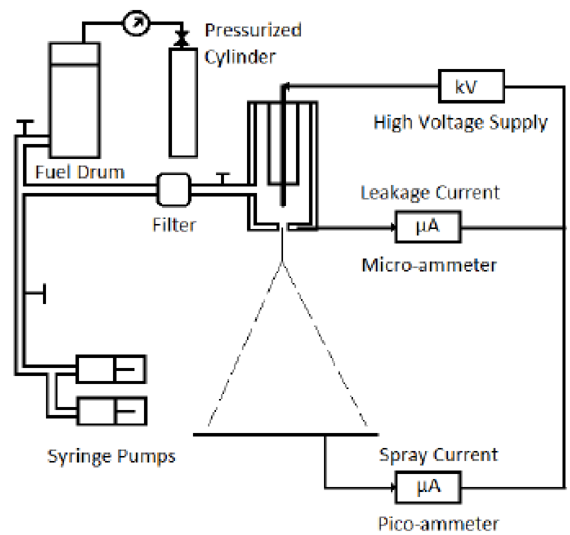

Fig. 1: Circuit Schematics of EHD Atomizer.

Figure 1 shows the circuit schematics of the EHD atomizer where high voltage is supplied with high voltage power supply and two ammeters connected in parallel connection. The experiments were done with two different hydraulic fuel circuit setups. The first setup consists of a simple flow rate control valve with a float connected to the pressurized cylinder vessel, while the second setup as shown in Figure 1 comprises of two syringe pumps connected in parallel. The fuel was supplied from a fuel drum with an oil filter and pressure tees and valves connected to filter contaminants and control the capacity of the syringe. The high voltage power supply used in the experiments is a Spellman SL Series; model SL10, which has a range from 1 kV to 130 kV and 10Watt power output.

The power supply is used with negative polarity from 0 to -14.5 kV.

The leakage current I_L was measured using a micro-ammeter connected to the orifice base disk and grounded with the high voltage power supply. The Simpson 04359 Taut-band 0-10 DC Micro Ammeter 1327 Series was used for this measurement which ranges from 0 to 10 μA with a least count of 0.2 μA. The leakage current was measured for the current from the electrode tip through the fuel leaked to the atomizer body.

The spray current I_S was measured using an ammeter connected to the spray collector tray and the ground. The spray current was measured for current carried with the fuel sprayed outside through the atomizer nozzle orifice collected at the ground. The Keithley Model 6485 Picoammeter was used for the measurement by taking a mean of the values observed on the device screen. The pressure cylinder was set to 40 psi to allow continuous and steady flow through the hydraulic circuit and the atomizer nozzle orifice. The flow rate was controlled initially with a simple flow control float value which was directly connected with a pipe to the atomizer fuel inlet. The flow control valve was calibrated for flow rates with the float. The operating condition for Diesel fuel was obtained at a flow rate of level 6 giving 9.31 mL/min of volumetric flow rate for constant nozzle diameter D=250μm and injected velocity $uinj$ = 3.4 m/s. Later on, the GenieTouch syringe pump system was used consisting of two syringes at a time facing the same direction with a capacity of up to 60ml. The flow rates were calibrated for different injected velocity $uinj$ = 2.5, 5, 7.8 and 10 m/s and constant nozzle diameter D=250μm giving volumetric flow rates of 7.36, 14.73, 22.90, 29.35 mL/min

The experiments on EHD atomization were completed using four different Biodiesel blends B1, B2, B3, and B4 with Diesel fuel as in previous work of Pham [20,21]. These Biodiesel blends B1, B2, B3 and B4 are the fatty acid methyl esters (FAMEs) produced from methanolysis transesterification of Palmere, Coconut, Pale, and Canola Oils respectively. These biofuels have different carbon chain lengths and saturation levels. B4 is almost fully unsaturated and has long and similar chain lengths to B3 as compared to B1 and B2, however, B3 is partially unsaturated. B1 and B2 are saturated FAMEs where B2 has a shorter carbon chain length as compared to B3 and B4 while B1 has the shortest carbon chain length among all four Biodiesels. The carbon chain length affects the fuel properties such as viscosity where larger chain lengths and large molecules are highly viscous thus also resulting in lower ionic mobility which is inversely proportional to the viscosity according to Walden's rule κ = Cμ-1 [22]. The early abbreviation used for B1, B2, B3, and B4 are C810, C1214, C1618, and C1875 respectively [21]. The fuel properties of different selected biodiesels and diesel fuel are shown in Table 1.

Table 1: Fuel Properties for the fuels [21]

Fuel Properties	B1	B2	B3	B4	Diesel
Average # of C atoms	9.5	14.8	18.3	18.7	-
Average # of H atoms	19.7	28.3	35.3	35.3	-
Relative density, (kg/m^3)	0.877	0.871	0.873	0.879	0.848
Viscosity, [Pa.s].10^3	1.71	3.81	4.32	4.65	3.2
Surface Tension, [N/m].10^3	26.1	28.4	29.9	29.96	23.0

3. RESULTS

The electrostatically charged sprays start forming by increasing applied voltage using a high-power supply. Electrical Characterization of Electrostatic Charged Atomization is discussed separately in terms of Spray current I_S, Specific Charge Q_V, and leakage current I_L.

3.1 Spray Current I_S

The spray current I_S for diesel and biodiesel blends B1, B2, B3, B4 at L/D = 1.5 and 2 and variable jet velocities of 2.5 m/s, 5 m/s, 7.8 m/s, and 10 m/s are plotted against the applied voltage V as shown in the Figures 2-6. The different plots of spray current show parabolic profile with increasing voltage and a peak value were reached at a certain voltage, known as critical voltage Vc. As the voltage increased beyond this point the spray current started decreasing and the spray collapsed at the jet and reached the breakdown. The profile increased significantly up to the critical voltage and after this point, the spray current dropped. The parabolic profile was dependent on the voltage, L/D ratios, jet velocities, and fuel type. Lower L/D ratio reaches maximum spray current prior to higher ratio and same for higher jet velocities.

Higher spray current values were observed for more viscous fuel such as Diesel, B3, B4 as compared to B1, B2 due to the lower ionic mobilities. The ionic mobility plays a vital role in the electrical performance of the fuel which is defined by Walden's rule [17] κ = Cμ-1, larger the molecular ions less sensitive the electric field. The electric field decreased as L/D increased which caused a low level of charge emittance and due to this phenomenon of electrohydrodynamics, the electric charge reduced the electrostatic force between the spray and the droplets which lead to narrow spray angle, large droplet sizes, and long jet breakup tip length.

When the jet collapsed on the orifice, all the spray current was transferred to the grounded atomizer body and after this point, the spray current did not significantly increase with applied voltage, however, the leakage current increased sharply. For some conditions of diesel and different biodiesel blends, there was no spray breakdown occurring at the nozzle orifice while increasing the applied voltage. The spray current profiles for the selected fuels were similar qualitatively, however, to achieve maximum spray current, higher applied voltage values were required for biodiesel blends.

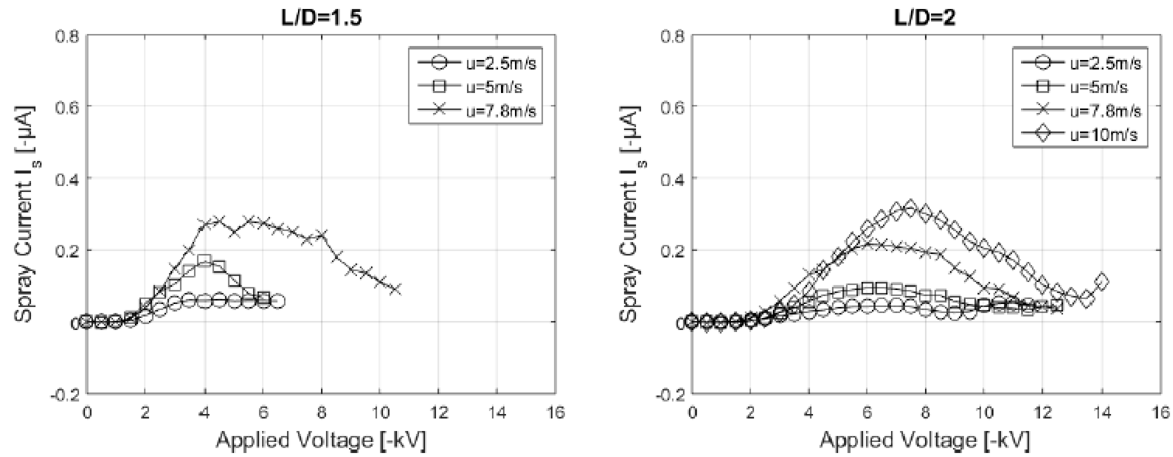

Fig. 2: Spray current versus voltage for Diesel at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

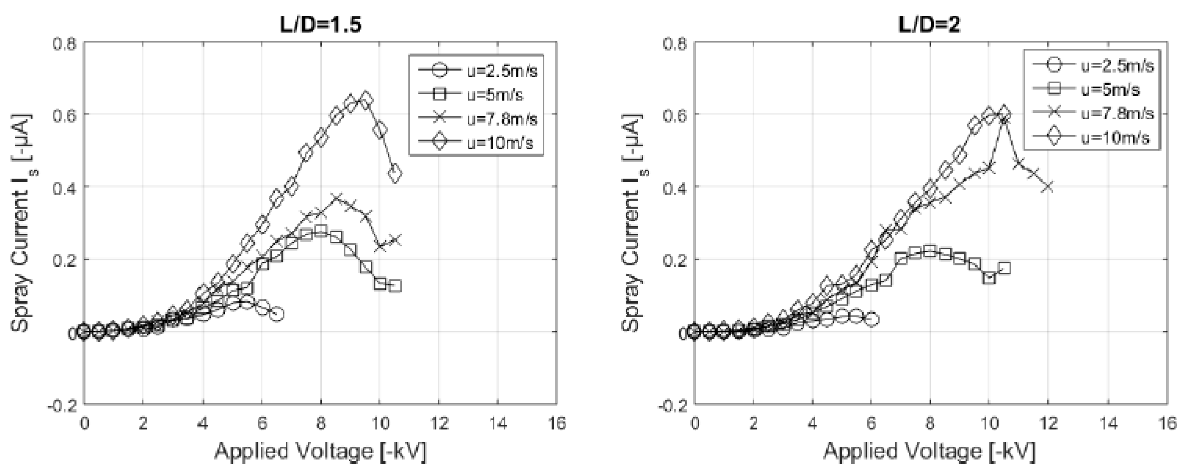

Fig. 3: Spray current versus voltage for Biodiesel B4 at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

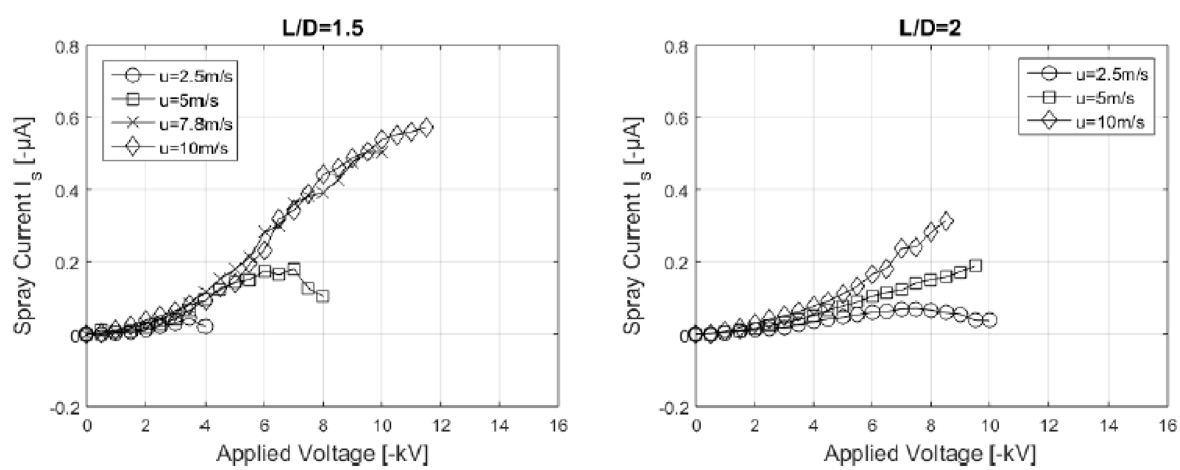

Fig. 4: Spray current versus voltage for Biodiesel B3 at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

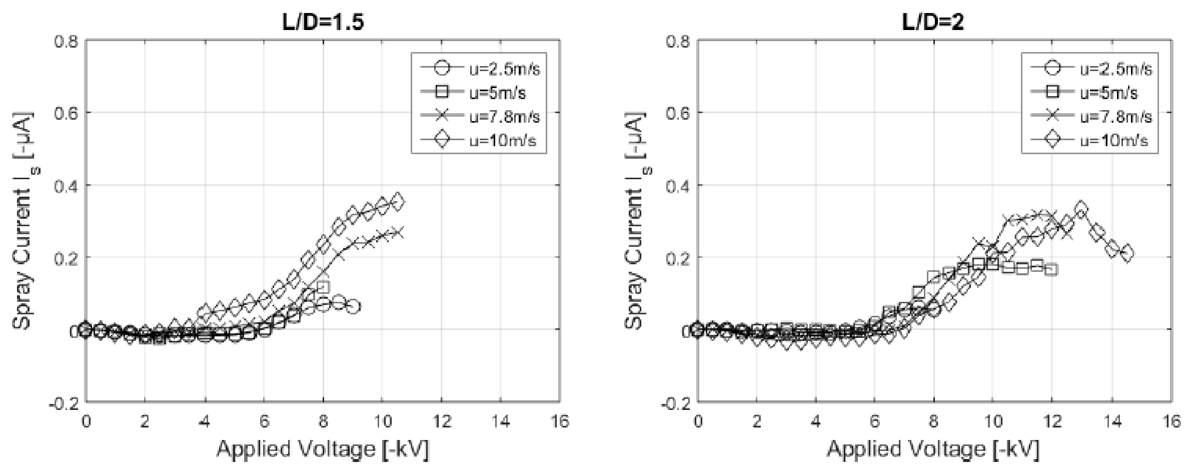

Fig. 5: Spray current versus voltage for Biodiesel B2 at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

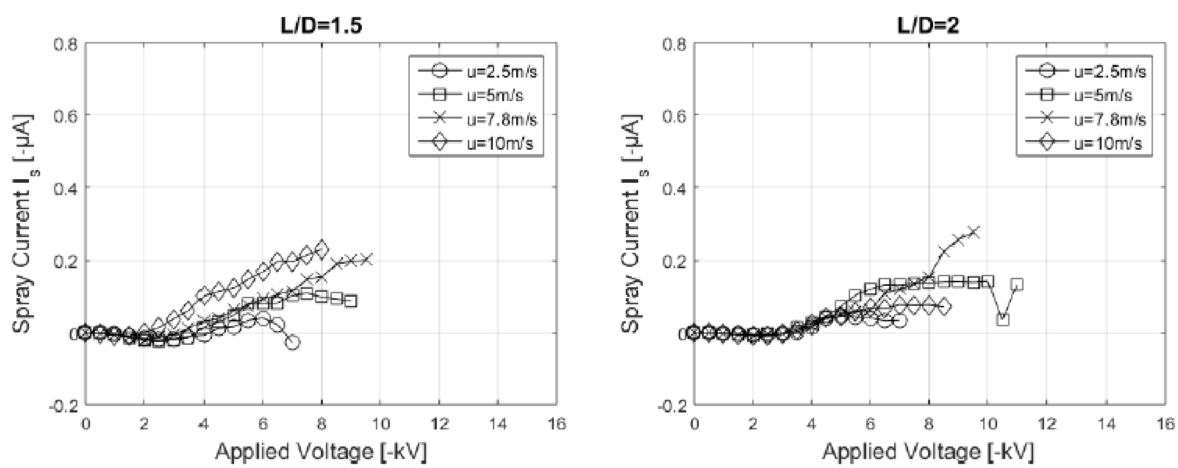

Fig. 6: Spray current versus voltage for Biodiesel B1 at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

3.2 Specific Charge QV

The specific charge is the ratio of spray current to the volumetric flow rate. The specific charge Q_V plots are obtained for different biodiesels and diesel at D=250µm, L/D=1.5, and 2 with different jet velocities uinj=2.5, 5, 7.8, and 10 m/s as shown in Figures 7-11. It has been observed that the specific charge was higher for higher fuel viscosity such as B4, B3, and Diesel and lower for B2 and B1 similar to the spray current profile whereas the leakage current was higher in B1 and B2, and got lower in B3, B4, and Diesel. The maximum spray specific charge was higher in EHD atomizer for smaller L/D=1.5 and showed a higher curve as compared to L/D=2. Furthermore, higher injection velocities allowed more charge to flow in the EHD atomization compared to low velocity.

The peak values of spray specific charge called maximum specific charge were obtained for different biodiesels and diesel and presented in Table 2. The biodiesels B1, B2, B3, B4 and Diesel were recorded with maximum specific charge 0.73, 0.86, 1.32, 1.55 and 0.79 C/m3 at critical voltages 9.5, 11.5, 9.5, 10.5 and 5 kV respectively at D=250µm, L/D=1.5 and 2 with different jet velocities uinj=2.5, 5, 7.8 and 10 m/s.

Table 2: Physical Properties of Diesel Fuel and different Biodiesel Blends

Fuel	Density, ρ (kg/m3)	Viscosity, µ (Pa.s)	Surface Tension, σ (N/m)	Max Qv (C/m^3)
B1	877	0.00171	0.0250	0.16 – 0.73
B2	871	0.00381	0.0330	0.48 – 0.86
B3	873	0.00432	0.0440	0.35 – 1.32
B4	879	0.00465	0.0280	0.35 – 1.55
Diesel	848	0.0032	0.0260	0.38 – 0.79

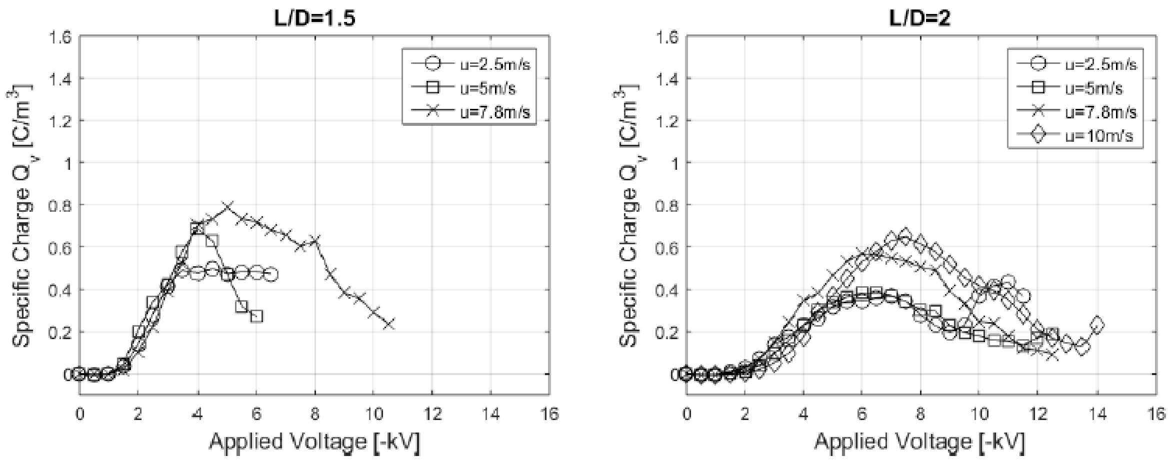

Fig. 7: Specific charge versus voltage for Diesel at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

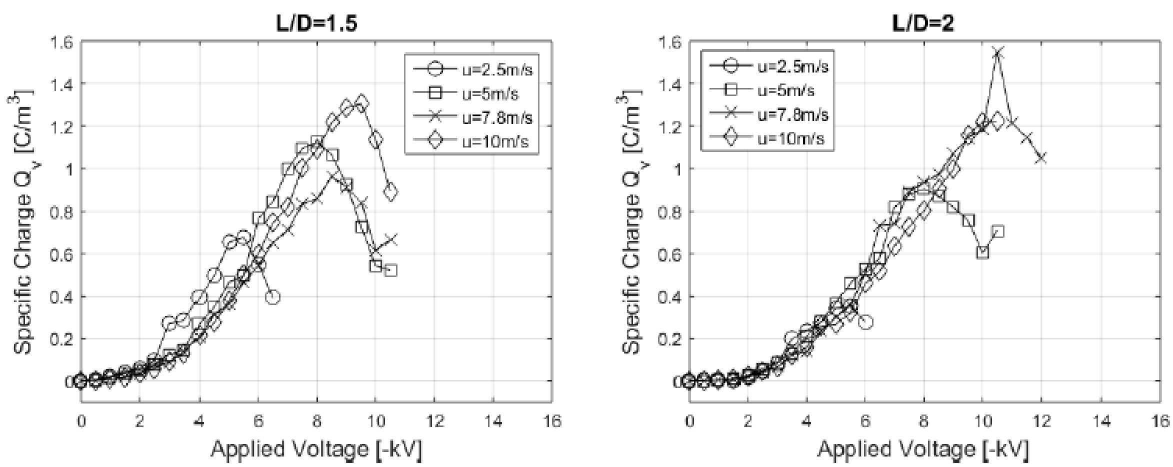

Fig. 8: Specific charge versus voltage for Biodiesel B4 at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

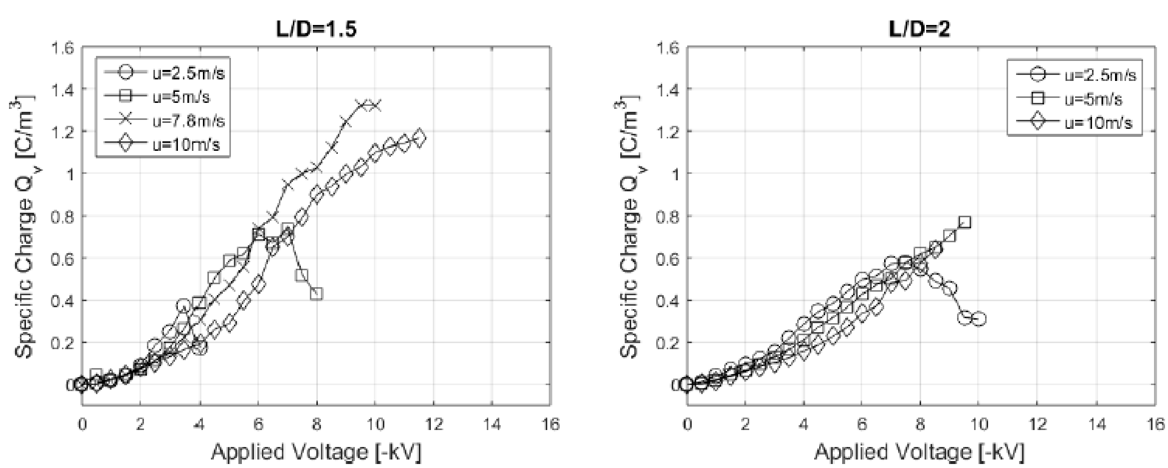

Fig. 9: Specific charge versus voltage for Biodiesel B3 at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

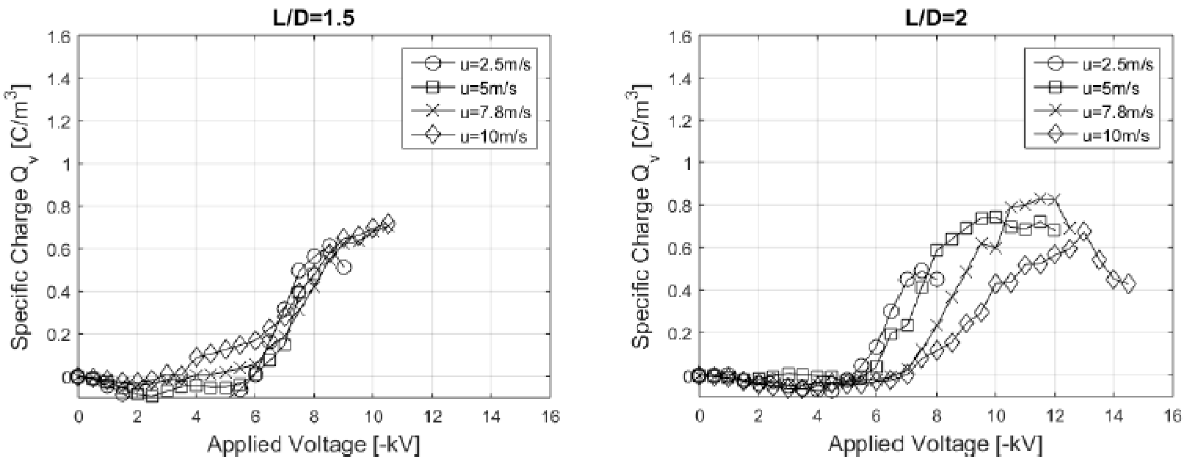

Fig. 10: Specific charge versus voltage for Biodiesel B2 at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

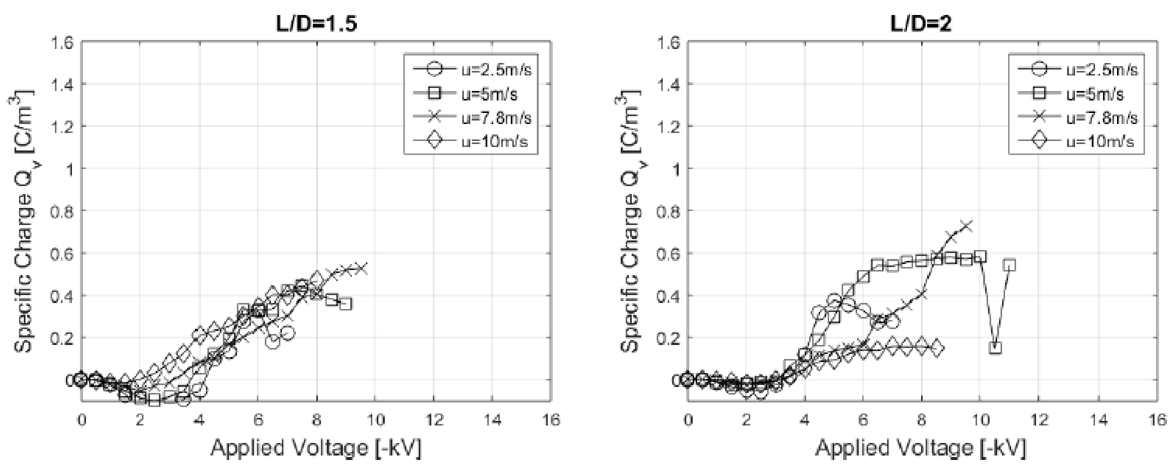

Fig. 11; Specific charge versus voltage for Biodiesel B1 at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

3.3 Leakage Current IL

The leakage current IL for diesel and biodiesel blends B1, B2, B3, B4 at D=250µm, L/D = 1.5 and 2 and variable jet velocities of 2.5 m/s, 5 m/s, 7.8 m/s, and 10 m/s are plotted against the applied voltage V as shown in the Figures 12-16. It is seen from different plots of spray current and leakage current, the leakage current increased very significantly on increasing after the critical voltage, however at a certain point the leakage current started developing above zero-level on the micro-ammeter. At this point the applied voltage was known as threshold voltage V0, which was also noticeable for more viscous Diesel, B3, B4 and reduced for B1, B2. The leakage current profile increased more sharply for low viscous B1, B2 as compared to the higher viscosity fuels. The leakage current plots for different jet velocities are very similar and do not vary that much, however, there is a slight difference for lower L/D where threshold voltage was a little lower and the profile developed prior to higher L/D. Thus the threshold voltage depended less on the L/D ratios and jet velocities but more on the liquid type, the lower ionic mobility of large molecular ions and higher viscosity developed the threshold voltage much later when the ion drift started through the liquid film from the needle electrode to the nozzle orifice. The leakage current increased slowly from V0 to VC for all selected fuels and conditions and after the critical point, it increased sharply due to breakdown which transferred all the spray current to the ground of the nozzle. The leakage current profile before critical voltage for more viscous fuels, Diesel, B3, B4 was much lower than B1, B2 which was also due to the effect of viscosity on charge distribution in the atomizer.

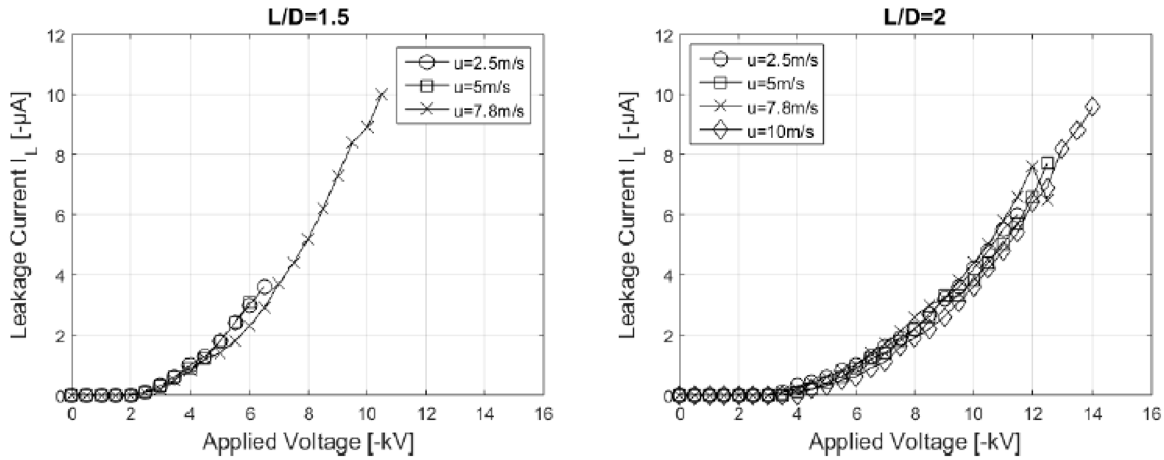

Fig. 12: Leakage current versus voltage for Diesel at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

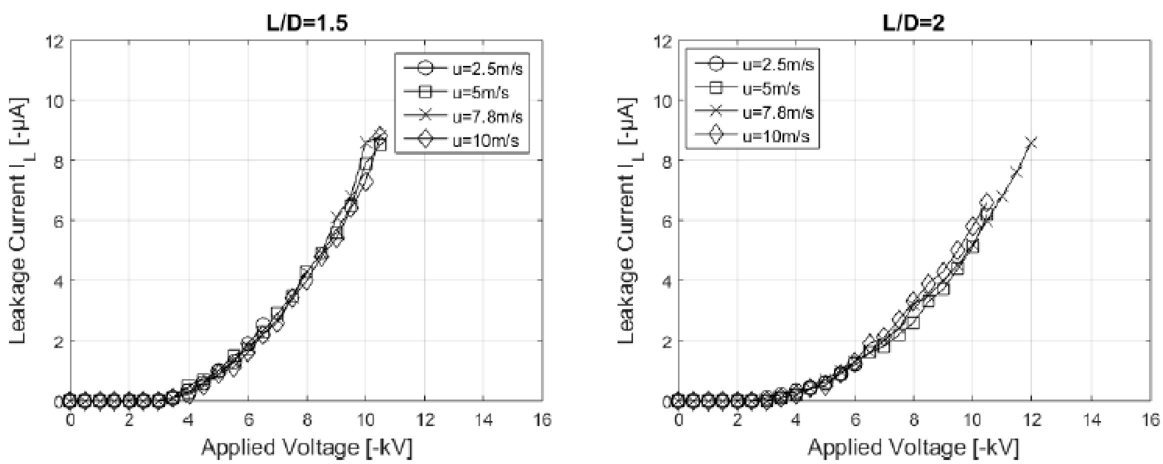

Fig. 13: Leakage current versus voltage for Biodiesel B4 at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

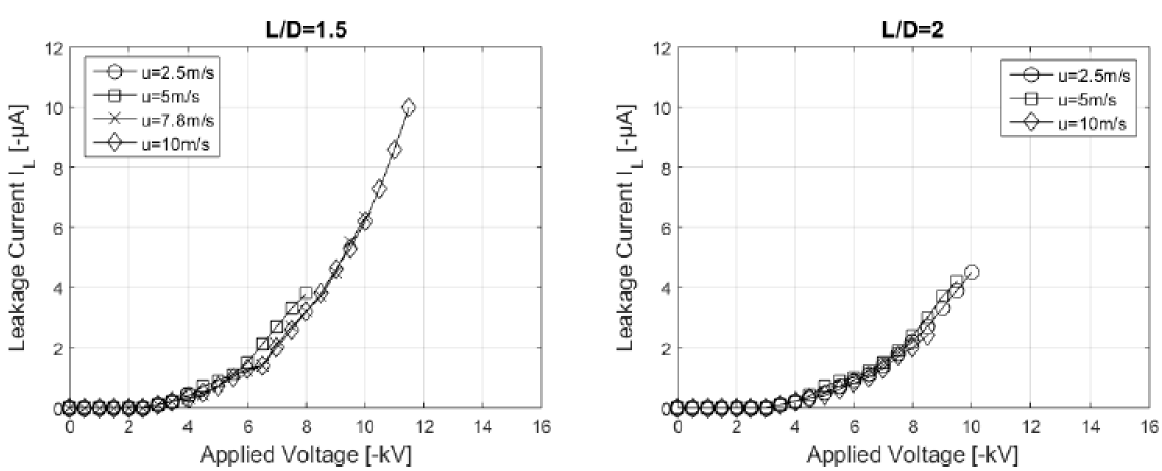

Fig. 14: Leakage current versus voltage for Biodiesel B3 at D=250µm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

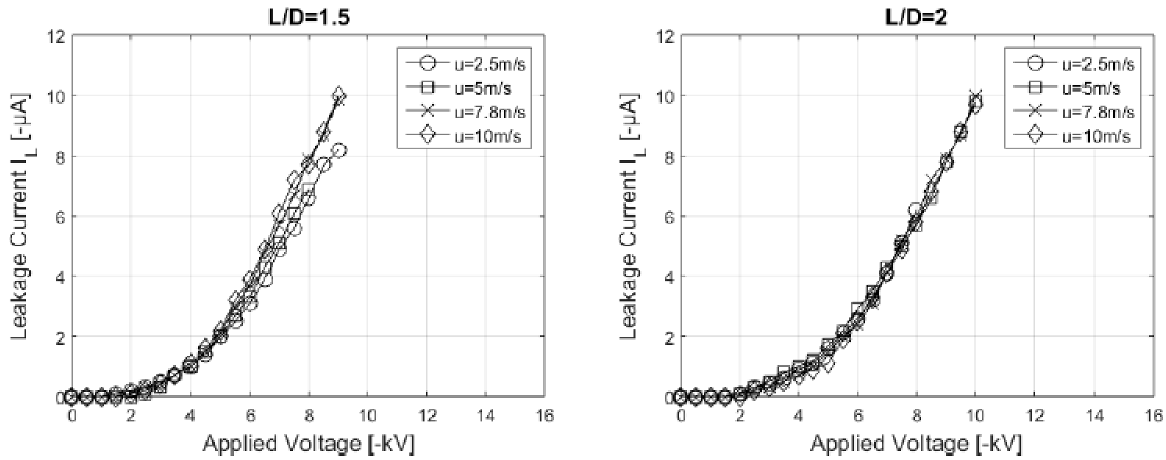

Fig. 15: Leakage current versus voltage for Biodiesel B2 at D=250μm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

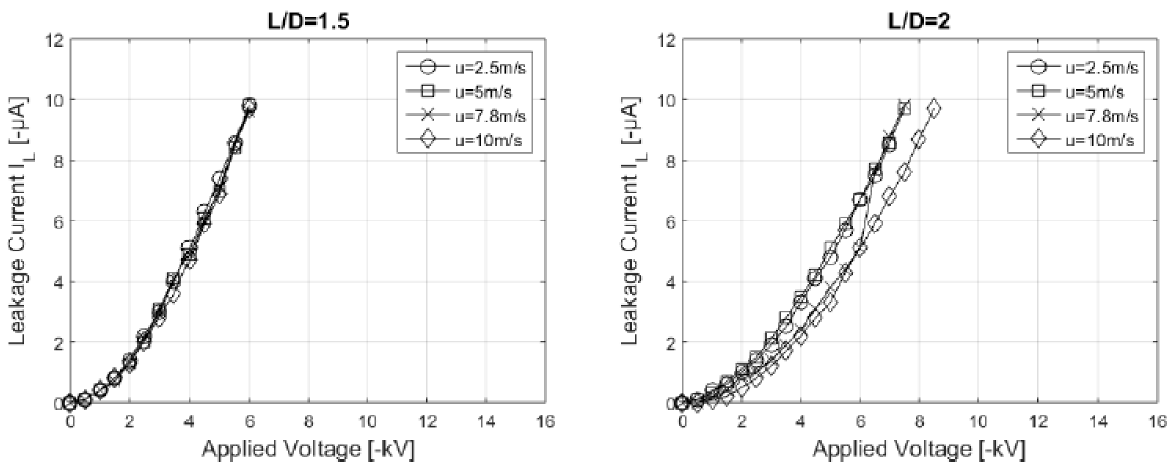

Fig. 16: Leakage current versus voltage for Biodiesel B1 at D=250μm, L/D=1.5 and 2 with different injection velocities uinj=2.5, 5, 7.8 and 10 m/s.

4. CONCLUSION

The experimental studies demonstrate that the parabolic profile of spray current with increasing voltage and a peak value was reached at a certain voltage, known as critical voltage Vc. The profile increased significantly up to the critical voltage and after this point, the spray current dropped. The parabolic profile was dependent on the voltage, L/D ratios, jet velocities, and fuel type. For the specific charge, It has been observed that the specific charge was higher for higher fuel viscosity such as B4, B3, and Diesel and lower for B2 and B1 similar to the spray current profile whereas the leakage current was observed higher in B1 and B2, and got lower in B3, B4 and Diesel. While the leakage current profile increased more sharply for low viscous fuels as compared to the higher viscosity fuels.

ACKNOWLEDGEMENTS

We would like to thank The University of Sydney for giving the opportunity to research in the field of Electrohydrodynamics.

REFERENCES

[1] Kim, K., Turnbull, J.: Generation of charged drops of insulating liquids by electrostatic spraying. Journal of Applied Physics 47(5), 1964 (1976)
[2] Kelly, A.J.: The electrostatic atomization of hydrocarbons. Journal of the Institute of Energy, 312–320 (June 1984)
[3] Jido, M.: Study of Electrostatic Charged Droplets: Part 1. J. Jap. Soc. Chem. Eng. 40, 24–33 (1986)
[4] Jido, M.: Study of Electrostatic Charged Droplets: Part 2. J. Jap. Soc. Chem. Eng. 41, 32–40 (1987)
[5] Shrimpton, J.S, Charge Injection System, Springer 2009
[6] Alj, A., Denat, A., Gosse, J.P., Gosse, B.: Creation of charge carriers in non-polar liquids. IEEE Transaction on Electrical Insulation 20(2), 221 (1985)

[7] Denat, A., Gosse, J.P., Gosse, B.: Electrical Conduction of Purified Cyclohexane in a Divergent Electric Field. IEEE Transactions on Electrical Insulation 23(4), 545–554 (1988)

[8] Nemamcha, M., Gosse, J.P., Gosse, B., Denat, A. Influence of insulating electrode coatings on the electrical conduction of cyclohexane. IEEE Transaction on Electrical Insulation 23(4), 529 (1988)

[9] Shrimpton, J.S.: Electrostatic Atomization and Combustion of Hydrocarbon Oils, PhD thesis, UMIST, Manchester, UK (1995)

[10] J.S. Shrimpton. Electrostatic Atomization and Combustion of Hydrocarbon Oils. UMIST, 1995.

[11] A.J. Yule, J.S. Shrimpton, A.P. Watkins, W. Balachandran, and D. Hu. Electrostatically atomized hydrocarbon sprays. Fuel, 74:10941103, (1995).

[12] Robinson, K. S., Turnbull, R. J., and Kim, K., "Electrostatic Spraying of Liquid Insulators," Trans. IEEE Ind. App. Sys. 16: 308-317, 1980.

[13] J.M. Crowley. Fundamentals of Applied Electrostatics. Laplacian Press, 1999.

[14] Singh, G., Pham, P. X., Kourmatzis, A., & Masri, A. R. (2019). Effect of electric charge and temperature on the near-field atomization of diesel and biodiesel. Fuel, 241, 941-953.

[15] Ahmed, T., Kourmatzis, A., Masri, A. R. (2020). Atomization behaviour of a hybrid air-blast-electrostatic atomizer for spray combustion. Fuel. (Accepted). 10.1016/j.fuel.2020.119716.

[16] Sirignano, W.A., Fluid Dynamics and Transport of Droplets and Sprays, 1999.

[17] Li, S., Zhuo, Z., He, L., & Huang, X. (2019). Atomization characteristics of nano-Al/ethanol nanofluid fuel in electrostatic field. Fuel, 236, 811–819

[18] Shrimpton JS, Laoonual Y. Dynamics of electrically charged transient evaporating sprays. Int J Numer Meth Eng 2006; 67:1063–81

[19] Khan, S. Y., Uzair, M., Allaudin, U., Masri, A. R. (2021). Experimental investigation of spray characteristics of electrohydrodynamic atomization. GMSARN International Journal 15, 250 – 258.

[20] P.X. Pham. A. Kourmatzis and A.R. Masri, 20th Australasian Fluid Mechanics Conference, Perth, Australia Dec. 2016

[21] P.X. Pham (2015) Influences of Molecular Profiles of Biodiesels on Atomization, Combustion and Emission Characteristics. PhD Thesis, The University of Sydney, Sydney, Australia

[22] Chang, J. S., Crowley, J. M., and Kelly, A. J., "Handbook of Electrostatic Processes. Dekkar," 1995.