Report

SmartSpark

hogeschool

Title : SmartSpark

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Date : August 18, 2022

Code :

Version : 1

Status : draft

Mailing list :

Copy to :

Classification : confidential

Contents

1 Introduction

Electrohydrodynamic Atomization (EHDA), also known as Electrospray (ES), is a technology that uses a strong electric field (kV/cm) to manipulate liquid breakup into droplets. This technique allows the generation of droplets smaller than the nozzle diameter with a controlled droplet size, which means it can be used to produce uniformly sized particles in the micro/nanoscale range. This liquid spraying technique can generate different modes when both the liquid flow rate and the voltage vary with a narrow size dispersion. The most known mode is the cone-jet mode, because it can produce droplets in the micro- and nanometric range with a narrow size dispersion. Many authors (7; 6; 4) have published about the relationship between voltage, flow rate and droplet size for this mode. More recently, Verdoold et al. (15) proposed the use of different variables based on current shape which can be used for classifying the ES modes.

1.1 Electrospray Technique

A literature review will be presented about the technique used to solve the electrical discharge problem. Usually, the electrohydrodynamic technique involves forcing the liquid through a capillary and electrified needle. The electric field that generates the charged liquid can be used to power electric devices or to power other devices.

In an electrospray technique, a feeding liquid is pulled through a small orifice by means of an applied voltage. The resulting spray is electrically charged, and the droplets repel one another. Fig. 1 shows this. The droplets are then accelerated towards the grounded electrode by the electric field. The size and shape of the droplets produced by the electrostatic atomization process depends on many variables that will be further explained, but our work is focus on the shape of the signal generated by the droplets because the automation of the system is based on it. The size of the droplets does not affect our system because the spray mode will be reached anyway.

The behaviour of an ES system depends on many factors like the geometry, polarity, material properties, occurring discharges, etc. which is reflected in the measured currents. As a result, it can be rather different (15).

1.1.1 Scaling laws

For a certain range of values of both the applied voltage and the injected liquid flow rate, the electrified meniscus adopts an almost conical shape (12). From the point of view of applications, the mode of greatest interest thus far has been the cone-jet mode in which the electrified meniscus adopts a conical shape, emitting a steady microscopic jet which leads to uniformly sized droplets (8). The scaling laws are available for electrospraying in the cone-jet mode of polar liquids. Due to the fact that ES applications are continuously being developed, research on the underlying mechanisms will likely provide helpful insights for making this complex system reliable and robust in practical production settings. The electric spray current is a very

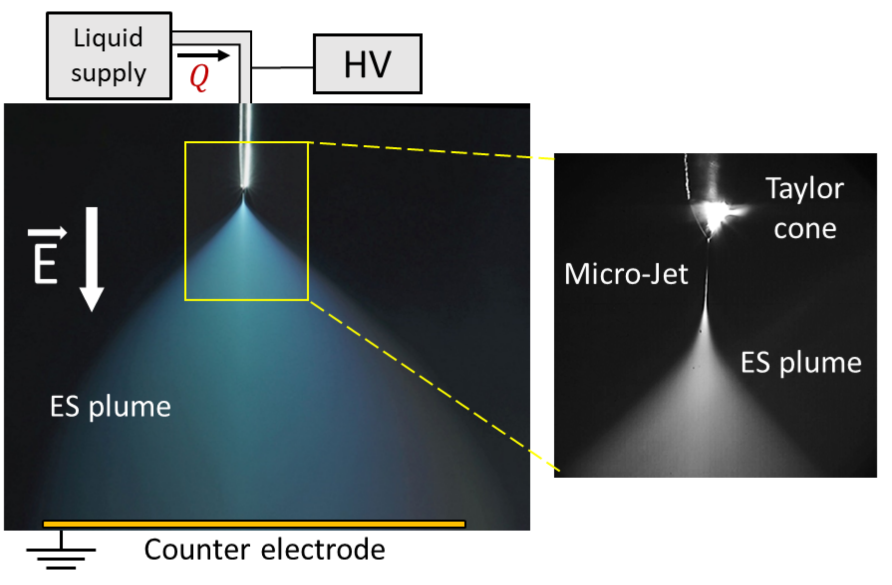


Figure 1. Electrospray main operation elements. L Left: Conventional ES setup. Right: Droplet emission region. (2)

important and explored variable in ES. It has been investigated by different authors (12), (6), (7), (11), resulting in scaling laws for the cone-jet mode, expressing the relationship between liquid flow rate, conductivity (two parameters that easily can be adjusted), surface tension, density and droplet diameter. Then, the scaling laws are useful tools for electrospraying practitioners since they can predict the order of magnitude of the size and charge of the emitted droplets (10).

Scaling laws are needed to characterize a defined ES system, providing better understanding of the mechanisms involved in the process (7). Two different approaches have been used to obtain the scaling laws in the studies of (6) and (4).

From the work of (7), we have a proportionality function based on the previous studies that can be seen in 1.

$$\alpha = (\frac{K \cdot Q \cdot \gamma}{\kappa})^{1/2} \tag{1}$$

1.1.2 Electrospray-modes

It was found that for Electrospraying modes resulting in a pulsed current, the pulse shape differs significantly between different spraying modes and various stages in the development of a pulse were identified (15). There are four common modes of EHDA: dripping, intermittent, cone-jet and multi-jet. There is an electrical current difference between EHDA modes. In the ES context, dripping mode occurs when the liquid being sprayed is broken up into small droplets due to the electrical potential applied to it. The liquid droplets are then driven towards the electrode and are eventually deposited onto the surface (2 A and 2 B in the Figure 2).

Intermittent mode is when the spray is turned on and off at regular intervals. This

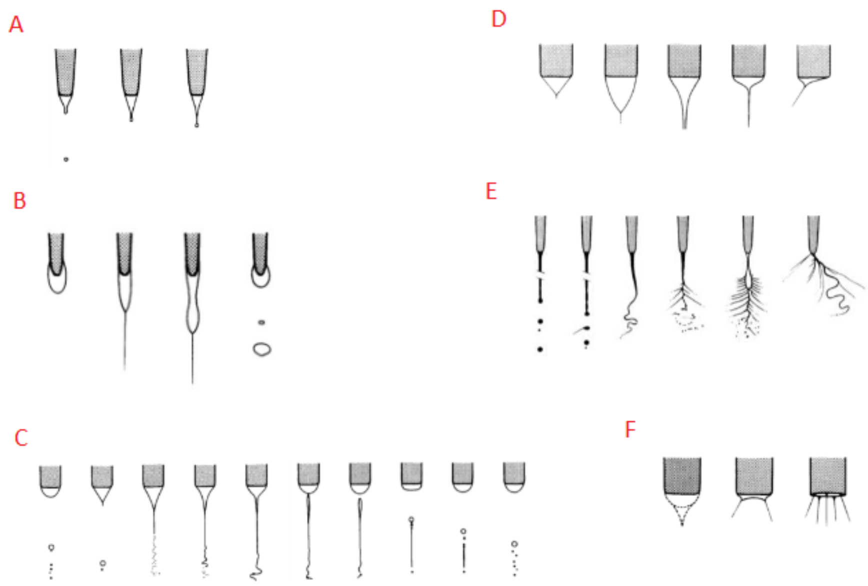


Figure 2. Spray modes (12)

can be used to control the amount of liquid that is sprayed, and can also help to prevent clogging (2 C and 2 E in the Figure 2). Cone-jet mode is a type of ES in which a cone-shaped spray is produced, with the droplets at the apex of the cone being the smallest. The cone-jet presents some different characteristics according to the literature and has some differentiations as can be seen in 2 D in the Figure 2.

Taylor (13) was the first to demonstrate that electrostatic pressure and capillary pressure can be balanced at any point on the surface of a liquid cone. The creation of a permanent jet, for its part, requires a penetration of the field lines in the liquid, so that the liquid must not be a perfect conductor. For liquids with relatively high conductivity, the jet formation zone is limited to the apex of the meniscus (16). Therefore, we shall use the term "cone-jet", whether the meniscus has a form corresponding essentially to a "Taylor cone" or to a "convergent jet" (12).

We consider the cone-jet configuration of figure 3. The steady Taylor cone-jets naturally occurs under relatively limited circumstances: when the applied field and flow rate are in the appropriate range, and the electrosprayed liquid exhibits the adequate physical properties, which entails having a field profile along the liquid surface necessary to get a potential drop in the liquid, from the polarizing electrode (either an immersed one, or the conductive capillary itself) to the cone apex, to accelerate the converging interfacial liquid to form the jet. This phenomenon exhibits certain physical balances and delicate symmetries which have attracted the attention of many researchers over the last decades, although still fundamental questions about the mechanisms responsible for both the establishment of steady Taylor cone-jets and their stability remain unanswered (10).

During the cone-jet, multiple parameters and variables influence the current, flow rate and voltage operational window. The operational window can be defined where

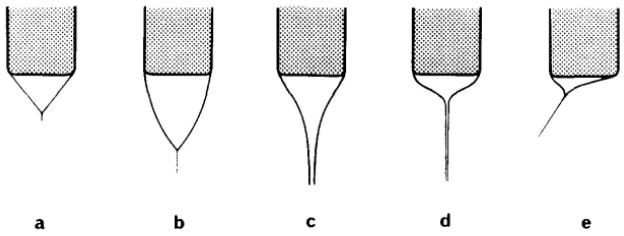


Figure 3. Cone jet modes (12)

the electrospray cone-jet mode can be stabilized based on the flow rate, voltage and the setup configuration (**?**). A group of symmetries rising at the cone-to-jet geometrical transition determines the scaling for the minimum flow rate and related variables. If the flow rate is decreased below that minimum value, these symmetries break down, which leads to dripping (1).

Finally, the multi-jet mode is a mode of operation in which multiple streams of liquid are emitted from the nozzle (see letter E and F in Figure 2). This mode is typically used when a high flow rate is required, or when the liquid being sprayed is viscous.

1.1.3 Classification of spray-modes

In (15), spray-mode types are summarized. The spray-modes are distinguishable by the current shape or level. For signals containing strong discharges and/or significant fluctuations the smoothing approach may not be sufficient. Using higher sampling rates may help in those situations (15). To describe the complete signal, all pulses need to be located individually. And after this, the results of all individual pulses are used to describe the complete signal. Classifying spray modes from electric current signal shapes would allow non-visual identification in opposite to visual classification.

Control variables (15) are implemented for three spray-modes (dripping, intermittent, cone-jet). Grounded plate and charged (HV) nozzle, nozzle diameter, nozzle-to-plate distance, flow rate and setup were defined according to this papers. S. Verdoold et al. (15) had done classification related to the shape of each current. They addressed different variables for each mode of the ES. It was possible to see their classification on the measurements conducted in the High Voltage Lab.

Interestingly, the present work are extending the non-visual classification method initiated by the author (15) using modern acquisition and signal treatment methods and adding new approaches for it. We also have integrated the signal in real time and in a data logger.

1.1.4 Streamer Corona and Transient Spark Discharges in air

At atmospheric pressure, glow discharges in air easily transition into spark discharges that significantly heat the gas, which is problematic for applications sensitive to temperature (3). Two types of DC discharges of both polarities operating in atmospheric air with/without water were applied: streamer corona (SC) and transient spark (TS).

The analysis of sparks requires a relation between liquid properties, flow rate, electric current and electric voltage that will be described. In stable ES system, currents are usually between 10 and 300 nA. On the other hand, with corona occurring at the nozzle currents go up to a few μA. Corona noise could be classified because of the frequency, which classify the signal. The distance between two signals can be shifted but the characteristic filters is in the signal.

2 Objectives

The following objectives were defined for SmartSpark.

- Fully automation and control of the spraying process.
- Discharges prevention mechanisms .
- Non-visual monitoring and classification of the spray mode.
- Evaluate the behaviour of the electric current in an EHDA system.

Initially, two demands were seen as crucial to improve the application of EHDA in industrial processes: 1) discharge prevention mechanisms and 2) non-visual monitoring and classification of the spray modes. Both can be tackled via an automated system. The study of the behaviour of the electric current is done in an EHDA setup for different spray-modes as well as during spark events.

In order to verify a spark in an EHDA system, we need to get closer to a fully automated control of the spraying process. Hence, identify the current state of the spraying process, and, if necessary, adapt the voltage to obtain a stable electrospray mode. Furthermore, it also increases safety, hence recognizing sparks and in consequence reducing the supplying voltage automatically.

In parallel, there is a comparison with measurements done by other authors (validation) and a complete new and automated system that will collect and classify the data structures from the WiFi Oscilloscope (TiePie Engineering). The work has been done throw software development using data structures (JSON) and the results presented were conducted through Python programming to communicate with the power supply (USB), pump (RJ11) and oscilloscope (WiFi) to classify the data collected of the system. For this, it was important as well to check the influence of the flow rate, electrical current, liquid properties (electrical conductivity, surface tension, viscosity, density), work distance, size of the nozzle, size of the syringe and generated mode. In addition, there is a monitoring system to verify if the electric current is on the desired spray-mode, done via Raspberry Pi and a Global System for Mobile Communication (GSM) module.

3 Materials and Methodology

Firstly, we will give the first step further in the automation process. Our goal is to gain better knowledge about the variables of the process, as well as the configuration procedures. There are information about materials, experimental system, configuration, electrical discharges, current measurements, measurement process, safety aspects and getting a clean signal.

Secondly, the method used was based primarily on the publications already made related to the EHDA technology. For this, we have performed the measurement protocol, design, system activities and requirements. This chapter covers this and the development necessary to built the project.

Furthermore, details about different setups, the data processing and the signal processing analysis and the closed loop system will be explained. After that, there is the information about how to use the SmartSpark system.

3.1 Materials and Setup

The materials of the setup consist of one power supply (brand: FUG, model: HCP35-20kV) and a pump (brand: master dual, model: WPI AL-1000) that can both be controlled via USB serial connections. The power supply's (HVPS) internal voltage and current measurements can be polled via an USB interface and it is included in the data logging.

HVPS provides the electrical potential to the liquid, which can be applied by connecting the HVPS directly to the liquid feeding capillary or needle to a grounded electrode (usually a plate or a ring) located downstream. The setup has the USB interface for controlling and polling measurements. To do the USB serial connection with the FUG Power Supply we have used the USB Cable 2-in1 Type C. The configuration was made on a Windows PC, following the manuals of its website and with the Baud rate of 115200. The interface between the syringe pump and the computer, a DB9 to RJ11 cable was made. In order to do the connection between nozzle and Power Supply, we have used the mounting Instruction for Plug HS21 + Cable 130660.

Most of the current measurements were performed at the nozzle-to-plate configuration. The material used for the nozzles was made of conducting materials. Current flows in the high voltage line with banana plug connection.

The current is measured via a TiePie WifiScope WS6 that is a battery powered oscilloscope capable of transmitting data via a WiFi connection allowing it to be placed in the high voltage or ground path. The current is routed directly via the input, hence the oscilloscope measures the voltage dropped via its input resistance (which can be switched between 1 or 2 MΩ).

TiePie WifiScope WS6 has a resolution of up to 16 bit at a minimal input range of 200 mV, sufficient to measure currents down to 1 nA. One of its functionalities is that the measurement displayed is constantly updated during the experiment. The

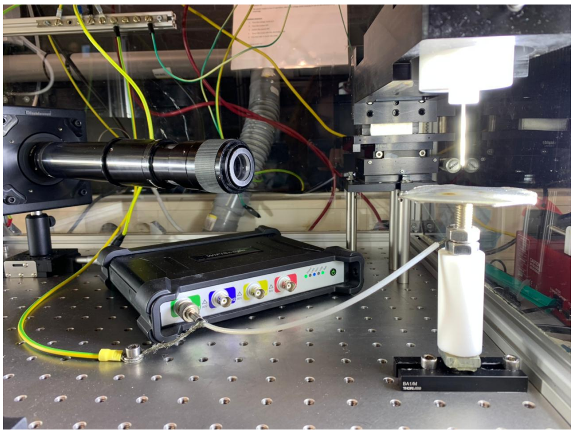


Figure 4. Setup nozzle-to-plate (*EHDA nozzle-to-plate setup*)

result do not have to wait until the whole measurement is completed to be shown (Engineering). The signal analysis with an oscilloscope using WiFi technology allows an in-depth case study of the electric current signal.

The capillary used was a PEEK Tubing 1/16” Outer Diameter (OD), 0.030” Inner Diameter (ID). The flow impedance of tubing/capillary is very important. The functions of the spray capillary are: 1) liquid transport from vessel to sprayer tip; 2) current transport from current coupling location to sprayer tip (via capillary material or liquid inside the capillary); 3) providing a contact geometry for the Taylor cone.

In relation to chemical experiments, solution preparation and characterization are important steps in order to ensure the validity of the results. The preparation of the solutions begins by following the basic safety information needed to perform the procedure. All the chemical reagents were used as purchased, without further purification. The liquids used: Ethanol absolute (99.7) 3 from VWR Chemicals, 2-Propanol HiPerSolv from VWR Chemicals and Ethylene Glycol from Fisher BioReagents.

Finally, characterization of solutions includes measuring the conductivity, surface tension, density, electrical conductivity. These measurements will be used in combination with the geometry of the setup in order to do the automation of the system.

To visually double validate the ES-mode classification there is a high speed camera imaging (Photron with a Navitar 125x microscopic lens). In runs in parallel to the experiment providing continuous monitoring of the ES modes.

The Experimental System of this work mostly use the EHDA nozzle-to-plate setup with cabinet 4. Figure 5 shows the diagram of the setup explained. Meanwhile, we can see the the setup with the cabinetry implemented 4 and nozzle-to-plate configuration, where the high voltage is applied in the white nozzle.

3.2 Flow of Information in the SmartSpark

The electric current is flowing through the oscilloscopes input resistance and the system is assuming current ranges of 1nA to 1μA resulting in voltage drop in the

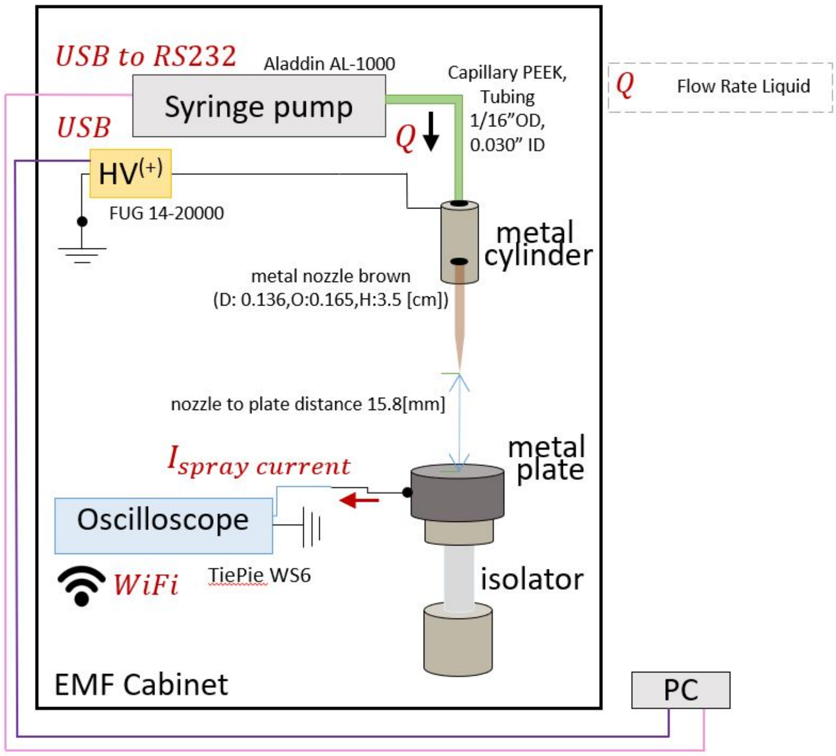


Figure 5. EHDA diagram setup nozzle-to-plate and ground line setup

range of 2mV to 2V. The sampling rate is 100kHz and the data blocks of 50kS, which is equivalent of 500ms as explained in 5.

$$U = R.I\Omega. \tag{2}$$

$$U = I.2M\Omega. \tag{3}$$

$$I[A] = \frac{U}{I.2.10^6\Omega} \tag{4}$$

$$I[nA] = \frac{U.10^9}{I.2.10^6\Omega} = U.500 \tag{5}$$

The diagram below 6 is the flow used to explain how does the information is in the experiments. 1) Input Parameters: you fill in the initial parameters about the liquid and the setup configuration. 2) Routine Definition: you define what is the pump flow rate, the voltage range involved from the power supply and what is the voltage regime (step, ramp, step size, etc). 3) Experiments: where you start the experiments and there is an output from the WiFi Oscilloscope. 4) Data Real Time Processing: applies statistical techniques, TF, low-pass filters and forms a diagram. From this there is a classification.

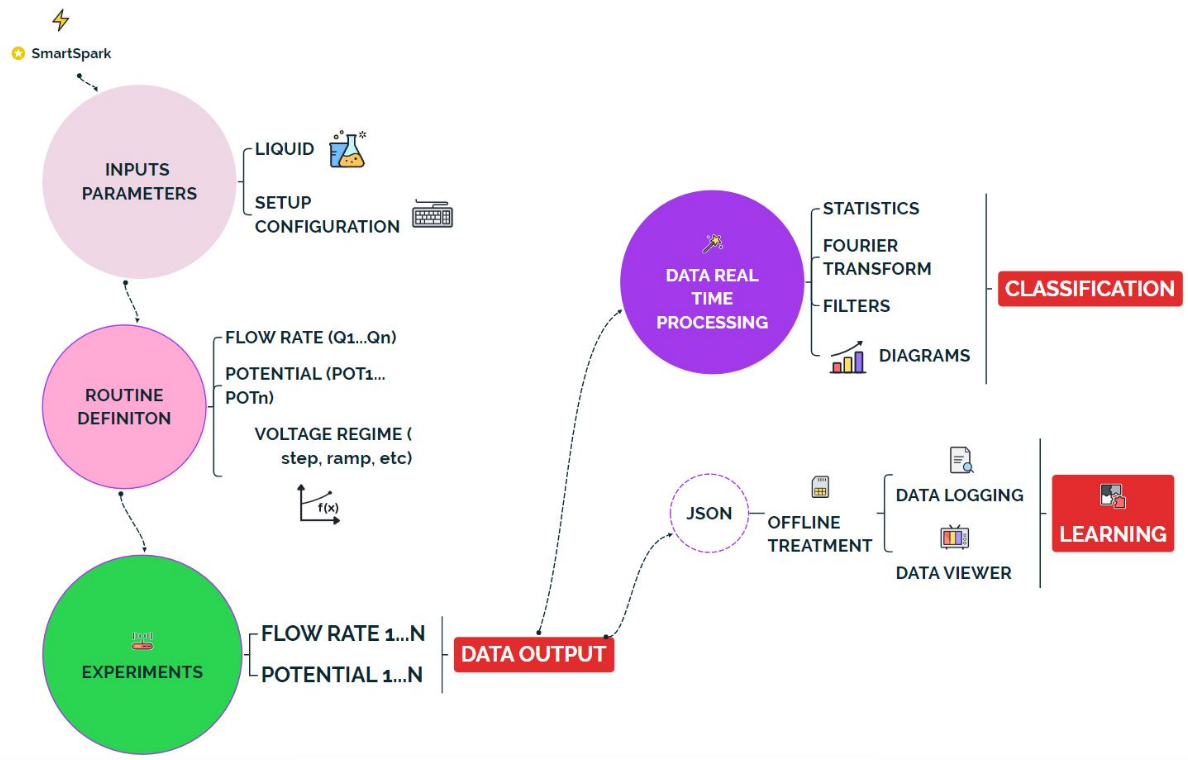


Figure 6. Flow of data

3.3 Data Processing

Since we have the Wifi Oscilloscope from Tiepie Engineering integrated in the system in real time, digital signal processing and statistics were applied in the data. We divided the class with its functionality based on the Fig. 7.

Each saved file has setup data, liquid properties and measurements. Every measurement has 50.000 data points and for each measurement and a lot of information based on digital signal processing techniques and statistics of the current data were done. We organized via JSON. JSON is easy to read and write and it is a lightweight text-based interchange format that is programming language independent.

3.4 Statistical Analysis

Some terms from Statistics are important in the ES system for the non-visual classification. The mean value represents the signal's DC content, which is the center tendency best if data points are symmetrically distributed above and below the mean, hence no outliers. The median value is less sensitive to outliers. The mean and standard deviation represents the signal to noise ratio and it also represents the AC Power content of a signal.

The Root Mean Square (RMS) is the sum of DC and AC signal power content. Mean-square in electrical terminology is often referred to as the average power (from the notion that the mean-square value of a voltage or current waveform, applied to

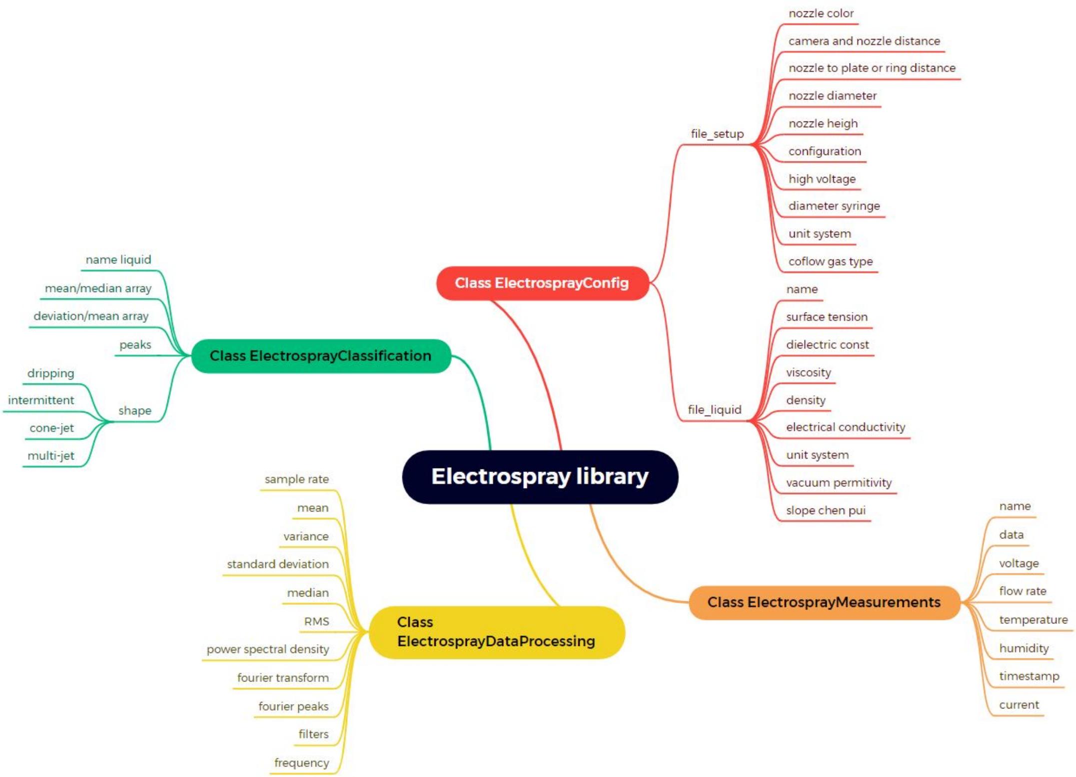


Figure 7. Library diagram

1-*Omega* resistor, gives the average power dissipation in watts) (9).

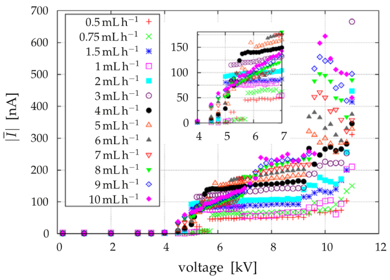
The variance is therefore similar to the mean-square, but with the mean removed. It follows that he variance is a measure of the average powers in all its other frequency components. The variable mean divided by standard deviation is the signal to noise ratio (9).

There are some variables used by (15) to classify the spray-modes that will be shown in the figure 8. In this section, we show the variables defined by his papers and we included our own method of classification in further chapter.

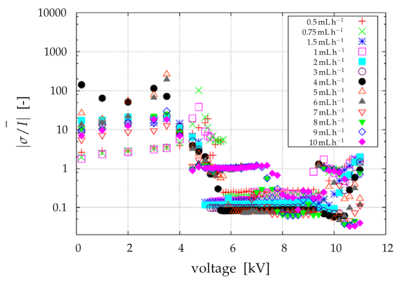
Configuration 4 type III is: the nozzle-to-plate configuration; the needle type has the outer diameter of a capillary (dcap) = 2.00 mm; the inner diameter of a capillary (dcap,in) = 0.20mm; distance from capillary and the plate (Lp) = 15mm; Resistance = 11460 Ω . We can see that the nozzle type have an inner diameter of 0.2 mm which is significantly smaller than dcap for the nozzles used in the current experiment (14).

3.5 Digital Signal Analysis

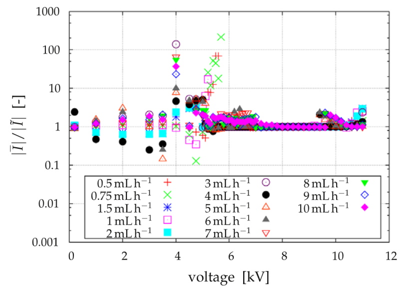
A signal is information that changes over time. For example, audio, video, and voltage traces are all examples of signals. A digital signal is a signal that is sampled at some regular interval, and then the samples are quantized. The digital signal can be either an analog signal that has been converted to a digital signal, or it can be a digital signal that has been generated by a digital device.



(a) X axis: electrical current mean; Y axis: voltage (15)



(b) X axis: relative standard deviation of electrical current divided by its mean; Y axis: voltage (15)



(c) X axis: current mean divided by its median; Y axis: voltage (15)

Figure 8. Typical processing results for the characteristics of Sections 4.1 and 4.2 for a configuration 4 (Type III) system spraying ethanol. (15)

Digital signal analysis is a powerful tool for extracting information from digital signals. It can be used to analyze signals in order to extract information about the underlying physical phenomena that generated the signal. Additionally, digital signal analysis can be used to improve the quality of digital signals. For example, digital signal analysis can be used to remove noise from a digital signal.

The Fourier Transform (FT) is a powerful tool that is used in many different fields, from signal processing to data analysis. The FT of a signal is a representation of the signal in the frequency domain. It can be used to find the frequencies that make up the signal, and to analyze how those frequencies change over time. Fourier transforms (FT) is good for analyse the spectrum (angle and phase and magnitude) of the signal. This is done via array to map the points from the FT.

Every time-domain functions has a counterpart in the frequency domain. In the case of an autocorrelation function (ACF) which is a function of the time-shifted variable m, the counterpart is called a power spectrum density or, more simply, a power spectrum. It indicates how the sequence's power or energy is distributes in the frequency domain, and is widely-used measure of random signals and noise (9).

One variation of the FT that is used when the signal is discrete, or digital is the Discrete Fourier Transform (DFT). The DFT is a powerful tool for analyzing signals and determining the frequencies that make up the signal. The DFT is a mathematical transformation that converts a signal from the time domain to the frequency domain. The DFT is used in many signal processing applications, such as filtering, equalization, and compression. The DFT can be used to determine the frequencies of a signal, as well as the amplitude and phase of each frequency component. The DFT is a valuable tool for analyzing signals that are not periodic, such as noise. The DFT can also be used to analyze signals that are periodic, but have a complex waveform, such as speech or in our case, an EHDA spray-modes signal and also sparks regions.

For doing the calculations, NumPy was used mostly. Numpy is a Python library for scientific computing. It provides a high-performance multidimensional array object, and tools for working with these arrays. Numpy is free and open-source software released under the three-clause BSD license. Numpy is a powerful tool for digital signal analysis. It is able to process large amounts of data very quickly, making it an essential tool for anyone working with digital signals. Numpy also has a wide range of functions for signal processing, making it a very versatile tool.

4 Results and Discussions

In this chapter we present the results obtained. From this project the main outcomes are:

- Software development;
- Co-routines to control the entire setup were designed;
- Digital signal and statistics techniques for spray-modes classification;
- Logging the information in a viewer window (offline visualization);
- Predict discharges (knowledge of the region before it happens);
- Automated system: prospective automation of the EHDA process;
- Datalogger with Raspberry Pi and GSM for monitoring the EHDA system;

Different insights on how to accomplish the results were found. These insights were obtained from the different activities carried out and are thus divided into four categories: Software Development, Setup, ES-modes Classification and Spark Suppression.

4.1 Software Development

Initially, JSON files were organized for each class as shown in Figure 9. Inside of the fields, the code bellow shows how the JSON were organized. The method previously showed in the chapter 3 in the subsection **??** and how the division of variables would be and this can be seen in this code automatically made by the SmartSpark with Oscilloscope real values.

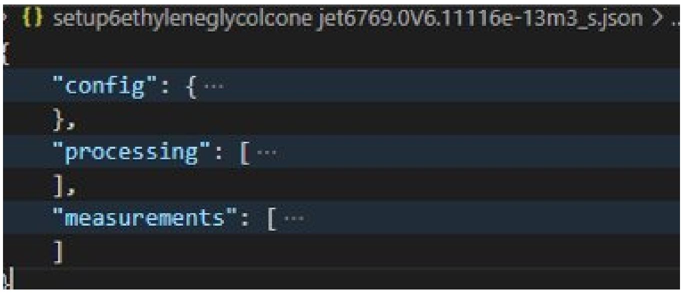


Figure 9. JSON file example


```
{    "config": {
    "liquid": {
            "name": "ethanol pure",
            "surface tension": 0.0219,
            "dielectric const": 24.55,
            "viscosity": 0.001086,
            "density": 784.93,
            "electrical conductivity": 0.00378,
            "unit system": "SI",     },
        "setup": {
            "nozzle color": "brown",
            "camera to nozzle distance": 16.5,
            "config": "nozzle to plate",
            "nozzle to plate or ring distance": 2.0,
            "nozzle diameter": 0.136,
            "nozzle outside": 0.165,
            "nozzle height": 3.5,
            "high voltage": "HV on the ground",
            "diameter syringe": 0.16,
            "units": "cm",
            "coflow gas type": "none",
            "voltage regime": {
                "sequency": "ramp",
                "start": "3000",
                "stop": "12000",
```

```
                "slope": "100",
                "size": "0",
                "step time": "3"}  }    },
    "processing": [        {
            "mean": -2.3827574253082275,
            "variance": 18.79721450805664,
            "deviation": 4.335575580596924,
            "median": -2.51572322845459,
            "rms": 4.947195529937744,
            "psd welch": [..],
            "fourier peaks": [..]    }     ],
     "measurements":        {
            "data [nA]": [...],
            "flow rate [m3/s]": 2.7778e-10,
            "voltage": 3042.7,
            "current PS": -3.76554e-07,
            "temperature": 21,
            "humidity": 31,
            "date and time": "Thu_31 Mar 2022",
            "spray mode": {"Sjaak": dripping", "Monica": "no streamer onset"}}
```


Regarding to the programming language, a major practical consideration when using Python is its speed, but in this system the performance in order to manipulate discharges was sufficient. Besides this, the execution of the work allowed visualizing that Python would not be the best language for applications that demand a high degree of speed, because it is not fast and the processing time is big.

It was possible to acquire much knowledge about threads and control between two different systems, as well as the use of the necessary conditions to have efficient resource consumption in a real-time application. Besides, the execution of the work allowed us to visualize the difficulties when increasing the number of threads so that there is synchrony between the conditions and the variables and instruments that are made for control and reference checking.

4.2 Setup

Even though the tests were conducted with defined sample rates and different voltage regimes (step, ramp), the proposed setup was enough to detect discharges in the range which is most applicable for this kind of application. This was only done because the system was automated throw the software development integrated with the hardware integration.

The power supply FUG in the setup works with DC and the SmartSpark is AC, so, it is not possible to use the electric current data from it. The data from the power supply is only used in relation to the real-time voltage and the measurements. The oscilloscope TiePie WS6 DIFF with direct measurement of down to 10uA is possible and practical. The configuration chosen with a WiFi scope was proven adequate to transmit the signals without big interference, noise and improved safety. Furthermore, We confirm in this work that high sample rates for getting a signal from sparks is good thanks to the integration with the Oscilloscope.

For the nozzle-to-plate setup, some results proved to be valid to show: 1) Less shielding proved to be enough. 2) Internal cables reduced shielding. 3) A lot of cables is not beneficial for noise.

The results of the different setups will now be presented in numerical form. 1) Tests performed with the oscilloscope on the High Voltage side showed that the signal is noisier than only in the ground line. This can be caused by a number of reasons, including electrical interference, bad wiring or soldering, larger wires, the wiring was done without fittings cables or even distance. The farther away the signal is from its source, the more likely it is to be interfered with. But, we can still verify the shape of each classification of ES. The setup could be a bit more optimized, but it works. 2) Oscilloscope as an internal resistor was very good and the setup remains only with it. 3) Parallel capacitor made no difference in setup. 4) Nice results when using the input resistor of the oscilloscopes directly as the shunt resistor.

In relation to the ring setup (see Figure **??**), it is better to apply the high voltage on the ring as well, for example. Droplet flyback towards the ring can be prevented robustly over a wide range of ring voltages. For example, the ring setup can be used if the ring is connected to a second power suply at the same voltage. The test with the ring setup has also shown a limitation for higher flow rates than 100 μL/hr. It is, nevertheless, believed that such limitation can be easily overcome by exploring other configurations like small reflection distance, more power and lower frequencies. Such conclusion also implies that the proposed technology is also promising for different applications in water technology, e.g. particle shape and density in reactors, annamox, etc, as well as for other industries, e.g. food technology, mining, etc.

During this setup chapter there is a open question that this works aims to answer: "What is relevant for your application?". You need to be aware and make decisions concerning the setup design, mainly the liquid (volatility, solvent properties, viscosity, surface tension), illumination (optical access to the spray-mode: cone, spray, jet break up), current transport (safety, impedance matching/self stabilization). There is not only one correct answer and this will change for every purpose.

4.3 ES-modes Classification

In order to do the classification, the Measurement Procedure shall be capable to facilitate that the next procedures are similar and there is a standard to be followed. The oscilloscope images (see figure 10) have shown electric current shapes, for the different ES modes, quite similar to those reported by (15). The obtained electric current shape was matched with the spray-mode using the high speed images (see figure 11). High speed allows good monitoring and measurements. The code does print screens from the high speed camera.

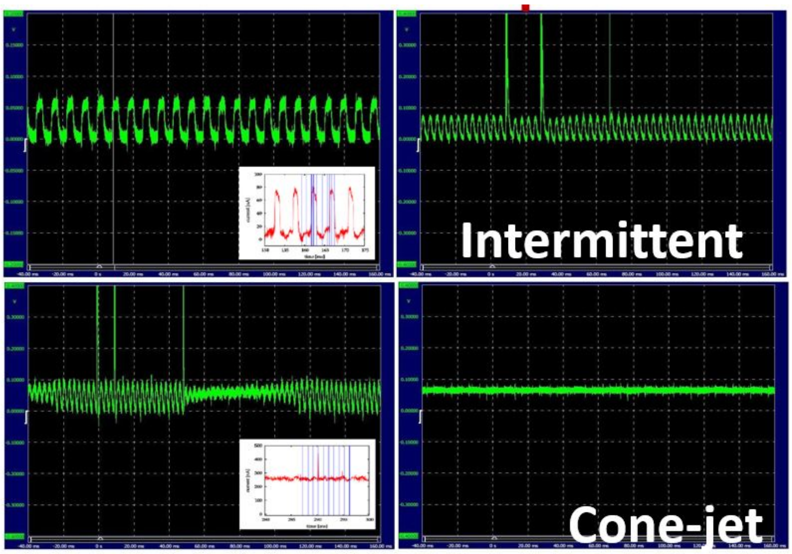


Figure 10. Printscreen of spray-modes from the oscilloscope TiePie

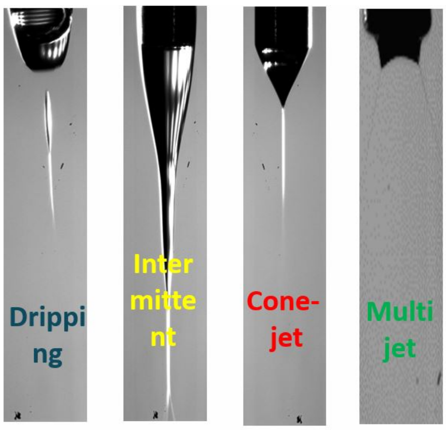
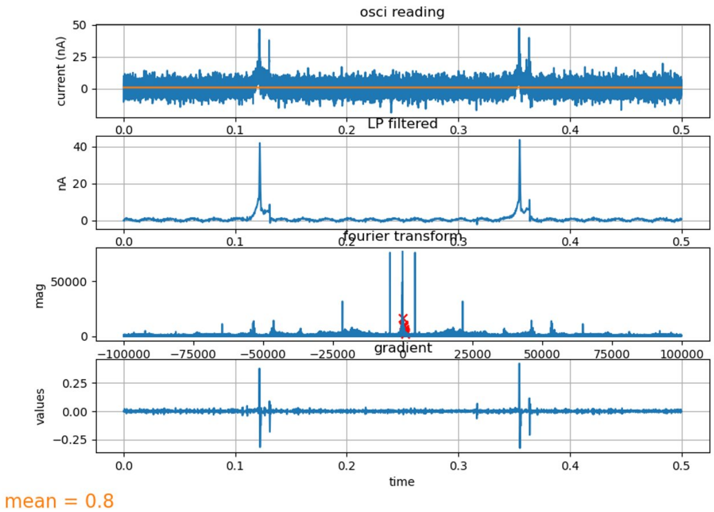
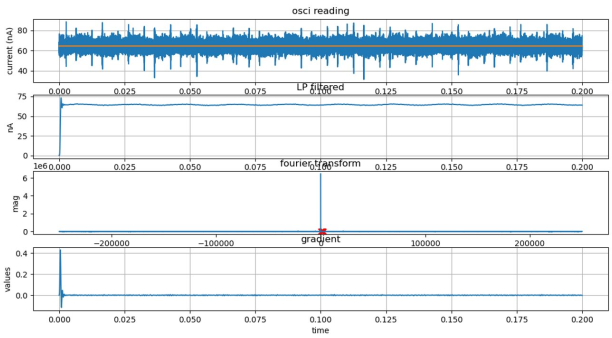


Figure 11. High speed camera images of the High Voltage Lab for Ethanol. Different flow rate and potential. Fps: 12500, shutter speed: 1/950000.

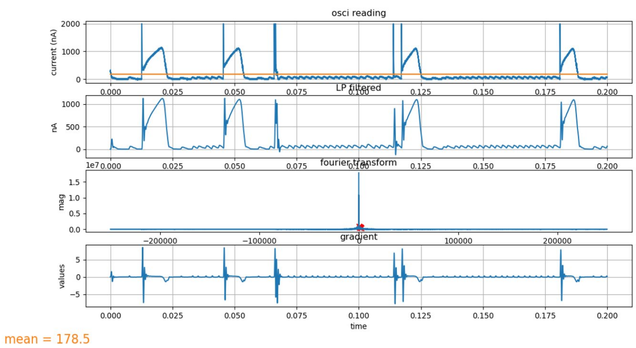
The implementation of an automatic classification was initially based on the same statistics proposed by (15). The electric current mean is gonna be referred as "VAR0". The Relative standard deviation of electrical current divided by mean its is gonna be referred as "VAR1". The mean divided by median will be "VAR2". After the collection of data with JSON, a viewer to analyse each mode was done. It is possible to verify in the Figure 12 the similarities of the signal based on the reference (15).



(a) Dripping signal (*User offline dripping signal*)



(b) Cone-jet signal (*User offline window cone-jet*)



(c) Multi-jet signal (*User offline multi-jet signal*)

Figure 12. Offline Viewer

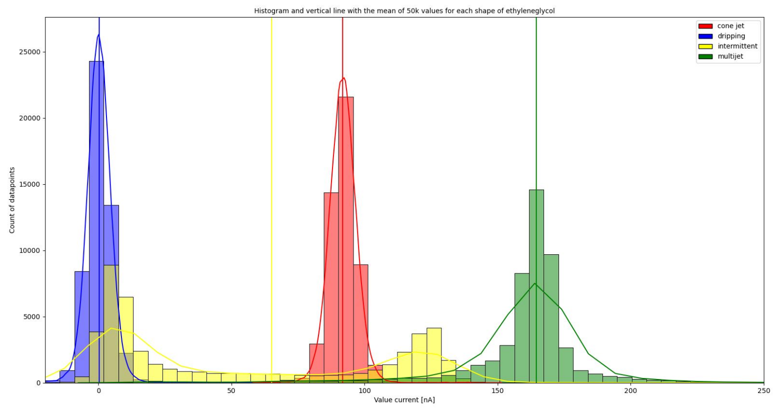


Figure 13. Histogram generated by SmartSpark

The literature helped but the present work extended what has been done. New features were added and improvements were made such as including statistics of FT coefficients of the signals. This was possible by visualizing all ES-mode in a methodical and automated way. Moreover, it is possible to say that the low pass filter proved to be enough to have good conditions to use the FT. In addition, FT proved to be a important classifier in the ES system. We could see there is no dominant peak in the cone-jet mode and when we have a stable EHDA system.

There is a region in the FFT of no interest, since it is part of the DC component and part of the electrical system (up to 50Hz). 50Hz notch filter (removing fourier coefficients at 50Hz and calculating inverse FFT) was implemented.

Since the FT needs to use a pattern, we could see this for the ES-modes. There is a FT peaks transformation for every shape - specially for multi-jet 12c, where we could verify that in greater flow rates, we have more peaks than in a smaller flow rate. In the intermittent mode was possible to see an annoying high pitch is going to show up just as a spike at some high frequency. The power spectrum shows the range of the dominant frequencies. High pass filter is not necessary.

After the automatic classification of the code, the signal histogram diagram for each mode was made. Based on a vast amount of data, we have a histogram made with the JSON files with the classification from (15). Histogram and Gaussian of the parameters help the visualization of the current data because we can see the distribution of the current for each spray-model in the Fig. 13. For each spray-mode we have different current ranges.

Diagrams were created in order to compare the variables and improve the classification of the system. This can be seen in Fig. 16, 17 and 14 and they are in the Ramp mode with the following specifications: "start": "3000" [V], "stop": "11000" [V], "slope": "200" [V/s].

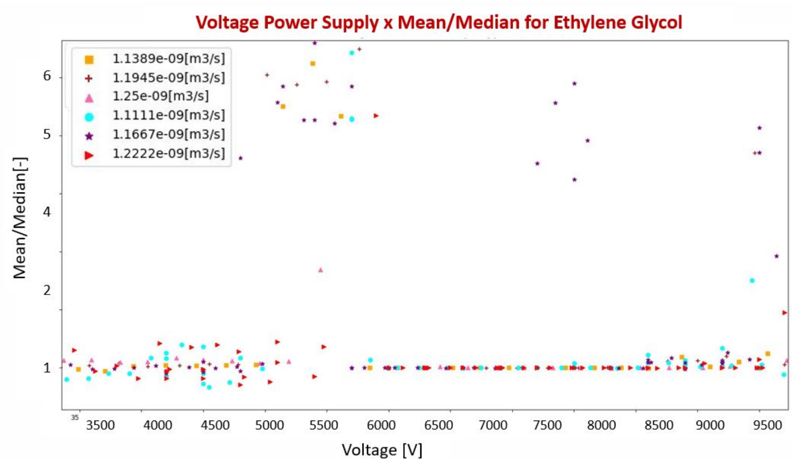
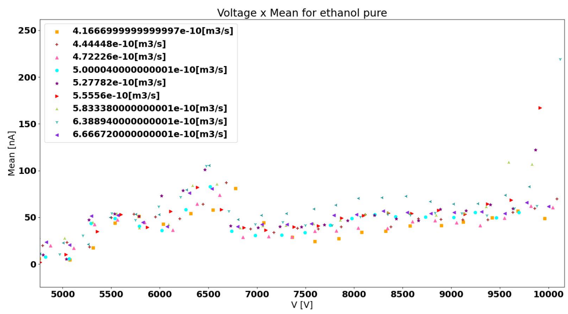
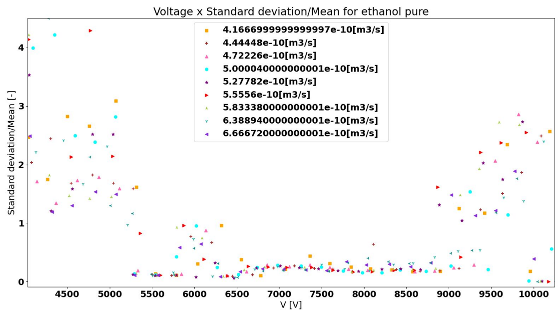


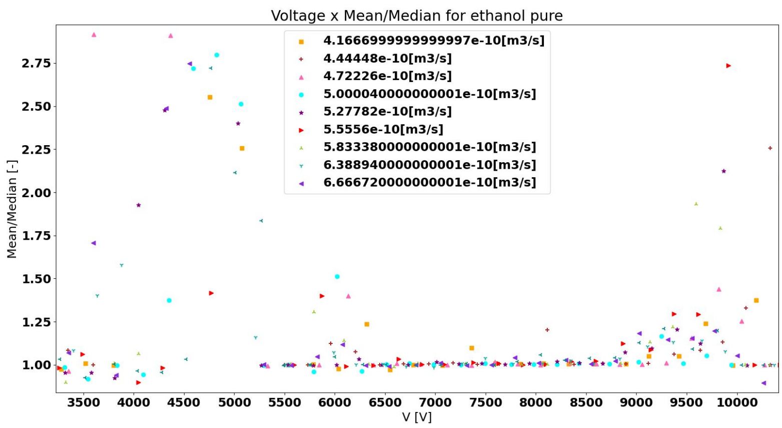
Figure 14. VAR2 for Ethylene Glycol (*Nozzle diagram*)



(a) VAR0 VS voltage

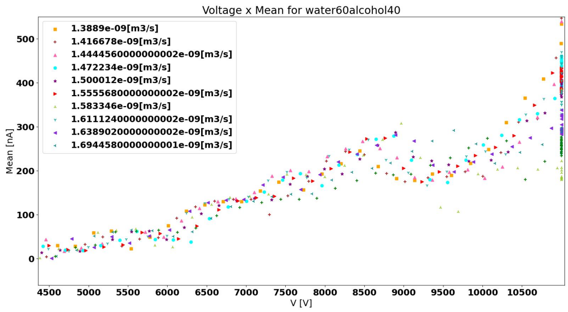


(b) VAR1 VS voltage

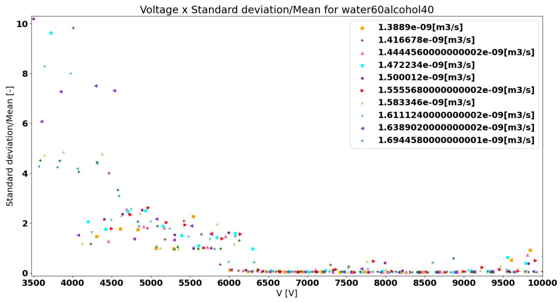


(c) VAR2 VS Voltage

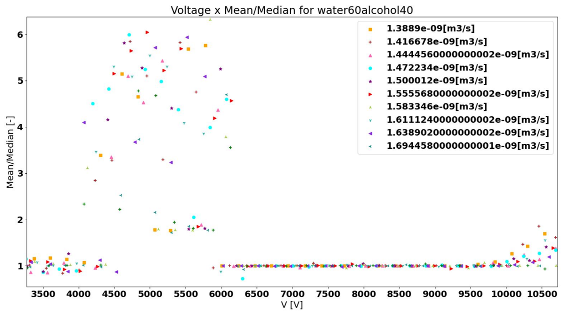
Figure 15. Smart Spark processing results for a configuration as the diagram of Figure 5; system spraying ethanol.



(a) VAR0 VS voltage

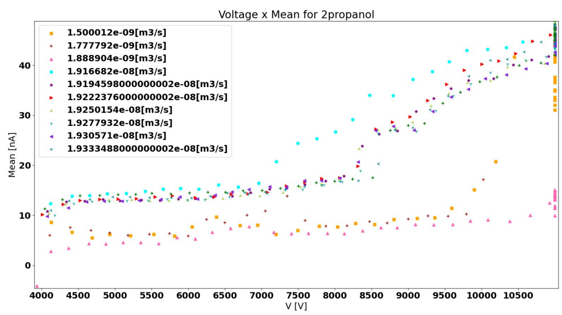


(b) VAR1 VS voltage

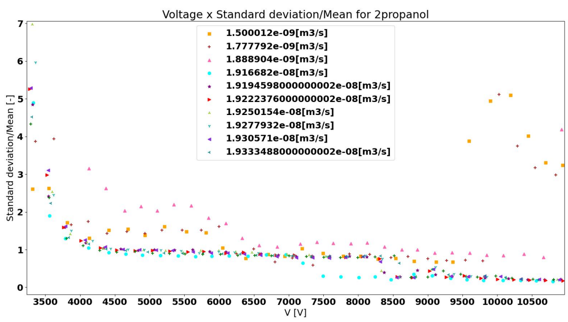


(c) VAR2 VS Voltage

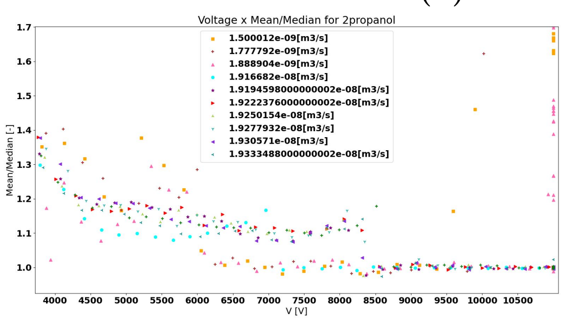
Figure 16. Smart Spark processing results for a configuration as the diagram of Figure 5; system spraying wateralcohol.



(a) VAR0 VS voltage



(b) VAR1 VS voltage



(c) VAR2 VS Voltage

Figure 17. Smart Spark processing results for a configuration as the diagram of Figure 5; system spraying 2propanol.

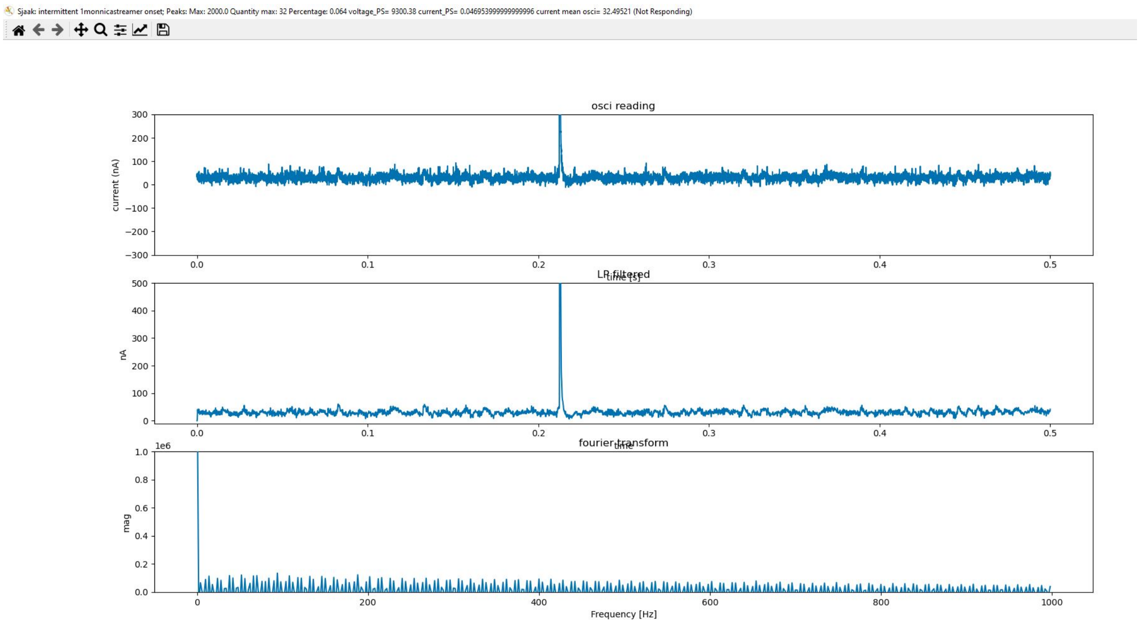


Figure 18. The classification can be seen in the window on the left and counts on the classification made by (*User main window*)

4.4 Spark Suppression

The frequency of the spark peaks are well defined based on the flow rate, voltage regime, current region, setup geometry and liquid properties. Although, if we know the region after the spray-mode multi-jet window, we can prevent sparks.

Streamer corona (SC) is the region where the sparks begin. It is possible to say that there is no discharge without SC. A significantly jump in the mean value of the current indicates corona onset. This project consider the identification of the SC as an important region of the SmartSpark.

Based on a vast amount of data we could build a system that detect the region of multi-jet and also the region right after the multi-jet region, and we define it as pre-spark region or corona streamer onset in our classification method.

The spark suppression uses serial commands for shut down the power supply voltage, which can goes from 10kV to 0V in less than 2 seconds. For our setup, this time is sufficient. The generalization of the spark event and at what current level corona actually occurs depends on the setup and of the liquid properties. The pre-spark region can be seen as the main relay and comparative area in the operation and prevention of spark. We demonstrate a continuous process for the effective prevention of sparks reducing their charge in the multi-jet region using serial commands from the controller.

Obviously detecting plasma forming and reducing the voltage over nozzle to counter electrode proved to be enough with the Python code. This was done with dry setup, which means, no liquid and/or no flow rate while the voltage was increased until more or less 20kV.

5 Conclusions

When looking back at the goal of automation of the EHDA process, it can be said that this was reached. Based on that, results have shown that the SmartSpark system can be used to measure the current and prevent discharges in ES applications because of the automation of the process.

The physical setup, measurement devices used and the developed Python libraries for signal processing are sufficiently capable for real-time classification of cone-jet, intermittent, dripping, and corona streamer onset correctly. This was only possible thanks to the automation involved in the process. SmartSpark is seen as an important tool towards the industrialization of EHDA processes. The compatibility between the bench scale tests and the real scale tests have also shown that, the technology, as tested, can be reliably applied in real scale.

Finally, we analysed the results and found that the signal follows the expected behavior as previous mentioned (15). In addition, we have extended the worked based on digital signal processing techniques and more accurate statistics variables, we have decreased the range of the statistics for the spray-mode cone-jet and we have added our own method for all the spray-modes and in the pre-spark region. This region is very important for industrial processes as mention in the GasUnie B.V. implementation.

Even though extended tests have to be conducted to verify the durability of the oscilloscope and the Raspberry Pi and GSM module, it is possible to say that the data-logger of the current works. Nevertheless, during winter as well as other possibilities with different sample rates collection of data are seeing as necessary in the future.

Besides that, some instabilities were seen to initialize the influxdb and in the ppp protocol in the Raspberry Pi using pon. It is necessary to read the documentation about the influxdb because there are versions problems not fixed. Always verify the file "sudo nano /etc/ppp/peers/provider" if the protocol PPP is not working in the Raspberry Pi. There are multiple ways of configuration of the APN, via AT Commands or via Phone are two possibilities of many ones.

With this study, we conclude this set of process on Electrospray system called SmartSpark. It has often been said that the purpose of this work is to automate the EHDA process. Throughout the practical study, we have tried to concentrate on the basic fundamentals of fluid mechanics and EHDA technology to provide a firm background for proceeding to applications and advanced topics related to it. As you know, we have only covered one set of geometry for the EHDA in the text and omitted the results from different setup because we could not have more time to do more experiments.

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