EHDA closed loop control system based on real time non-visual spray mode classification

Report

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Abstract

Electrohydrodynamic Atomization (EHDA), also called electrospray, is a liquid atomization technique that produces micro- and nanometric charged droplets within a narrow size distribution by using high electric fields (kV/cm). According to Cloupeau and Prunet-Foch[1] (1994), electrosprays can generate droplets in different ways, which the authors named "electrospray modes". These modes may be adjusted by varying the strength of the electric field and flow rate, but also depend on liquid properties and system geometry. In their work, the authors proposed four possible EHDA modes: dripping, intermittent, cone-jet and multi-jet, which are generally distinguished visually. Verdoold et al.[2] (2014) recently suggested a classification approach based on the behavior of the electric current of the electrospray process.

This project develops a closed-loop control method for EHDA devices that uses real-time, electric current-based (hence non-visual) spray mode classification. The proposed electrospray system is entirely automatic, where all the peripherals, such as HV power supply and syringe pump, are controlled by a computer which executes their routines. The system classifies spray mode dynamics using real-time current data and changes EHDA operating parameters such as liquid flowrate and applied voltage to achieve and maintain the chosen spray mode. The electrospray modes are validated in real time by using a high-speed camera. As compared to conventional manual approaches, the implemented control algorithm achieves higher accuracy and lower transient time. Therefore, a completely autonomous EHDA system opens the door to potential industrial applications. In addition, the use of the electric current signal will be useful to further study electrospray processes, leading to better control on droplet generation (frequency, size and charge). The incorporation of Machine Learning to improve mode categorization will be a future development.

Chapter 1

Introduction

Electrohydrodynamic Atomization (EHDA), also known as Electrospray (ES), is a way to disintegrate a liquid into droplets by exposing it to a strong electric field. The electric current flowing transported by the spray reveals characteristic shapes for different spray modes. Signal processing techniques can allow a non-visual classification of the spray mode based on the electric current shape.[2] The spray process imposes noise and random sequences on the measured signal making its classification not a trivial task. Industrial applications demand automated stabilization of a spray mode. This can be achieved by a closed-loop control system. This project is about to develop an application that can classify what dynamics the EHDA experiment is current in and control the variables to stabilize in the desired mode. In the figure we can see how EHDA experiment works.

1.1 Motivation and Justify

As pesquisas de EHDA têm contribuído como uma importante ferramenta para o desenvolvimento da tecnologia da água (dessalinização térmica e recuperação de metais), ciências dos materiais (nanofibras e fabricação de nanoesferas, recuperação de metal, membranas seletivas e baterias) e aplicação biomédica (encapsulamento). Além disso, o projeto está integrado à estratégia de Transição Energética e à Agenda de Inovação Agricultura, água e alimentos, tecnologias facilitadoras essenciais (KETs). Embora existam aplicações de EHDA em indústria, a estabilização do modo de pulverização de jato cônico é feita empiricamente e com base em medições de corrente média. A corrente elétrica que flui transportada pelo spray revela formas características para diferentes modos de atomização. Essas formas não podem ser simplesmente resumidas por seu valor médio. Na figura um podemos ver um exemplo de cone-jet modo eletrospray.

Figura 1: exemplo de EHDA

As técnicas de processamento de sinal podem permitir uma classificação não visual do modo de pulverização com base no elétrico forma atual. O processo de pulverização impõe ruídos e sequências aleatórias no sinal medido tornando-o classificação não é uma tarefa trivial. Aplicações industriais exigem estabilização automatizada de um modo de pulverização. Isso pode ser obtido por um sistema fechado sistema de controle de circuito. A classificação automatizada do modo de pulverização é uma parte crucial de um sistema de controle, assim como o desenvolvimento de um algoritmo de controle apropriado.

1.2 Project objectives

Tendo em vista o exposto acima, este projeto tem por objetivos:

a) Item 1;

b) Item 2;

c) Etc.

O conteúdo desta seção pode se sobrepor um pouco com o da seção anterior, podendo ela ser um sumário dos pontos expostos anteriormente. A escolha do título da seção talvez seja mais apropriada para a fase de proposta do projeto. Afinal, nesta fase se conhecem os objetivos e não os resultados. Por outro lado, fará pouco sentido discutir objetivos quando o projeto está finalizado, especialmente se tais objetivos não foram alcançados.

1.3 People envolved

Implementações de processamento de sinal de projetos anteriores do grupo NHL Stenden Water Technology estão mostrando bons resultados de classificação. Mais pesquisas são necessário para melhorar a precisão da classificação e pesquisa e implementação de uma classificação adequada algoritmo. Por causa disso, o trabalho será feito pelo Water Technology Group da NHL Stenden University de Ciências Aplicadas e em combinação com empresas holandesas para combinar possibilidades de análise com conhecimento e disponibilidade de infraestrutura.

Chapter 2

System Description

2.1 EHDA

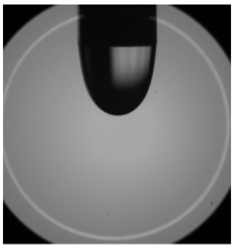

Figure 2.1: Dripping

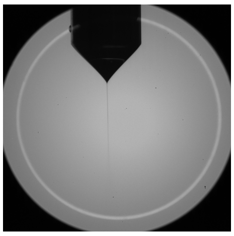

Figure 2.2: Cone Jet

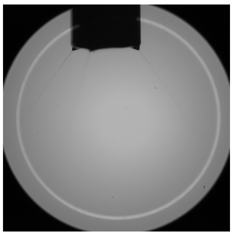

Figure 2.3: Multi Jet

2.2 Instrumentation

The peripherals automation routine was already developed by another student. In order to continue the research I took some time to understand the physical concept behind EHDA experiments and the project knowledge. I made upgrades in the routine to include the high speed camera with a hardware triggering routine using an arduino microcontroler. This will be usefull to validate the further classification of the spray dynamics.

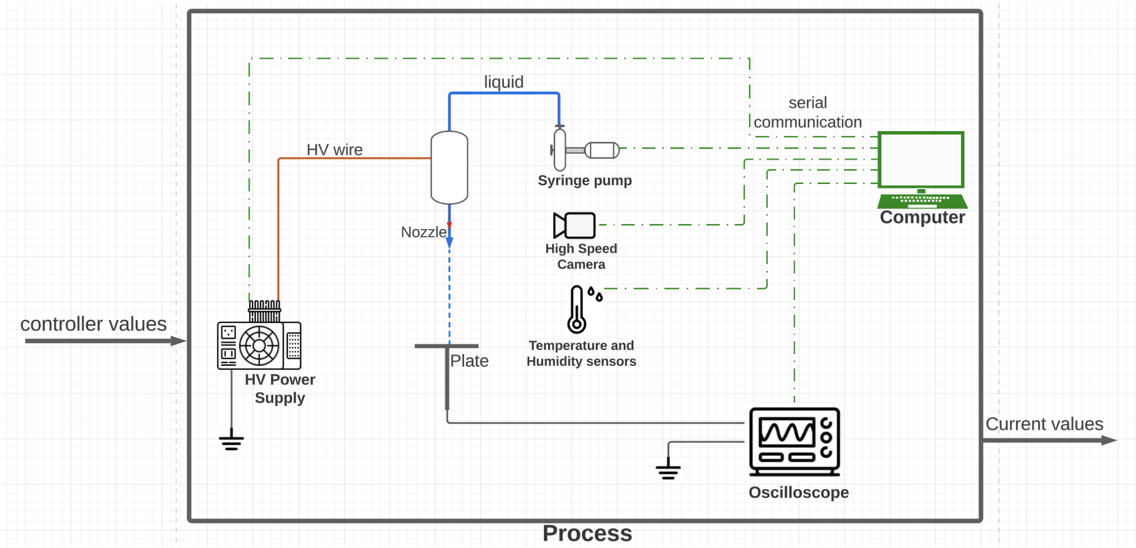

Figure 2.4: EHDA automation system setup

2.3 First Experiments

Initial tests were made to verify the setup assembly and the automation routine integration. In this step I could unterstand in practise how electrospray works. I noticed that we need a large set of variables in the range to produce the desired dynamics of electrospray, which most of the time is cone-jet mode. Those variables can be the liquid properties such as surface tension, dielectric constant, viscosity, density, electrical conductivity and vacuum permitivity. And also physical variables such as flowrate, system impedance, system temperature, system humidity, nozzle to plate distance, nozzle dimensions and applied voltage. The instruments used in the setup are:

a High Voltage Power Supply (FUG)

b Oscilloscope TiePie WS6 DIFF

c Humidity and Temperature sensor (DHT11 + Arduino Uno)

d High Speed Camera - Photron fastcam mini

e Syringe pump

Chapter 3

Metodology

3.1 System Model

ilustramos o processo com a Figura 3.1.

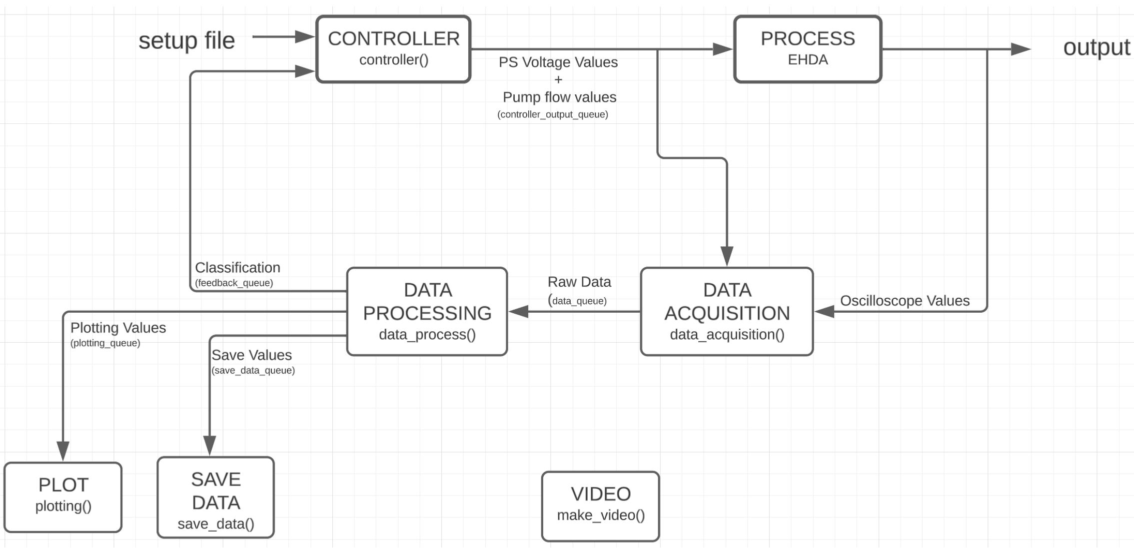

Figure 3.1: EHDA automation system setup

3.2 Threading and Queues

3.3 Classification

3.3.1 Statistical Analisys

According to [2] evaluating the current data flowing through the nozzle to the plate we can analyze the signa that represents the spraying dynamics. through statistical analysis in this signal such as mean value and standart deviation we can analyze if the signal is stable or not.

Our classification by statistical analysis was implemented in the automation library made by the previous student [3].

Each current sample is 0.5s of current data in 10kHz sampling frequency. By the processing thread we take this sample and evaluate the followings statistical values.

- Sjaak Classification -> Classifies Dripping, Intermittent and Cone Jet

- Monica Classification -> Classifies Corona Sparks

- João Classification -> Classifies Multi Jet

The algorithm implemented works in the following way:

Algorithm 1 Statistical Classification

```
function STATISTICAL_CLASSIFICATION(sample)
    spray_mode ← "Undefined";
    mean ← sample.mean;
    std_deviation ← sample.std_deviation;
    median ← sample.median;
    if mean/std_deviation > 2.5 then                              ▷ Sjaak classification [2]
        spray_mode ← "Dripping";
    else if 2.5 < mean/std_deviation < 2.5 & mean/std_deviation > 0.3 then
        spray_mode ← "Intermittent";
    else if mean/std_deviation < 0.3 then
        spray_mode ← "ConeJet";
        cone_jet_mean ← mean;
    end if
    if mean/std_deviation > 2.5 then                              ▷ Monica classification [3]
    end if
    if spray_mode == "ConeJet" then                               ▷ João classification
        if cone_jet_mean > 1.14 × mean then
            spray_mode ← "MultiJet";
        end if
    end if
    return spray_mode;
end function
```

3.3.2 Machine Learning

3.4 Routine Sequences

3.4.1 Ramp

3.4.2 Step

3.4.3 Map

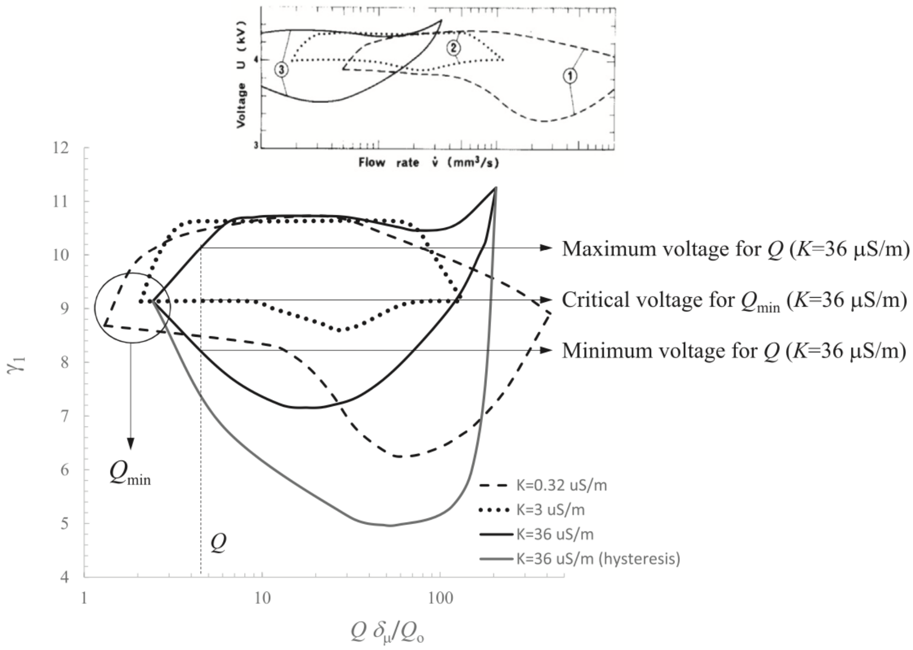

Figure 3.2: Domains of existence (stability) of Taylor cone-jets. [4]

Algorithm 2 MAP sequence in controller thread

---

procedure MAP($flowrate\_values$)
  for all flowrate_values **do** ▷ scanning in the flowrate range
    SEND_FLOWRATE_COMMAND(flowrate)
    $voltage \leftarrow voltage\_start$
    while $voltage \leq voltage\_stop$ **do** ▷ scanning in the voltage range
      SEND_VOLTAGE_COMMAND(voltage)
      SLEEP(step _time)
      $voltage \leftarrow voltage + step\_size$
    end while
  end for
end procedure

In the figures 5 and 6 we can see the results of this mapping experiments. The liquid used is pure ethanol. Each figure has 3 graphs with shared x axis representing the samples collected. The first is the current values collected through all the experiment. The second is the voltage values applied in each window of data collected. The colors represent the spraying classification defined by our routine. The third graph shows the current mean value of each data sample. Note that the experiment is composed of loops that increase voltage, change flowrate and repeat.

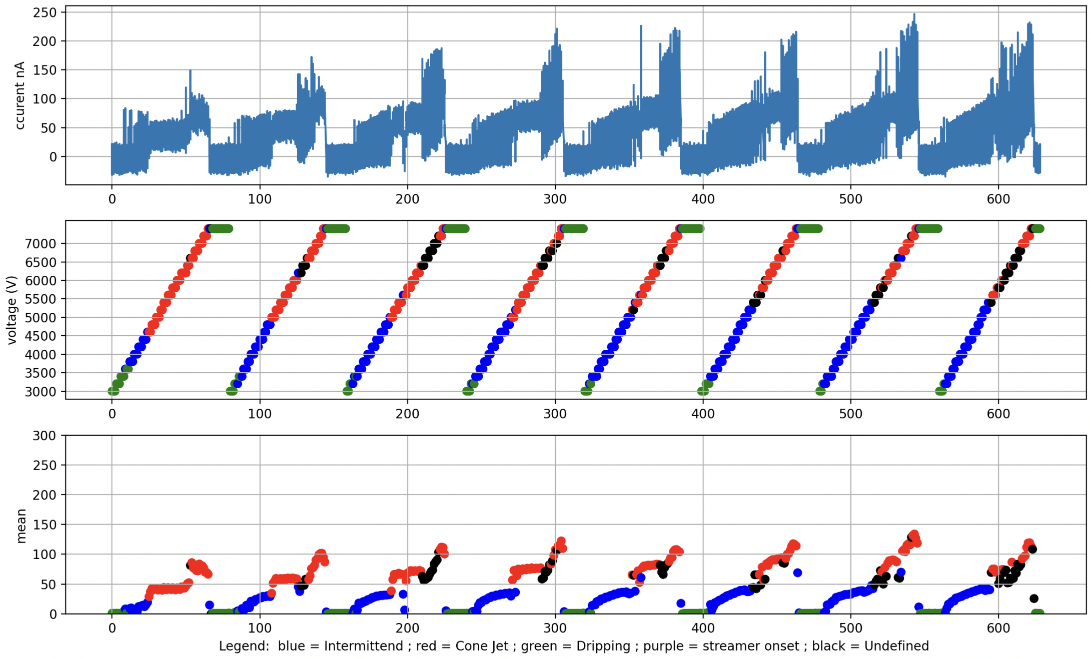

Figure 3.3: Mapping Experiment example 1

3.4.4 Control

3.5 Optimizations

About the python algorithm to turn the experiment autonomous it was made a study and modelling of the software architecture to optimize it for further control loop application to be implemented. From the changes made until now it highlights:

- Integrate high speed camera to the experiment routine.

- Remodel the software to support threads in order to separate the sensoring and controlling routines.

- Reduce the data collected size.

- Synchronize the power supply step commands and voltage sensoring.

- Reestructure the setup file in order to make it more intuitive to use the experiment.

- Improvements in code organization and readability.

About the setup,integrate was changed the liquid, nozzle diameter and distance to the plate in order to make the experiment the most stable and easy to reach cone-jet mode as possible. For example, while doing experiments we discovered that the frequency of the pump machine internal motors was creating an interference in the flowrate. Therefore compromising the stabilization in cone jet mode. A solution for that was to increasethe flowrate wich smooths this pumping noise. For that was also necessary to increase the nozzle diameter to balance with all other variables from the experiment.

3.5.1 Pump Integration

The pump integration in the automation algorithm bring us a new controllable variable, the Flowrate. Now we can control the spraying mode with the two main variables that afect the system. It will bring more complexity for the system since now we are dealing with multivariable control. Controlling also the flowrate gives to this project a new dimension in the system giving us freedom to explore the flowrate properties.

About the pump interface. As I could not find a good ready-to-use library for this pump I developed an simple and intuitive interface to be our software routine. The communication protocol used is RS-232. In the software routine the communication used is python serial interface. The pump commands list were found in the user manual.

Chapter 4

Results

Para a execução do projeto, algumas etapas de desenvolvimento tiveram de ser seguidas: familiarização com o sistema, estudo dos módulos envolvidos, leitura dos requisitos, elaboração de documento descrevendo todo o processo de implementação e relacionamento com os diversos módulos, implementação e testes.

4.1 Atividades do Projeto

4.2 Requisitos do Sistema

Chapter 5

Conclusion

References

[1] CLOUPEAU, M.; PRUNET-FOCH, B. Electrohydrodynamic spraying functioning modes: a critical review. *Journal of Aerosol Science*, v. 25, n. 6, p. 1021–1036, 1994.

[2] VERDOOLD, S. et al. A generic electrospray classification. *Journal of Aerosol Science*, Elsevier, v. 67, p. 87–103, 2014. ISSN 18791964. Disponível em: <http://dx.doi.org/10.1016/j.jaerosci.2013.09.008>.

[3] EMEDIATO, M. *Spark Detection And Prevention Device For Electrohydrodynamic Atomization Applications*. [S.l.], 2022.

[4] GAÑÁN-CALVO, A. M. et al. Review on the physics of electrospray: From electrokinetics to the operating conditions of single and coaxial taylor cone-jets, and ac electrospray. *Journal of Aerosol Science*, v. 125, p. 32–56, 2018.

Appendix A

O que ficou para depois

Inclua aqui informações que não sejam tão relevantes para o entendimento do projeto mas que ainda sejam importantes para documentá-lo.

Appendix B

O que mais faltou

Inclua aqui informações que não sejam tão relevantes para o entendimento do projeto mas que ainda sejam importantes para documentá-lo.