DEPARTMENT OF MECHANICAL ENGINEERING

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LITERATURE REVIEW

Electrosprays as a future technology for clean aeronautical propulsion systems

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ABSTRACT

Charge injection atomization is a promising technology, opening new horizons for the aviation industry: its ability to deliver enhanced fuel-air mixing, and subsequently increased engine efficiency, can be a worthy asset to reach carbon neutrality by 2050. This literature review focuses on the experimental methods used to assess the performance of charge injection atomizers before delving into an overview of the various geometries and improvements tested for these devices. According to existing research, performance is mainly investigated through the charge produced per unit volume or examined using advanced interferometry methods such as Phase Doppler Anemometry. As far as nozzle geometry is concerned, Kelly's work on his Spray Triode remains a cornerstone in the electrostatic atomization field. Later experiments from Shrimpton and Kourmatzis explored improving performance by reducing the atomizer's orifice diameter. However, more recent studies underscore the potential of a plane-plane geometry for industrial applications, departing from Kelly's point-to-plane apparatus. Additionnally, Li's work on nano-fluids opens fascinating new perspectives, promising an intriguing confrontation of the plane-plane atomizer's capabilities to these innovative fuels. This work will constitute the basis of further investigation, aimed at optimizing the atomizer's design to improve its efficiency.

STATEMENT OF OBJECTIVES

We will seek to identify a precise methodology that enables us to optimize our design to achieve better atomization performance. Our first mandatory step will be to conduct a comprehensive literature review on the matter. We will then attempt to model the injector behavior, establishing a blueprint of the aforementioned injector and deriving ideal electrical and geometrical corresponding to our objectives of fuel distribution.

Once the hefty theoretical work has been completed, we shall move to the computational section of the project, starting with coldflow simulations. We will indeed focus our efforts on determining a coldflow setup - in defining a computational mesh, choosing which gases will be used for the non-reacting pilot flame in the following simulations, selecting boundary conditions for the flow rate of fuel, temperature of air, pressure, inlet velocity and velocity at the inner wall. This setup will be refined through iterations, testing the efficiency of the previously established design. Eventually, we will direct our attention to reacting flows, building an initial setup meeting our criteria for further investigation from the insights of our cold-flow simulations before reworking and improving it over the summer.

CONTENTS

1 INTRODUCTION

Drastically cutting back on CO_2 emissions is the major challenge the aeronautics industry will have to tackle in the next decades. Curbing these emissions by 90 % below the levels reached in 2019 by 2050 will soon become mandatory if the aviation industry is to meet the demands of the Paris Agreement. Therefore, solutions such as improving the efficiency of combustion engines are particularly investigated. In these engines, atomization is a crucial process, describing the breaking down of fuel into small droplets to improve combustion. We will focus here on enhancing atomization through electrohydrodynamics. Electrostatic atomization is indeed faster than regular atomization as the Coulomb repulsion of similarly charged droplets enhances the dispersion of these droplets within the air stream.

This report is devoted to a comprehensive literature review on the performance of charge injection atomizers. In these systems, a sharp needle (cathode) is immersed in an insulating liquid (such as a hydrocarbon fuel) and elevated to a high-voltage. This process enables charge extraction from the needle, which is then injected in the flowing liquid later exiting the atomizer through the orifice of a grounded plate (anode).
Our final objective is the experimental design of a charge injection atomizer with improved performance. Therefore, we aim to review and discuss the methods used to evaluate performance, the geometry and parameters (such as voltages and applied flow rates) found in the literature dealing with charge injection atomizers.

2
ASSESSING THE PERFORMANCE OF CHARGE INJECTION ATOMIZERS

2.1 Spray-specific charge

Evaluating the electrical performance of a charge injection atomizer starts by examining the total injection current I_T. Although direct measurement of such a current presents challenges, two other currents can be investigated: the spray current I_s, representing the current carried away by the liquid, and the leakage current I_l, flowing through the fluid to the nozzle body. The total injection current is distributed between the spray and leakage currents $I_T = I_s + I_l$ [?] [1]. A Faraday Cage can also be used to mitigate the risk of induced currents arising from local electric fields and influencing the measurements [2]. With such considerations, the spray-specific charge Q_V, defined as the ratio of the spray current I_s to the liquid flow rate $\dot{\tau}$, can be calculated. Q_V is a telltale indicator of the atomization quality, providing relevant information on the fuel droplets' later behavior, dispersion and trajectory.

2.2 Visualization techniques

2.2.1 • Spray imagery

Relevant information concerning the spray characteristics can also be collected using photography [3], high-speed video recording, and image analysis. Data collected from such analysis enables the calculation of the spray cone angle α and jet breakup length l_j defined by the following equation [4],

$$l_j = u_{inj} t_j$$

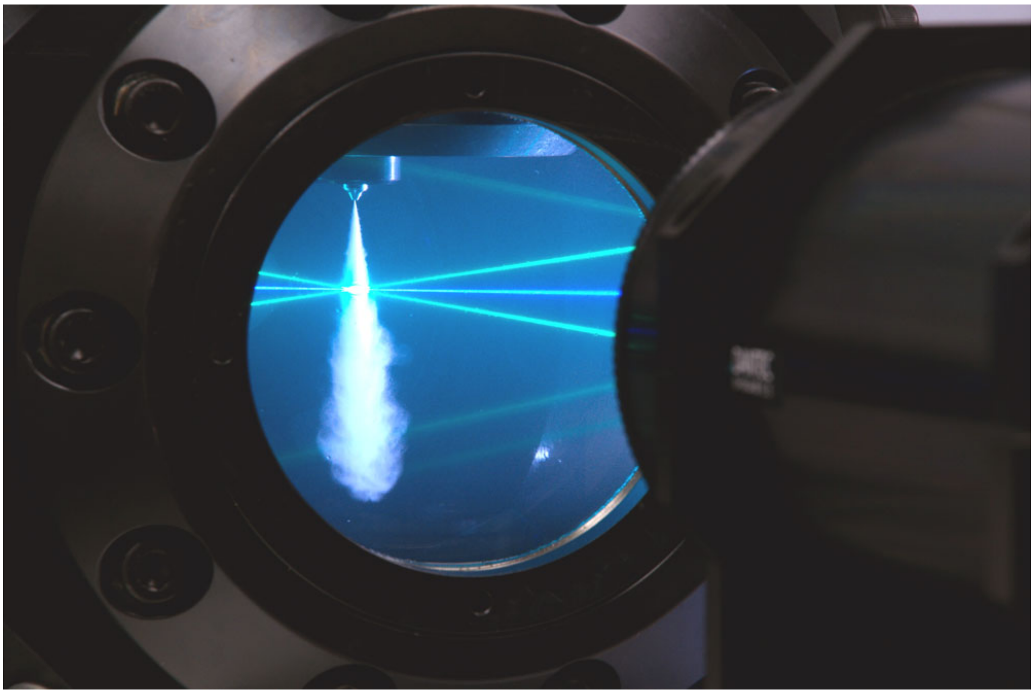

Figure 1: Phase Doppler Anemometry - Dantect Dynamics

where u_{inj} is the velocity of the injected flow and t_j refers to a characteristic time needed by a charged fluid element to go from the center of the jet to its surface. The applied flow rate $\dot{\tau}$ is obtained by multiplying the injection velocity u_{inj} by the effective surface of the atomizer's orifice.

Physical quantities such as this spray cone angle or the jet breakup length facilitate the comprehension of the spray structure.

2.2.2 • Phase Doppler Anemometry

More advanced techniques are required for a better in-depth examination of the spray characteristics. Although Fraunhofer diffraction has been used at times [1], Phase Doppler Anemometry (PDA) is a much more widespread method. Two (or more) lasers are directed at the spray, often at Brewster's angle, defining by their intersection a measuring volume. Laser light is scattered by the fuel droplets crossing this measuring volume before being analyzed with interferometry methods. Such an approach focuses on the measurement of the phase difference between the

Description	Value	Units
Laser power	100	mW
Light wavelength (u)	5145	nm
Light wavelength (v)	415	nm
Beam separation	40	mm
Focal length (transmitting)	600	mm
Focal length (receiving)	600	mm
Measurement volume diameter	0.3	mm
Off axis angle	70.6	°
Liquid refractive index (C_{10})	1.46	—

Figure 2: Characteristics of a PDA system [3]

quasi-periodic signals collected by two detectors (giving the droplets' sizes) and the frequency of the deflected light (providing information about the droplets' velocities) [5]. By combining velocity and size measurements, PDA offers a good understanding of the distribution of particles within a flowing fluid, facilitating spray visualization. 2D Dantec PDA systems are commonly used in experimentation.

Rigit and Shrimpton have recently advanced the field of PDA using a novel approach [6]. They coupled spatially resolved mass and charge flux distributions obtained through direct measurements with probability density functions of drop velocity and size. This enables a more comprehensive quantification of the spray characteristics and an overall better examination of the spraying performance.

3
POINT-TO-PLANE NOZZLE GEOMETRY

3.1 Early attempts at charge injection atomization

Charge injection atomizers were introduced through the works of Kim and Turnbull ([7]), later followed by Robinson [8]. However, this first atomizer offered a limited performance with low flow rates (10^{-4}mL.s^{-1} $\leq \dot{\tau} \leq$ 10^{-3}mL.s^{-1}) and injected currents ($10^{-10}\mu A \leq I_T \leq 10^{-8}\mu A$) [7].

Besides, the extremity of the needle suffered extensive damage from Joule heating: as the tip experiences intense electric fields, its electrons undergo quantum tunneling and are emitted from the needle. This field emission mechanism repeatedly exposes the needle tip to electric currents leading to a burnout phenomenon.

Robinson [et al.] ([8]) were later successful in producing a spray, extracting charge from the cathode through either field emission or field ionization. As far as experimental parameters were concerned, they reported that the voltage required for field emission ranged between 6 and 15 kV whereas it varied between 9 and 15 kV (with a maximum current of 0.1 μA) for field ionization.

3.2 Kelly's experimental and theoretical contribution

3.2.1 • The Spray Triode

Kelly ([9]) improved the existing design, turning it into a point-to-plane geometry as he sought to solve the low flow rate and injection level issues that had plagued his predecessors. His spray triode removed the distance between the cathode and anode existing in Kim and Turnbull's

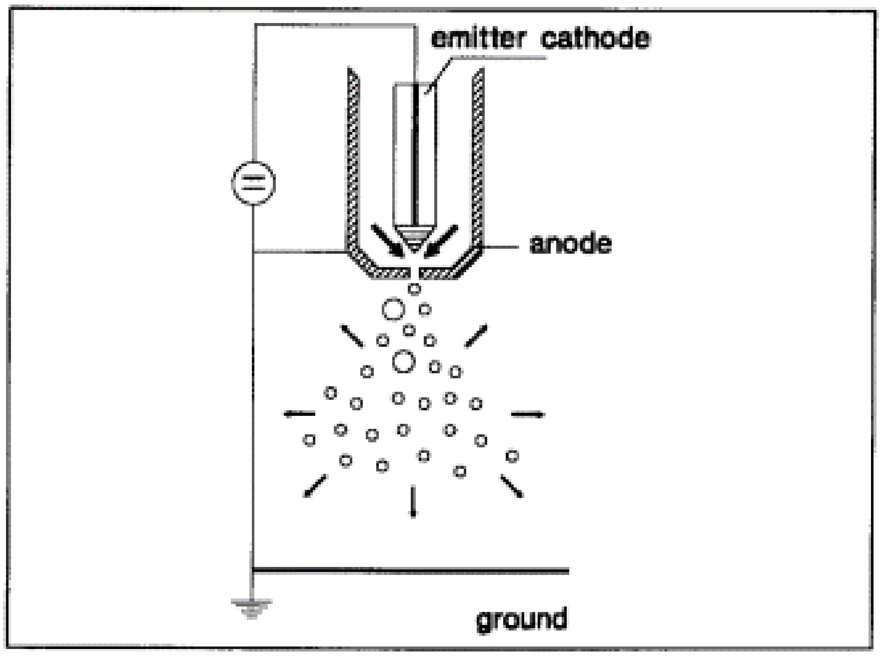

Figure 3: Schematic of Kelly's Spray Triode [10]

design with the cathode's tip centered precisely above the orifice of the anode. Inadequate centering indeed leads to an uneven charge distribution and poor atomization performance: thus, this alignment condition is an essential aspect of Kelly's system.

Kelly effectively achieved higher flow rates than his predecessors, obtaining with his spray triode up to a flow rate $\dot{\tau} \approx 1\text{mL.s}^{-1}$, a thousand times greater than the typical flow rate previously achieved. The shortened distance between the cathode's tip and the anode's orifice increases the bulk flow, also improving the efficiency of charge extraction from the emitter. Both the total injected current I_T and the spray current I_s are therefore increased. The spray triode was later put to good service by Banskton [et al.] [11].

Moreover, Kelly noted an electric field intensity $E \approx 6.5 \times 10^9\text{V.m}^{-1}$, much greater than the average breakdown strength of most hydrocarbon fuels, $E \approx 2 \times 10^7\text{V.m}^{-1}$. In the face of such high field intensity, Kelly suggested that the injection current I_T be supplied continuously to preserve the emitting electrode from the same ensuing burnout that had been detrimental to Kim and Turnbull's apparatus.

3.2.2 • Maximum spray-specific charge achievable

Kelly shed light on the existence of a corona discharge effect in his design [10]. When the increasing strength of the electric field reaches the threshold for corona onset in the surrounding fluid, a corona discharge is initiated, ionizing the fluid and causing a partial discharge of the fluid stream upon exit. This raises the question of the maximum spray-specific charge Q_V attainable under such conditions.

Kelly [12], Lehr and Hiller [10] showed that the radial component of the electric field produced by the jet E_r is a function of Q_V and the orifice diameter d, defined by the following equation[12] [10] [13]:

$$E_r = \frac{Q_V d}{4\epsilon_r \epsilon_0}$$

where ϵ_r is the relative permittivity of the liquid and ϵ_0 is the permittivity of the vacuum. The maximum spray charge Q_V is attained when the radial field strength E_r on the surface of the emitter reaches the threshold for corona onset, cementing the corona discharge as a major limiting factor of the atomizer's performance. Moreover, it appears that at a constant E_r, liquid jets generated from smaller orifice diameters contain a higher specific charge.

4
FURTHER IMPROVING ATOMIZATION PERFORMANCE

4.1 Smaller orifice diameter designs

4.1.1 • Two flow regimes

Using as a starting point a nozzle geometry described by Jido [14], Shrimpton and Yule reported two different flow regimes under atomizer operation. The subcritical (at low flow rates) regime does not lead to finely atomized sprays while in the supercritical regime (high flow rates) finely atomized sprays are achievable without constraint on the upper flow rate limit [15] [2]. As discussed previously, atomization performance is defined by Q_V, which depends on d and is restrained by a corona discharge phenomenon. Hence, we will investigate nozzle geometries offering high flow rates $t\dot{a}u$ and small orifice diameters d.

4.1.2 • Influence of fluid properties

However, atomization quality with this first geometry left a lot to be desired. The design was modified in favor of the classic point-to-plane geometry advocated by Kelly [9], with flow rates $\dot{\tau}$ ranging from 0.18 and 3.57 mL.s^{-1} and orifice diameters d varying between 150 and 250 μm. It successfully enabled the production of a fuel spray with a specific charge $Q_V \approx$ 3.0C.m^{-3} for an orifice diameter of 150 μm. Shrimpton and Yule concluded that $L_i/d \approx 1$ and $L_o/d \approx 2$ ratios for the inter-electrode distance and orifice length were optimal for a better performance [13].

Rigit and Shrimpton [13] developed a new design, which aims to study the upshot of smaller orifice diameters and a more viscous fluid on electrical performance [16] [17]. This converging

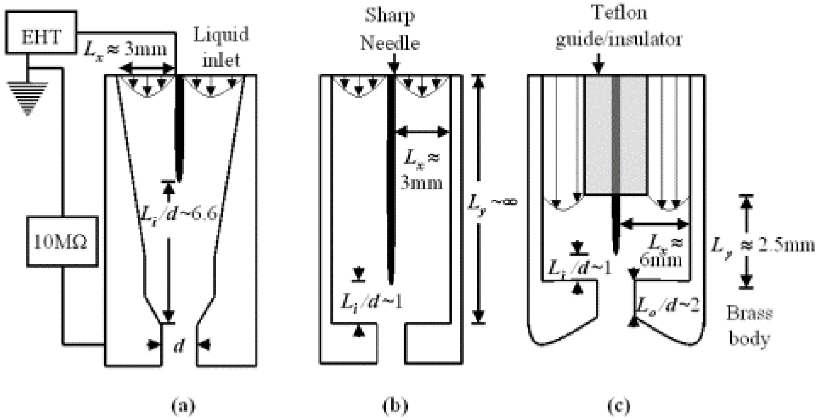

Figure 4: Schematics of different charge injection atomizer designs [13]

geometry concentrates the bulk flow near the orifice, thus improving charge injection quality. The specific charge Q_V reached with this third design and diesel oil is higher than the one obtained with the second design (see 4) and kerosene oil for similar d in the supercritical regime. This illustrates the importance of the fuel properties in the atomization quality since a higher spray-specific charge for a more viscous liquid such as diesel oil. A 1.77 C.m^{-3} value for Q_V was attained with $d = 250\mu m$, $u_{inj} = 20$m.s^{-1} and supply voltages up to 24 kV.

Li [18] and Lu [19] have very recently ventured into the relatively unknown territory of nanofluids to investigate a potential increase in atomization performance. Li focused on nano-aluminum and reported that voltage and particle concentration were determining factors influencing the efficiency of the process, a conclusion Lu shared. Li observed that enhancing the voltage (17-25 kV) decreased the average fuel droplet diameter, which connected to the applied flow rate according to the following power law: $D \propto \dot{\tau}^{1/2}$ [18]. He also reported the best atomization efficiency was reached for a nano-aluminium concentration of 5.0 mg.L^{-1} while Lu underscored that the minimum average diameter of fuel droplets decreases with nanoparticle concentration, attaining $\approx 55.4\mu m$ at 6.0 mg.mL^{-1} [19]. They also confirmed that decreasing the orifice diameter d bolstered atomization quality. It is however unfortunate that no study of the maximum spray-specific charge Q_V was conducted to provide a better comparison point of these electrical performances with previously existing data.

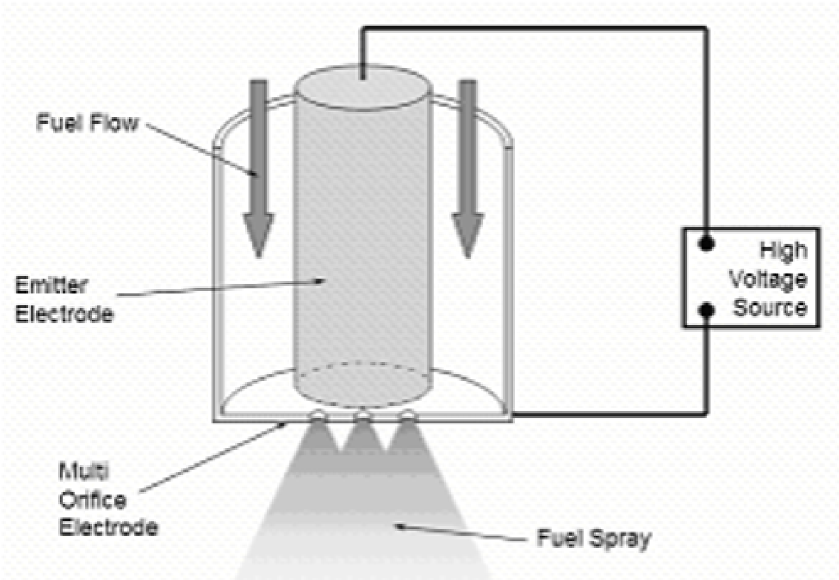

Figure 5: Schematic of a plane-plane atomizer [20]

4.2 Plane-plane atomizer

Allen [et al.] [20] recommended to evolve the design of the charge injection atomizer from a point-plane geometry to a plane-plane geometry. Indeed, Kelly's alignment requirement [9] [15] [13] constrains both the minimum diameter d conceivable for the anode orifice and the maximum supply pressure this orifice can withstand. Yet, high flow rates demand high supply pressures [2]: a single-aperture geometry restricts the flow rates achievable under a given pressure condition, thus curbing the overall atomization performance.

Allen's design introduces an emitting cathode with a planer design and facetted microstructure made possible by the use of a diamond burr (available for commercial purposes). This cathode is then placed close to the anode, which encompasses multiple fluid discharge orifices. For such an atomizer, axial alignment is no more critical to its good operation and performance: the orifice only needs to be installed within the circumference of the cathode. The manufacturing of such openings (in this case holes of sizes ranging from 60 to 150 μm) remains the only limiting factor to the decrease in drop diameter. It is worth taking into account that

Allen's atomizer integrates a Vernier adjustment scale, allowing him to tailor the L_i/d ratio according to his needs.

Allen obtained droplets characterized by a Sauter Mean Diameter (the volume-weighted average diameter for these droplets) $D_{SMD} = 0.5 \times d$ where d is the anode orifice diameter [20]. Thus, he demonstrated that atomization of dielectric fluids could be accomplished at high flow rates with such a multi-orifice plane-plane design and without the alignment constraint. Kourmatzis [et al.] [2] went a step further by comparing the performance of plane-plane atomizers to the existing research on point-to-plane atomizers, examining both a single-orifice and a multi-orifice design.

They [2] investigated the total injection current I_T and spray-specific charge Q_V with various supply voltages (up to 12 kV), L_i/d ratios and injection velocities (5, 10, 15 m.s^{-1}) in the cases of two plane-plane atomizer designs, the first incorporating a 1 × 100 µm–hole orifice anode, and the second containing a 9 × 100 µm–hole orifice plate. Firstly, the electrical efficiency appears to increase with the number of holes: the efficiency of the single-hole plane-plane apparatus mostly remains stuck under 20% while the 9-hole atomizer boasts an efficiency ranging from 7 to 65%, which tops the efficiency of the point-plane atomizer, varying between 8 and 50 % [21][13]. This can be simply understood when considering that the 9-hole plane-plane design offers shorter paths for an increased ion expulsion, hence improving the electrical efficiency of the atomizer. Besides, the specific charge Q_V is shown to increase with the flow rate and maximal values of this spray-specific charge can be achieved at quite lower supply voltages (up to 6 kV) for the single-hole system. Yet, a drawback of the plane-plane geometry stands out as experimental results point to a drop in specific charge as the number of holes increases. The 9-hole atomizer indeed comes with a 75% loss in Q_V.

This system holds great promise, demonstrating the potential to achieve high flow rates and produce fine sprays. In the case of the multi-orifice plane-plane design, it has even shown the capability to surpass the quality of a conventional charge injection atomizer, with reported mean arithmetic diameters as low as 0.25 times the diameter d by Kourmatzis [et al.] [2]. However, despite these interesting results, further comprehensive testing is required to establish the system's capabilities, including its upper limits in terms of flow rates and maximum spray-specific charge Q_V. Besides, doubts persist regarding potential losses in spray-specific charge for multiple apertures. While the overall atomization is satisfactory, Allen observed variations for which the precise explanation as far as the fluid's properties were concerned, remains elusive [20]. Further exploring the behavior of this atomizer with different fluids of varying properties opens exciting prospects for the future, especially if this plane-plane geometry is to be tested with nanofluids [18] [19].

5
CONCLUSION

Assessing the electrical performance of a charge injection atomizer boils down to deriving the maximum value of the spray-specific charge and analyzing the fuel jet with Phase Doppler Anemometry.
High atomization quality can be achieved with converging point-to-plane geometries with a ratio $L_i/d \approx 1$, high voltages, high applied flow rates, and a small orifice diameter.

The plane-plane atomizer holds great promise. A more in-depth investigation of his potential and the influence of fluid properties on his performance could be a fascinating next direction for our research project.

REVIEW OF THE USE OF GENERATIVE AI

The use of generative AI in the writing of this report was strictly limited to ChatGPT4 for translation, research paper examination, and readability improvement.

Firstly, English is not my mother tongue, which has led me to struggle at times with some technical terms introduced in the papers I have read. A particularly good example of this is the term *diamond burr* I have discovered in Allen's work [20]. This has led me to enter the following prompt in GPT4: "*Can you give me the meaning of burr in French ?*", which gave me the answer *fraise*. It is a convenient tool to bolster my understanding of the information gathered over the course of this project.

Besides, I have also used it for a faster identification of whether or not a paper I was interested in reading was relevant to my project. To this end, I have fed the abstract of a handful of papers to ChatGPT, asking it to break down their main conclusions to me. For instance, I used this method to pinpoint the new approach Li's research epitomized, entering the following prompt: "*Hi ! Here is the abstract of a research paper, I would like you to give me the main ideas explored in the paper !*" and pasting the abstract of the aforementioned paper.

Eventually, I relied on GPT's proficiency in academic English to obtain suggestions to improve the readability of my work. I am quite prone to using a flourished language while writing in English and I am aware this does not match the requirements of scientific writing. I have therefore used the following prompt: "*Can you give me suggestions to improve the readability of this paragraph ?*" before pasting the lines I had written about Shrimpton's two flow regimes. I ended up selecting the suggestions that felt the best on paper.

Despite the mammoth possibilities offered by ChatGPT, I have tried my very best to only use it as a suggestive tool, always striving to prioritize my originality and own ideas. In my opinion, generative AI can be of great use to research, enabling authors to focus solely on the ideas they want to emphasize, on how to organize them instead of struggling with a foreign language or formatting issues (if using LaTeX for instance). Provided its role remains limited to the one of a diligent assistant, AI may help the researcher devote more of its time and resources to the core of his work. However, this is a slippery slope as the temptation of relying too heavily onto this proficient helper is easy to succumb to.

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APPENDIX

A Specification Table

Source	**Fuel**	**d**	**L/d**	**V**	$\dot{\tau}$	$\mathbf{Q_V}$
Balachadran *et al.*, 1994	diesel kerosene	500 μm	6.6	15-17 kV	150-160 mL/min 120 mL/min	
Malkawi *et al.*, 2010	diesel corn oil	254 μm	1	3.5, 5 kV 8, 9, 10, 12 kV	30 mL/min 45 mL/min	0.30 C/m^3 0.58 C/m^3
Shrimpton and Yule, 1999		250 μm		0 - 16 kV	30 mL/min 50 mL/min	1.20 C/m^3 1.80 C/m^3

Table 1: Comparison of charge injection atomizers parameters