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Fabrication and Enhancement of Ionic Wind Speed in EHD Propulsion Systems with Airfoil-Type Electrodes

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Abstract

This paper highlights the importance of sustainable propulsion technology to reduce the harmful effects of fossil fuel use. It strongly supports electrohydrodynamic (EHD) propulsion systems as better, cleaner, and more environmentally friendly options that use electric fields to create ionic wind for air propulsion, though they produce ozone gas. The multistage Electrohydrodynamic (EHD) propulsion systems with electrodes that resemble airfoils have a lot of promise for use in a variety of aerospace, robotics, and transportation-related applications including Unmanned Aerial Vehicles (UAVs), Electric Aircraft, Transport Systems, and Aerospace Analysis. The study examines the development of multistage EHD systems, focusing on how voltage affects air velocity. The *experiment demonstrates that the electrodes are 2 cm apart from each other, and the air velocity increases gradually with the increase in voltage. But after reaching a certain velocity, the velocity does not increase with the voltage increment. The experiment carefully analyzes the relationship between voltage and air velocity, showing that with electrodes 2 cm apart, the air velocity was 1.6 m/s at 33 kV and reached 2 m/s at 56 kV. The maximum air velocity achieved in this study was 2m/s at 56 KV when the electrodes were 2 cm apart. The experiment may have varied under the influence of rain and temperature. This study does not consider the effects of temperature, humidity, and electrode properties on air velocity.*

Keywords: Sustainable propulsion technology, Fossil fuel, electrohydrodynamic (EHD), Ionic wind, Air propulsion, Ozone gas, Multistage EHD systems, Voltage, Air velocity.

1. Introduction

The heavy dependence on fossil fuels in conventional propulsion systems in recent decades has increased worries about the effects on the environment, climate change, and the depletion of scarce resources. In aviation engines and other conventional propulsion methods, the combustion of fossil fuels or aviation fuel, such as jet fuel, Avgas, biofuel, compressed natural gas, and liquefied natural gas, etc., releases greenhouse gases and other pollutants that contribute to global warming and air pollution [1]. Fossil fuel combustion results in the emission of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and others into the atmosphere, which exacerbates the greenhouse effect and contributes to a change in the earth's climate. The combustion of fossil fuels releases carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases into the atmosphere, exacerbating the greenhouse effect and contributing to global climate change. With the exclusion of induced cirrus clouds, whose radioactive forcing is predicted to be 1.3–1.4 times greater than that of CO_2 alone, they are thought to be a source of radiation. 2.4% of all CO_2 emissions in 2018 came from business activities throughout the world. Between 1967 and 2007, the fuel efficiency of jet aircraft increased by 70%, and in 2018, CO_2 emissions per revenue ton-kilometer (RTK) were 47% lower than in 1990. The average amount of CO_2 emitted per revenue passenger per kilometer in 2018 was 88 grams. Despite the aviation sector's improved fuel efficiency, total emissions have gone up along with the growth in air travel. Aviation emissions increased by 70% by 2020 compared to 2005, and they may increase by 300% by 2050. [2] The search for workable substitutes has become more intense in response to the environmental problems caused by fossil fuels. Several environmentally friendly propulsion technologies have developed as viable alternatives to current fossil fuel-based systems. The use of electricity from renewable sources to power automobiles and other machinery has drawn a lot of interest. With no exhaust emissions and a decreased reliance on fossil fuels, battery electric cars (BEVs) and hydrogen fuel cell vehicles (FCVs) are promising examples of electric propulsion. Additionally, ethanol and biodiesel, two biofuels made from renewable organic matter, offer a temporary fix that can dramatically lower greenhouse gas emissions. Synthetic fuels, commonly referred to as carbon-neutral fuels or synthetic fuels, have enormous potential as a replacement for fossil fuels in propulsion systems. These fuels are created by absorbing and recycling carbon dioxide that is released during industrial or combustion operations, therefore reducing their overall carbon impact. Without requiring any changes, synthetic fuels may be used in current internal combustion engines and gas turbines, potentially serving as a transitional

technology to more environmentally friendly propulsion methods. But one of the most significant expenditures for an aircraft is fuel, which is possibly the biggest obstacle for synthetic fuels. Synthetic fuels must have costs and performance levels that are on par with or lower than those of traditional fuels to be competitive in the market. However, because the manufacture of synthetic fuel is more intricate, it comes at a higher cost. [3].In parallel, cutting-edge, eco-friendly electro-hydrodynamics (EHD) propulsion technologies have arisen. EHD propulsion systems provide a fresh approach to the propulsion of vehicles and aircraft by harnessing electric fields to produce ionic wind. EHD systems eliminate the need for fossil fuels since they run quietly and produce no hazardous emissions of greenhouse gases. EHD technology offers the potential to revolutionize the transportation sector and lessen its ecological effect as research into it develops. The search for sustainable propulsion solutions is becoming increasingly intense as fossil fuel's environmental effects become more obvious. EHD propulsion technologies provide cleaner and more environmentally friendly modes of transportation. A multistage system is investigated to improve EHD efficiency by modifying voltage, stage-to-stage gap, stage count, and airfoil electrode type to affect air velocity.

A more environmentally friendly option to conventional fossil fuel- or aviation fuel-based propulsion systems is electrohydrodynamics (EHD) propulsion. EHD propulsion doesn't require combustion, which considerably lowers carbon emissions. EHD systems employ electric fields to create ionic wind instead of internal combustion engines, which burn fossil fuels and emit greenhouse gases and other harmful pollutants. EHD propulsion is a desirable alternative for sustainable transportation because of its eco-friendly quality, which helps to create a future that is greener and more ecologically conscious.

The corona discharges those forms at the ends of some sharp conductors (such as points or blades) When they are subjected to high voltage about the ground, it is what is known as an ionic discharge, which causes an airflow. An electrohydrodynamic phenomenon is ion wind. The air around the electrodes becomes ionized when a high voltage is applied between two electrodes (the cathode and the anode). Positively charged ions (cations) and negatively charged ions (anions) are produced during this ionization process. The impact of the electric field causes the charged ions to migrate in the direction of the appropriate electrodes. These ions gain velocity by colliding with neutral air molecules as they approach the electrodes.

The primary objective of this study is to fabricate basic and multi-stage Electrohydrodynamic (EHD) propulsion systems. Furthermore the effect of air velocity, number of stages, stage-to-stage gap, and high voltage applied to the electrode on the generation of ionic wind and subsequent thrust output have been evaluated.

2. Literature review

Significant investigations on EHD propulsion system are illustrated briefly in this section. Li, H., Guo, C., Li, Y., Hong, X., Zhu, J., & Chen, Z. investigated that an ionic wind was produced using a needle-to-cylinder electrode configuration at atmospheric pressure. Experiments revealed that the ionic wind velocity does not rise monotonically with increasing discharge current, but grows with increasing voltage in the corona discharge phase while falling in the glow discharge phase. This information can be used to establish a design guide for EHD systems [4]. Mazumder, A., & Lai, F. investigated that the two-stage EHD gas pump is considered more efficient when it is operated with unevenly applied voltages. It is capable of producing and maintaining air flows with a maximum volume flow rate of 35 L/J [5]. Ibrahim, K., Sampath, S., & Nalianda, D. studied that it is essential to take the fan design and thrust needs into account to generate optimal voltage and current values for an electrical propulsion system. These variables have a direct effect on the ideal voltage and current, causing changes in device sizes and propulsion system performance as a whole [6]. In an EHD corona thruster, the collector electrode geometries were examined by Belan, M. et al. The findings from NACA 0010-shaped collectors, which balanced thrust-to-power ratio and thrust density, were the most encouraging. Future research into altered collector forms is advised for improved EHD propulsion system performance and informative data for simulations and design [7]. An experimental investigation on a low-power, unipolar wire-to-mesh ionizer for electrostatic flow control was done by Monrolin, Plouraboué, and Praud. Investigating the ionizer's performance in terms of wire voltage, mesh voltage, and wire-to-mesh distance, the research reveals how complicated and nonlinear its behavior is. The efficacy of the ionizer and its effect on the flow field and aerodynamic forces are improved by increasing wire voltage. The importance of wire-to-mesh distance in affecting the ionizer's effectiveness is emphasized by the study. The outcomes offer insightful information for electrostatic flow control applications that optimize wire-to-mesh ionizers [8]. The electrohydrodynamic effect's function in producing thrust in a wire-cylinder structure at 10 high DC voltage was the topic of research by Kiousis, K., Moronis, A. & Fruh, and W. The goal was to determine a link between the generated thrust and the corona discharge current while also investigating how the electrodes' geometrical characteristics, such as electrode gap, wire radius, and cylinder radius, affect this relationship. The discharge current and produced thrust were shown to be linearly related by the experimental investigation. Furthermore, the parametric analysis showed that although bigger emitter radii and electrode gaps resulted in decreased total thrust, they improved the thrust-to-

power ratio. The study's objective was to obtain a greater comprehension of the fundamental concepts behind thrust production in EHD-based propulsion systems with wire-cylinder configurations [9].
The existing research demonstrates the potential of electrohydrodynamic (EHD) propulsion, it leaves critical gaps in understanding the impact of environmental conditions such as temperature, humidity, and rain on EHD system efficiency. The current research does not fully explore alternative electrode designs or materials, such as airfoil-shaped and copper electrodes, which could enhance thrust and system performance. Additionally, the nonlinear behavior between voltage and air velocity beyond a certain threshold remains underexplored, especially in relation to optimizing stage gaps and improving power-to-thrust ratios. The scope of future research lies in addressing these gaps by investigating the influence of varying environmental conditions on EHD propulsion performance, exploring advanced electrode designs (e.g., airfoil and copper), and optimizing stage gaps to enhance ionic wind generation. Additionally, developing more efficient power circuits, such as Zero Voltage Switching (ZVS), and studying the impact of dimensional changes on system efficiency will be crucial for improving the scalability and real-world application of EHD propulsion systems.

3. Research methodology

The research methodology for this project follows a systematic approach, beginning with the design and fabrication of a basic Electrohydrodynamic (EHD) propulsion system. The electrode spacing and material selection were optimized to enhance ionization efficiency and airflow dynamics while ensuring stability. Larger electrode gaps required higher voltages but often failed due to potential drops, whereas narrower gaps improved airflow velocity but risked electrical arcing. A balanced spacing was chosen to ensure efficient propulsion. Stainless steel rods were used as electrodes for their smooth surface, reducing energy losses and enhancing ionization, while PVC provided safe insulation due to its dielectric properties. Additionally, 3D-printed components enabled precise geometries and structural integrity in the multi-stage design. A high-voltage circuit was constructed to power the system, after which its functionality was tested. Upon successful validation, a more complex multi-stage EHD propulsion system was designed and fabricated. Air velocity measurements were conducted to evaluate the system's performance. Finally, various parameters were modified to measure the propulsion system's air velocity at different conditions. This iterative process of design, testing, and refinement ensures a comprehensive analysis and improvement of the EHD system. A high-voltage generator circuit with a fly-back transformer in its core is shown in Fig. 1. A 1.5A safety fuse is thoughtfully incorporated into the circuit, which is powered by a 12V battery, to improve circuit safety. The key component, a transistor identified as S11B02FX, is responsible for constant switching, which produces high-frequency pulses. This transistor plays a key role in regulating the circuit's current flow.

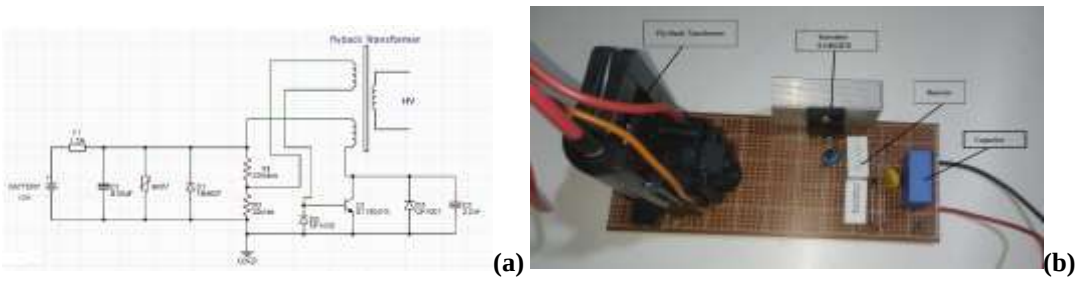


Fig. 1. (a) Schematic diagram of high voltage generator circuit, (b) Circuit of flyback transformer driver

Fig. 1 depicted the actual circuit diagram, which used to provide the high voltage. A ready-made module has also been used in the research which can boost 3-6V to approximately 400KV. Various methods exist for measuring high voltage, including Voltage Dividers, High Voltage Probes, Voltage Transformers (VT), and the Spark Gap method. In the Spark Gap method, high voltage causes a spark to jump across a gap, and the spark characteristics provide voltage insights, following Paschen's law. The breakdown voltage (V_B) required for an electric arc between two electrodes in a gas is determined by pressure and gap length using Paschen's law:

$$V_B = \frac{Bpd}{\ln(Apd) - \ln\left(\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right)} \quad (1)$$

Where (V_B) is in volts, p is pressure, d is gap distance, γ_{se} is the secondary-electron-emission coefficient, and A and B are constants, experimentally determined as $112.50(kPa \cdot cm)^{-1}$ and $2737.50\, V/(kPa \cdot cm)$, respectively.
The 3D models for the EHD propulsion systems were designed using SolidWorks 2020. Fig. 2 presents the basic

single-stage EHD propulsion system, while Fig. 3 shows how multiple single-stage models can be combined to form a multi-stage system. Fig. 2 illustrates a real-time basic EHD unit, validating the project's concept, and Fig. 3 displays the multi-stage unit, where the first and second stages are fabricated from PVC, and the final stage is 3D printed.



Fig. 2. Model of basic EHD propulsion system

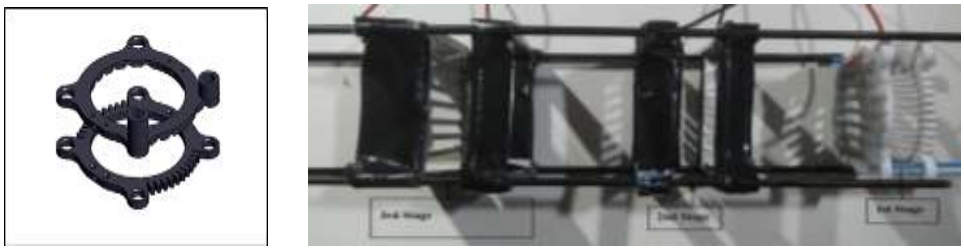


Fig. 3. Model of multi-stage EHD Unit.

4. Data collection and results

This research aims to confirm the feasibility of Electro Hydrodynamic (EHD) propulsion, focusing solely on its practical and theoretical viability without considering efficiency or weight-to-thrust ratio. EHD propulsion generates thrust using the interaction between electric fields and fluid media, eliminating conventional mechanical components. The data collection process involved several key steps: initiating the power supply, adjusting the voltage to the required high levels, measuring the high voltage using the spark gap method based on Paschen's law, and configuring electrode distance. A digital anemometer (Victor 816B) was used to measure air velocity, and the process was repeated for various configurations and parameter settings. Each experimental value, including voltage, electrode distance, and air velocity, was meticulously recorded. Systematic variation of parameters allowed for a comprehensive evaluation of the EHD system under different conditions, providing essential groundwork for future advancements in propulsion technology. The experiment involved data collection across distinct categories. These comprised electrode-to-electrode distance and the initial state of the power supply, along with high voltage and power supply information. A digital anemometer was used to record the air velocity measurements. The data of different categories are given in Table 1:

Table 1: Air velocities concerning different spacing of electrodes and high voltage

High Voltage (KV)	Air Velocity (*s*)		
	For electrode spacing of 2 cm.	For electrode spacing of 2.5 cm.	For electrode spacing of 3 cm.
33	1.6	1.25	0.30
45	1.9	1.74	0.76
56	2.0	1.80	1.13
66	2.0	1.82	1.30

Analysis of the experiment's results is essential to determining its ultimate result. This section presents a graphic representation of the findings in Fig. 4. The graph in Fig. 4 illustrates the relationship between air velocity and voltage for three different electrode spacing: 2 cm, 2.5 cm, and 3 cm. As the voltage increases, the air velocity rises for all spacing configurations, though the rate of increase diminishes at higher voltages, particularly around 50–60 kV. The 2 cm spacing produces the highest air velocity, reaching approximately 2.2 m/s at 60 kV, followed by the 2.5 cm spacing at 1.8 m/s, and the 3 cm spacing at about 1.4 m/s. This behavior can be explained by the electric field's dependence on electrode distance, where a smaller spacing generates a stronger field, leading to greater ionization of air molecules and higher air velocities. The results demonstrate that

reducing the electrode spacing increases the air velocity, a finding that is significant in applications involving ion wind or electrohydrodynamic flow, where air movement is influenced by high-voltage electric fields.

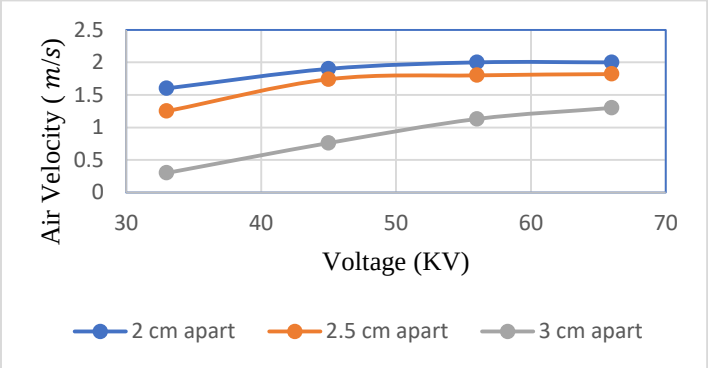


Fig. 4. Air Velocity vs. Voltage for electrode spacing of 2 cm, 2.5 cm, and 3 cm.

Validation

All collected data underwent thorough validation procedures, including cross-referencing with known standards, repetition of measurements for consistency, and verification against established protocols, ensuring the integrity and reliability of the dataset. We approached several studies and chose the one that closely matched our experimental setting to ensure that our technique matched known procedures. Ionic wind generators with six stages in succession were studied by C. Kim et al., and they achieved a noteworthy conversion efficiency of 1.0%. They showed a steady flow rate of more than 2000 liters per minute, and the wind speed showed a relationship to the square roots of the current and voltage. The study's experimental values are listed in the fig. 5 [10].

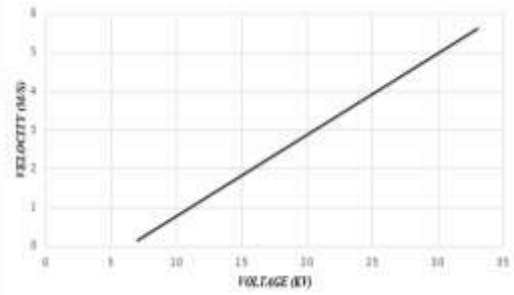


Fig. 5. Stacking characteristics of voltage-velocity for 3-stage systems.

The graph shows that the velocity reaches about 5.6 m/s at a voltage of 33 kV. On the other hand, in our experiment, with electrodes spaced 2 cm apart, the measured velocity was 1.6 m/s at the same voltage. Among the three cases, the electrode separation of 2 cm demonstrated the highest performance, indicating a relationship between voltage and air velocity. There were variances in the experimental settings, particularly the electrode designs, which were responsible for the reported discrepancies in air velocity. Unlike earlier setups that used wire-cylinder layouts, the project used a system with stripped stainless ring electrodes with saw tooth-shaped pins on the top side. Within the confines of this investigation, the 2 cm electrode spacing produced the best results, even though variables like temperature, humidity, air content, electrode material, and diameter may also affect output velocity.

To contextualize the findings of this study, comparisons with previous research are essential. In the study by Kim et al. (2010), ionic wind generators with saw tooth-ring electrode configurations achieved an air velocity of 5.6 m/s at 33 kV, significantly higher than the 1.6 m/s achieved in our experiment with wire-cylinder electrodes at the same voltage. This discrepancy can be attributed to differences in electrode geometry and experimental setups. Similarly, Li et al. (2016) observed a nonlinear relationship between ionic wind velocity and voltage, noting a saturation phase beyond certain thresholds, which aligns with the behavior observed in our study. Mazumder et al. (2019) reported a maximum volume flow rate of 35 L/J in a two-stage EHD system with uneven voltage application, highlighting the efficiency benefits of multi-stage setups. Unlike these prior works, our study focuses on optimizing electrode spacing and configuration within a wire-cylinder design,

demonstrating that a spacing of 2 cm achieves the highest air velocity. This finding emphasizes the importance of geometric and spacing optimization for compact EHD propulsion systems. Table 2 provides a comparative summary of key performance metrics from these studies, further highlighting the novelty and implications of this research.

Table 2: Comparison of Results with Previous Studies.

Study	Electrode Type	Voltage (kV)	Air Velocity (m/s)
Kim et al. (2010)	Saw tooth-ring	33	5.6
Li et al. (2016)	Needle-cylinder	Varied	Nonlinear behavior
Mazumder et al. (2019)	Two-stage gas pump	Varied	N/A
This Study	Wire-cylinder	33	1.6

5. Conclusions

This study highlights the potential of electrohydrodynamic (EHD) propulsion as an eco-friendly alternative to conventional fossil-fuel-based systems, using electric fields to generate ionic wind and reduce carbon emissions. The research demonstrated a linear relationship between voltage and air velocity while increasing electrode distance decreased velocity. A saturation point was identified, beyond which higher voltage no longer boosted air velocity. Despite challenges in adverse weather conditions, EHD propulsion offers promise for sustainable transportation. Future research will explore airfoil-shaped electrodes for enhanced thrust, develop Zero Voltage Switching (ZVS) circuits to optimize power-to-thrust ratios, investigate copper electrodes, and study the effects of dimensional changes on system performance.

In addition to its environmental benefits, EHD propulsion shows potential for real-world applications, such as UAVs for low-emission surveillance missions and electric aircraft to revolutionize sustainable aviation. With further advancements, this technology could contribute to cleaner urban transport and innovative satellite propulsion systems. Despite its potential, EHD propulsion has significant limitations in specific environmental conditions. Rain and airborne moisture can disrupt airflow patterns, hinder ionization, and reduce the efficiency of ionic wind generation, making the system less effective in wet or highly humid conditions. Additionally, temperature extremes can impact ionization efficiency and the mobility of charged particles, altering the dynamics of ionic wind. Both extreme heat and cold can impair the performance of the EHD propulsion system, highlighting the need for further research to mitigate these environmental challenges.

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