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Study of Ionic Propulsion and Development of AaLaboratory-Scale Ionic Thruster Model

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Abstract- Electric propulsion encompasses a family of propulsion technologies in which electrical energy is used to accelerate charged particles and generate momentum exchange. This paper presents a study of ionic propulsion with particular emphasis on the distinction between vacuum ion thrusters used for spacecraft and atmospheric electrohydrodynamic (EHD), or electroaerodynamic (EAD), propulsion. In addition, the paper describes the design, construction, and experimental observation of a low-cost laboratory-scale atmospheric ionic thruster model developed as the author's final-semester project in 2023. The experimental model employed a high-voltage electrode assembly consisting of copper-tube emitter elements and a fine-wire collector, together with a compact high-voltage multiplier supplied from a low-voltage rechargeable battery. The atmospheric device operates through corona discharge: ions generated near the high-field emitter are accelerated through the surrounding air and transfer momentum to neutral molecules through ion-neutral collisions. The resulting bulk gas motion is commonly referred to as ionic wind. Three electrode arrangements—pointed, lined, and gridded—were investigated qualitatively and comparatively. Directional ionic airflow was confirmed using a candle-flame visualization method and a digital anemometer. Recorded airflow velocities were approximately 0.4–2.1 m/s under the reported experimental conditions, with the gridded arrangement producing the strongest and most spatially uniform observed flow. Variation of the electrode gap demonstrated the expected trade-off between corona stability, discharge current, electric-field strength, and airflow generation. The paper also reviews the development of space ion propulsion, including NASA's NSTAR technology and subsequent electric-propulsion systems, and discusses recent progress in atmospheric EAD propulsion. The successful flight of a solid-state EAD aircraft demonstrated the feasibility of atmospheric electric propulsion, while later multistage ducted EAD research has substantially increased reported thrust density. The present laboratory model does not attempt to reproduce the performance of a flight-qualified propulsion system; rather, its principal value is educational and experimental, providing a comparatively accessible platform for studying corona discharge, ionic wind, electrode geometry, and electrohydrodynamic momentum transfer.

Keywords- ionic propulsion; ion thruster; electrohydrodynamic propulsion; electroaerodynamics; corona discharge; ionic wind; electric propulsion; high-voltage propulsion; electrode geometry; atmospheric propulsion

I. INTRODUCTION

Propulsion is fundamentally concerned with the generation of force through the transfer of momentum. Conventional aircraft and rockets generally obtain this momentum transfer through combustion, turbomachinery, propellers, or other mechanical systems. Electric propulsion provides an alternative approach in which electrical energy is used to accelerate charged particles or to generate a flow in an electrically active fluid.

The expression ionic propulsion is often used broadly, but two physically different applications should be distinguished. In space electric propulsion, a propellant is ionized and the resulting ions are accelerated electrostatically or electromagnetically. Because spacecraft operate in vacuum, the accelerated ion beam itself provides the principal momentum exchange with the spacecraft. Gridded ion thrusters are a mature example of this technology.

In contrast, an atmospheric electrohydrodynamic (EHD) or electroaerodynamic (EAD) thruster operates in the presence of neutral gas. A high electric field near an emitter electrode produces corona discharge and charged particles. These charged particles drift through the gas and collide with

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neutral molecules, transferring momentum and producing a directed airflow. The resulting airflow can generate a reaction force on the electrode assembly.

The distinction is important because the atmosphere itself acts as the medium through which momentum is transferred in an EHD thruster. Therefore, an atmospheric EHD device should not be described simply as a conventional space ion engine operating in air.

The potential advantages of atmospheric EHD propulsion include the absence of rotating mechanical components, potentially low acoustic noise, compact solid-state construction, and direct conversion of electrical energy into fluid momentum. In 2018, Xu et al. demonstrated sustained powered flight of a five-metre-span aircraft using electroaerodynamic propulsion, establishing a significant experimental milestone for atmospheric electric propulsion.

The objective of the present work is threefold: to review the physical principles of ionic and electric propulsion; to describe the development of a laboratory-scale atmospheric ionic thruster model constructed in 2023; and to experimentally examine the influence of electrode configuration and electrode spacing on the observed ionic wind.
The model is intended primarily as a proof-of-concept educational EHD thruster, not as a flight-qualified propulsion system.

Background and Historical Development
Electric propulsion is attractive because high exhaust velocity can reduce the propellant mass required for a given spacecraft velocity change. Practical development accelerated during the twentieth century, with Harold Kaufman's work at NASA's Lewis Research Center providing important foundations for practical gridded ion propulsion. The technology subsequently matured through ground testing and space demonstrations.

NASA's NSTAR system was developed for long-duration deep-space propulsion. It flew on Deep Space 1 and later provided propulsion heritage for Dawn. Modern electric propulsion includes gridded electrostatic ion thrusters, Hall-effect thrusters, radio-frequency and microwave ion thrusters, field-emission electric propulsion systems, pulsed plasma thrusters, and atmospheric EHD/EAD propulsion.

Space-Based Ion Propulsion
A conventional gridded ion thruster generally consists of a propellant feed system, ionization/discharge chamber, ion-extraction and acceleration grids, a neutralizer, and a power-processing system. Xenon has historically been widely used because it is inert, relatively heavy, and comparatively easy to store.

The basic thrust relation is
$T = \dot{m} v_e$
where T is thrust, $\dot{m}$ is propellant mass-flow rate, and v_e is effective exhaust velocity.
Specific impulse is defined by
$I_{sp} = T / (\dot{m} g_0)$
and therefore
$v_e = g_0 I_{sp}$.

The key characteristic of space ion propulsion is high exhaust velocity and low thrust, rather than high instantaneous acceleration.

II. ATMOSPHERIC IONIC PROPULSION

Atmospheric EHD propulsion operates according to a different momentum-transfer mechanism. When a sufficiently high electric potential is applied between asymmetric electrodes, the electric field becomes particularly strong near the emitter. When the local field reaches the appropriate corona-onset condition, gas molecules become ionized in the region surrounding the emitter.

For a positive-corona configuration, positive ions move away from the positively biased emitter toward the collector. During their motion, the ions undergo collisions with neutral molecules. This produces bulk gas motion, commonly called ionic wind.

The sequence is:

High electric field -> Corona discharge -> Ion generation -> Ion acceleration -> Ion-neutral collisions -> Bulk gas motion.

The reaction force associated with momentum transferred to the neutral gas produces EHD thrust on the electrode system.

III. GOVERNING PHYSICAL RELATIONSHIPS

The electrostatic force acting on a charged particle is $F_e = qE$

where q is particle charge and E is electric-field vector.

For a simplified uniform-field geometry,

E approximately equals V/d.

In a simplified mobility model,

$v_i = mu E$

where v_i is ion drift velocity and mu is ion mobility. For a simplified unipolar corona-flow model, an often-used relationship is

T approximately equals I d / mu.

This should be regarded as a simplified model rather than a universal thrust equation because real EHD thrusters involve non-uniform fields, space-charge effects, recombination, secondary ionization, airflow, electrode geometry, and boundary effects.

For a planar space-charge-limited vacuum diode, the Child–Langmuir relationship is

$J = (4 epsilon_0 / 9) sqrt(2q/m) V^(3/2) / d^2.$

This law is relevant to vacuum ion extraction systems but should not be applied directly as a quantitative atmospheric-corona model.

IV. LABORATORY-SCALE IONIC THRUSTER MODEL

The experimental model was developed during the author's final-semester project in 2023. The principal objective was to demonstrate experimentally that a high-voltage electrostatic field could generate directed airflow without conventional rotating mechanical components.

The model was deliberately designed using accessible components so that the underlying physical phenomena could be observed in a laboratory environment. It should therefore be regarded as a proof-of-concept educational EHD thruster rather than a scaled replica of a spacecraft ion engine.

Design Configuration

The model consisted principally of high-voltage emitter electrodes, a fine-wire collector electrode, a high-voltage multiplier/power-supply assembly, a low-voltage rechargeable source, insulated high-voltage wiring, mechanical spacers and support structure, and airflow measurement equipment.

Copper was selected for the electrode structure because of its electrical conductivity, availability, ease of fabrication, and suitability for experimental electrode assemblies. The reported nominal electrode spacing was approximately 25–40 mm for the principal configuration.

Electrode Configurations

Three configurations were investigated.

Pointed Configuration

Sharpened emitter elements were used. A sharp emitter produces locally enhanced electric field and can initiate corona at lower voltage under comparable conditions. The resulting ionic flow tends to be spatially concentrated.

Lined Configuration

A single-row emitter/collector geometry produced a more extended airflow region and provided an intermediate configuration between a point source and a large-area grid.

Gridded Configuration

Multiple emitter elements were distributed across an area opposite a fine-wire collector. This arrangement provided a larger active region and produced the strongest and most spatially uniform airflow observed during the experiments.

V. EXPERIMENTAL METHODOLOGY

The model was operated using a high-voltage electrical supply connected across the emitter and collector electrodes.

Qualitative visualization was performed with a candle flame positioned near the airflow region. Deflection indicated the direction of induced airflow; it was not used as a quantitative thrust measurement.

A digital anemometer was positioned downstream of the collector region. Reported measurements indicated airflow velocities approximately within 0.4–2.1 m/s depending on configuration and operating condition. The gridded arrangement produced the highest observed airflow velocity.

VI. EXPERIMENTAL OBSERVATIONS

When the applied voltage reached the corona operating region, a faint luminous discharge could be observed near high-field electrode regions. The presence of corona provided qualitative confirmation that the electric field was sufficiently strong to initiate ion production.

A directional airflow was observed from the emitter region toward the collector and beyond the collector. The measured airflow velocity increased with operating condition within the tested range, although the relationship was not necessarily linear. The observed flow demonstrates the central atmospheric EHD mechanism:

Electrical energy -> ion motion -> momentum transfer -> neutral-gas motion.

Effect of Electrode Separation

Electrode gap is an important design parameter. For a given applied voltage, increasing electrode separation generally decreases the average electric-field magnitude according to E approximately V/d. Actual corona current depends on electrode curvature, local field enhancement, space charge, atmospheric conditions, and geometry.

In the present experiment, increasing separation from approximately 25 mm toward 40 mm resulted in a reduction of observed airflow under the tested conditions. At smaller separation, stronger electric-field interaction produced increased airflow but also increased the possibility of unstable discharge or electrical breakdown.

The reported practical operating region of approximately 25–40 mm should therefore be regarded as a model-specific experimental observation, not a universal optimum.

VII. RESULTS

The principal observations are summarized below.
Model type: Atmospheric EHD ionic thruster
Development: Final-semester project, 2023
Primary emitter material: Copper
Collector: Fine-wire electrode
Principal electrode gap: Approximately 25–40 mm
Configurations: Pointed, lined, gridded
Airflow measurement: Digital anemometer
Qualitative visualization: Candle-flame deflection
Reported airflow range: Approximately 0.4–2.1 m/s
Highest observed airflow: Gridded configuration
Main physical phenomenon: Corona-induced ionic wind

Mechanical rotating components: None

The experiment demonstrates that electrode geometry significantly influences the spatial distribution and strength of ionic airflow. Because direct force measurements were not reported, a numerical thrust value should not be assigned solely from anemometer readings.

Thrust Estimation and Experimental Limitations
A direct thrust measurement requires a force-balance or load-cell arrangement.

For airflow measurement, a simplified momentum-flux estimate can be written as
T approximately equals m_dot v
with
m_dot = rho A v.

Therefore,
T approximately equals rho A v^2
under a simplified uniform-flow assumption.

However, this estimate is highly sensitive to the definition of effective flow area and velocity profile. A handheld anemometer samples a local velocity rather than the complete velocity field. Consequently, the present study treats anemometer measurements primarily as evidence of ionic airflow, not as definitive thrust measurements.

Future experiments should incorporate calibrated load-cell thrust measurement, high-voltage and discharge-current measurement, input-power measurement, repeated measurements, uncertainty analysis, controlled humidity and temperature, controlled electrode spacing, and velocity mapping.

Comparison with Established EAD Research
The present model operates at a much smaller scale than dedicated research systems.
The 2018 MIT demonstration was significant because a five-metre-span aircraft achieved sustained powered flight using electroaerodynamic propulsion. The system used a high-voltage converter and demonstrated that atmospheric EAD propulsion could produce sufficient force for a carefully designed lightweight aircraft.

Subsequent research has focused on overcoming the principal limitation of atmospheric EAD systems: relatively low thrust density. In 2024, Gomez-Vega and Barrett reported experiments with multistaged ducted EAD thrusters containing up to ten stages. Their ten-stage configuration achieved a reported maximum thrust density of approximately 26 N/m^2.

These developments indicate that EHD propulsion is evolving from a demonstration technology toward increasingly engineered propulsion architectures. The present 2023 laboratory model is an earlier and simpler educational platform whose primary purpose is to demonstrate the physical mechanism.

VIII. SPACE ION PROPULSION VERSUS ATMOSPHERIC EHD PROPULSION

Space Ion Thruster: vacuum environment; supplied ionizable propellant; ion beam momentum transfer; no neutral gas required; primary uses include spacecraft propulsion.

Atmospheric EHD Thruster: atmospheric environment; ambient air; ion-neutral momentum transfer; neutral gas required; primary uses include airflow and atmospheric propulsion.

The distinction is central to the scientific interpretation of the present work.

Applications
Spacecraft Propulsion
Vacuum ion propulsion is an established technology for long-duration spacecraft missions.

Satellite Station-Keeping
Low-thrust electric propulsion is attractive for long-duration station-keeping and orbit maintenance.

Atmospheric Aircraft
The 2018 MIT flight experiment established that EAD propulsion can support sustained aircraft flight under carefully optimized conditions.

Air Movement and Cooling
Corona-based EHD airflow can be used for fluid movement and thermal-management applications.

High-Altitude Applications
Performance depends strongly on air density, pressure, humidity, and electrical properties of the gas; high-altitude applications require dedicated analysis.

Advantages

- No conventional rotating propulsion components.
- Potentially low mechanical noise.
- Compact solid-state architecture.
- High exhaust velocity in space electric propulsion.
- Long operating duration in properly designed and qualified space systems.

Limitations

- Low absolute thrust compared with chemical propulsion.
- Atmospheric drag is a major challenge for atmospheric vehicles.
- High-voltage operation requires strict safety controls.
- Corona discharge can produce reactive species including ozone and nitrogen oxides.
- Overall performance depends on electrical conversion efficiency, corona losses, leakage, dielectric losses, and power-supply efficiency.

Safety Considerations

The laboratory model involves potentially lethal high voltage. Reproduction should be limited to appropriately trained personnel using suitable high-voltage laboratory procedures.

Essential precautions include insulated and secure supports, restricted access to energized electrodes, appropriate discharge/bleeder arrangements where applicable, verification of de-energization before adjustment, current limiting, suitable electrical protection, adequate clearance and insulation, avoidance of flammable materials, and ventilation where corona discharge is produced.

Future Scope

Future work should focus on direct thrust measurement with a precision load cell or force balance; complete current-voltage characterization; systematic electrode optimization; multistage EHD propulsion; and computational modelling combining electric field, space charge, ion mobility, corona current, neutral-fluid flow, and pressure distribution.

The reported 2024 multistage ducted research demonstrates substantial potential for increasing EAD thrust density through carefully integrated electrical and aerodynamic design.

Discussion

The laboratory experiment demonstrates that a mechanical rotor is not fundamentally necessary for producing directed airflow. The electric field performs work on charged particles, and those particles transfer momentum to neutral molecules through collisions. Electrical energy is thereby converted into macroscopic fluid motion.

The significance of the experiment is not simply the measured airflow velocity. Its greater value lies in demonstrating the physical chain connecting microscopic charge transport with macroscopic propulsion.

The gridded electrode arrangement increased the active region and produced a more distributed ionic wind than the pointed configuration. Nevertheless, producing a visible ionic wind is much easier than producing large useful thrust at high efficiency. This distinction separates laboratory demonstrations from practical propulsion systems.

Modern research is therefore moving toward optimized geometries, multistage systems, ducts, aerodynamic collectors, improved power electronics, and integrated propulsion architectures.

IX. CONCLUSION

This paper presented a study of ionic propulsion with particular emphasis on the distinction between vacuum ion propulsion and atmospheric electrohydrodynamic propulsion.

A low-cost laboratory-scale atmospheric ionic thruster model developed during the author's final-semester project in 2023 was examined. The model used high-voltage asymmetric electrodes to generate corona discharge and directional ionic airflow without conventional rotating mechanical components.

Three electrode arrangements—pointed, lined, and gridded—were investigated. The gridded configuration produced the strongest and most spatially uniform ionic wind observed during the experiments. Digital-anemometer measurements indicated airflow velocities in the approximate range of 0.4–2.1 m/s under the reported test conditions.
The experiment demonstrates the fundamental atmospheric EHD mechanism:

Electrical energy -> Corona ionization -> Ion acceleration -> Ion-neutral momentum transfer -> Ionic wind.

The study emphasizes that atmospheric EHD propulsion should not be confused with conventional vacuum ion thrusters. Space ion engines accelerate a propellant ion beam directly in vacuum, whereas atmospheric EHD devices use charged particles to transfer momentum to surrounding neutral gas.

The present model represents an instructive bridge between fundamental electrostatics and modern electric-propulsion research. Its principal contribution is the practical demonstration that corona-generated ionic motion can be observed, measured, and systematically studied using a relatively simple laboratory apparatus.

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