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REVIEW ARTICLE

# Ionic Wind Propulsion for Aircraft: A Review of Fundamental Limitations and Scaling Barriers

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ABSTRACT: Ionic wind propulsion (IWP) generates thrust through electric field acceleration of ionized air. This produces a silent, fuel-efficient alternative to traditional combustion-powered aircraft. The technology shows promise because of its environmental advantages and quiet operation. However, its low thrust-to-weight ratio under atmospheric conditions makes it unsuitable for applications larger than drones. The paper evaluates IWP aviation potential through experimental data from unmanned airships and the well-known MIT ion-propelled drone and other small-scale prototypes. In order to understand performance improvement and flight duration capabilities, this research evaluates thrust generation, power consumption, and physical behavior. According to the analysis, IWP technology has several basic challenges when trying to scale up for larger aircraft: it requires high voltage operation, has efficiency limitations, and produces very little absolute thrust. In an effort to avoid having unreasonable goals regarding sustainable aviation solutions, the review sets performance boundaries.

KEYWORDS: Engineering, Aerospace Engineering, Electrohydrodynamic Propulsion, Ionic Wind, Corona Discharge, Aircraft Sustainability.

## Introduction

The topic of emission-free flight has interested engineers since the early demonstrations of ionic wind in the 1920s.[1] Ionic wind propulsion (IWP), also known as electrohydrodynamic (EHD) propulsion, generates thrust by accelerating ionized air molecules through high-voltage electric fields. This offers a revolutionary alternative to traditional combustion-based aviation. Unlike conventional aircraft engines that rely on moving parts and fossil fuel combustion, IWP systems create thrust through the fundamental interaction between electric fields and charged particles.

When a high voltage is applied between two asymmetric electrodes, which are typically a sharp emitter and a blunt collector, it creates an intense electric field that ionizes air molecules near the emitter. These ions are then accelerated toward the collector, colliding with neutral air molecules along the way and transferring momentum to create a net airflow.[2] This phenomenon, known as corona discharge, can generate thrust without any moving mechanical parts, combustion emissions, or significant noise. It addresses major challenges facing modern aviation.

Recent interest in IWP technology stems from increasing pressure to develop zero-emission aircraft and reduce aviation's environmental impact, including emissions and noise. While early theoretical work established the fundamental physics controlling ionic thrust, researchers have already recognized a critical trade-off. The conditions that maximize efficiency often result in minimal absolute thrust. This fundamental challenge has persisted through decades of research, from Christenson and Moller's 1967 foundational experiments to modern optimization attempts.[3]

Given the surge in IWP research and an increasing number of claims about its potential applications, a question emerges: What is the true feasibility of ionic wind propulsion for practical aviation applications? Demonstrations like MIT's 2018 airplane with no moving parts (shown in Figure 1) and various ionic wind drones have been widely celebrated. However, the technological gap between laboratory achievements and commercial viability remains large. Recent studies have shown promising advances in electrode design and system optimization,[4] yet questions about scalability and practical implementation are still unanswered.

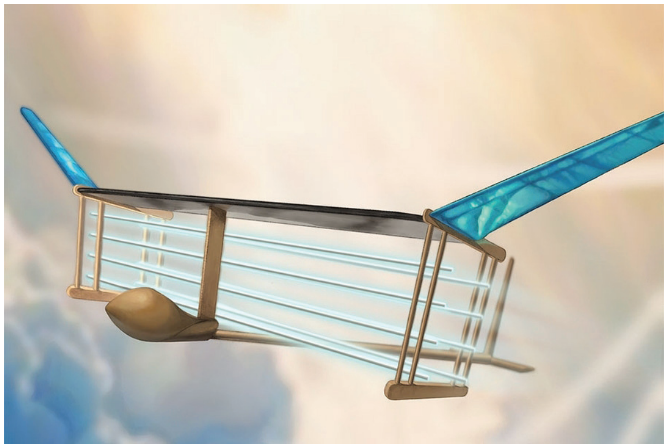

**Figure 1:** Rendering of MIT's ionic wind aircraft demonstrating electrohydrodynamic propulsion. Source: MIT News, Christine Y. He.

### *1.1 Review of Experimental Performance Studies :*

MIT researchers Gilmore and Barrett established the first performance standards for electroaerodynamic thrusters through detailed analysis of wire-to-cylinder electrode configurations.[5] Under controlled laboratory conditions, they achieved thrust to power ratios of 5.8–10.2 N/kW and maximum thrust densities of 3.3 N/m$^2$ at 30 mm gap distances and

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2.6 N/m$^2$ at 50 mm gaps when operating at 39–40 kV. Their findings showed that the "achievable thrust per unit area of 3.3 N/m$^2$ and thrust per unit volume of up to 110 N/m$^3$" were far below what is required for conventional large aircraft.

NASA conducted an electroaerodynamic feasibility study to validate MIT's results, testing different thruster configurations including wire, knife-edge, and pin array electrodes.[2] Peak thrust output reached 0.5 N across 0.33 m$^2$ of frontal area using pin arrays, yielding a thrust density of 1.5 N/m$^2$, with thrust to power ratios ranging from 2.6 to 20 N/kW depending on operating conditions. A scaling analysis led the researchers to conclude that even tripled thrust from cascaded configurations would reach only 4.5 N/m$^2$, confirming the impracticality of corona discharge propulsion for large-scale use. To illustrate the real-world implication: a Boeing 737 wing has approximately 125 m$^2$ of surface area, yet even covering the entire wing with NASA's best electrode configuration would generate only 562 N of thrust, less than 0.5% of the 120 kN needed for takeoff. This means ionic wind cannot serve as primary propulsion for commercial aircraft, regardless of electrode optimization.

European research institutions have replicated these findings through their studies of different electrode geometries and operational strategies. At the Technical University of Košice, electrohydrodynamic propeller experiments produced air velocities of 2.31 m/s at 8.71 kV and showed 1.71% system efficiency, but also revealed major performance limitations for practical electrode sizes.[6] Experiments at Politecnico Milano confirmed theoretical thrust models while highlighting that actual system performance consistently falls below predictions, primarily due to electrode drag, current loss, and uneven electric fields.[7] Research at the University of Washington by Vaddi demonstrated that advanced DC increased dielectric barrier discharge actuators produced twice the thrust of traditional DBD systems, and optimized electrode designs achieved four times the thrust of classic DBDs, yet these results remained within the thrust density boundaries established by MIT and NASA.[8]

Other verification such as those from Worcester Polytechnic Institute, further confirmed these performance boundaries. Wire-to-airfoil tests produced thrust densities between 150 and 200 mN/m at 20 kV with 30 mm electrode gaps, consistent with MIT findings, and demonstrated how electrode design and spacing influence performance.[9] The study also highlighted that power supply units are among the heaviest components of ionic wind propulsion systems, and drag forces during high-speed operation reduce efficiency, confirming inherent speed limitations of the technology.

Consistent results across international research groups indicate that these limitations arise from fundamental physical boundaries rather than specific technological choices. Thrust density measurements from MIT's wire-to-cylinder setups, NASA's pin arrays, European multi-stage systems, improved DBD actuators, and rotational EHD propellers all fall within a narrow range of 1.5 to 18 N/m$^2$. This consistency across diverse research approaches, spanning different countries, institutions, electrode geometries, and voltage configurations, demonstrates that ionic wind performance has reached its physical ceiling. For aircraft designers, this means no amount of engineering refinement will bridge the 500-fold gap between current maximum thrust density (18 N/m$^2$) and the minimum viable thrust density for manned aircraft (approximately 10,000 N/m$^2$ for jet engines). The five-stage ducted configuration developed by Nelson and Drew achieved the highest performance at 18 N/m$^2$ while operating at 1.86 mN/W efficiency.[10] Experiments using converging nozzle configurations to boost exit velocities to 9.2 m/s required 18 kV power supplies, demonstrating that corona discharge physics inherently limits the relationship between power and thrust.

### *1.2 Research Objective and Scope:*

This paper argues that the realistic potential of IWP is severely constrained by fundamental physical limitations that render it impractical for mainstream aviation applications, despite growing interest in sustainable aviation research. Optimization studies revealed maximum velocities of only 2.2 m/s, even with improved nozzle configurations, while power requirements remain excessively high for anything beyond small vehicles.[11] More recent experiments using converging nozzles achieved exit velocities up to 9.2 m/s, but required 18 kV power supplies that would be impractical for larger aircraft.[12] These findings suggest that despite its desired advantages, IWP may face large barriers to scaling beyond tested applications.

Through analysis of experimental data from prototypes, theoretical constraints imposed by corona discharge physics, and engineering challenges, this paper demonstrates that IWP's role in future aviation will likely remain confined to specialized small-scale applications rather than revolutionizing commercial flight as some articles suggested. This paper evaluates whether ionic wind propulsion can realistically power aircraft by examining the fundamental physics behind EHD thrust, scaling requirements for commercial implementation, successful niche applications, and viable zero-emission alternatives.

Section 2 explores the fundamental physics behind EHD thrust and why certain performance trade-offs appear unavoidable. Section 3 uses experimental data to calculate what it would take to power a commercial aircraft, revealing the scale of the challenge. Section 4 looks at successful small-scale applications for ionic wind propulsion. Section 5 discusses alternatives for zero-emission aviation options.

## ■ Fundamental Physics and Performance Trade-offs:

Ionic wind propulsion faces inherent limits due to the physics that govern its operation. These fundamental constraints define theoretical ceilings for both thrust generation and system efficiency, which cannot be overcome simply through technological improvements. Understanding these physical mechanisms is necessary to determine whether performance shortfalls are due to engineering challenges or unavoidable limitations imposed by fluid dynamics and electromagnetic field theory.

### *2.1. Electrostatic Field Theory and Ion Transport Mechanisms:*

The electric field distribution around asymmetric electrodes is determined by Maxwell's equations and Poisson's equation, as expressed in Equation 1:

$$\nabla^2 V = -\rho/\varepsilon_0 \qquad (1)$$

where V is the electric potential, ρ is the space charge density, and $\varepsilon_0$ is the permittivity of free space. The field gradient is strongest at sharp emitter tips, reaching dielectric breakdown levels in air at roughly 30 kV/cm under standard conditions.[2] Asymmetric electrode designs localize ionization to the emitter tip, separating regions of ion generation and acceleration, which is fundamental for creating thrust via momentum transfer. This voltage ceiling imposes a hard limit on maximum achievable thrust density, meaning that scaling to aircraft-sized systems would require impractically large electrode arrays rather than simply increasing voltage.

Corona discharge produces positive ions near the emitter through impact ionization cascades.[1] Ion movement between electrodes is governed by diffusion, which moves ions along concentration gradients, convection, which transports ions with bulk airflow, and conduction, which drives ions under electric fields.[6] The combined ion transport is described by Equation 2:

$$\partial t \partial \rho i + \nabla \cdot (\rho i v) = \nabla \cdot (\mu \rho i E) + \nabla \cdot (D \nabla \rho i) \qquad (2)$$

Here, $\rho i$ is the positive ion density, v is the fluid velocity, μ is the ion mobility (≈ $1.8\times10^{-4}$ m$^2$/V·s in air), E is the electric field strength, and D is the diffusion coefficient (≈ $5.3\times10^{-5}$ m$^2$/s).[14] Thrust efficiency depends on how effectively ions transfer momentum to neutral air molecules. As ions drift toward the collector electrode, collisions with neutral molecules create bulk airflow.[2] Because ion mobility in air is fixed, momentum transfer efficiency and thrust per unit current are fundamentally limited.[15] Unlike conventional propulsion systems, where higher fuel flow directly produces proportionally greater thrust, ionic wind systems cannot overcome this mobility constraint—meaning that doubling the current does not double the effective thrust, creating an insurmountable barrier for achieving the thrust levels required by passenger aircraft."

Ionic wind airflow can also be described using the Navier–Stokes equations with electrohydrodynamic body forces, as shown in Equation 3:

$$\rho(\partial v/\partial t + v\cdot\nabla v) = -\nabla p + \mu\nabla^2 v + \rho_e E \qquad (3)$$

The term $\rho_e E$ represents the force per unit volume from the electric field acting on the space charge density $\rho_e$, while ∇p represents the pressure gradient in the fluid. Together, these terms generate airflow and thrust without moving mechanical parts.[14]

Theoretical analyses show that thrust follows predictable scaling patterns. For single-stage thrusters, thrust depends on both ion current and electrode gap, expressed as $F = Id/\mu$ [9]. While increasing current or widening the gap can raise thrust, doing so also drives power consumption higher and requires elevated operating voltages. Corona discharge current follows Equation 4:

$$I = CV(V - V_0)$$

Here, C depends on electrode geometry, and $V_0$ is the corona onset voltage. Thrust scales with the square of applied voltage but decreases as gap size increases, with laboratory-scale devices limited by electrical breakdown at 30–40 kV.[5] For a real-world aircraft, this creates a critical design paradox: achieving meaningful thrust requires either dangerously high voltages that risk electrical arcing and pose safety hazards, or electrode arrays so large they would dwarf the aircraft itself, adding prohibitive structural weight and drag.

The interconnected effects of electromagnetic fields, ion motion, and air fluid dynamics establish unavoidable tradeoffs. These limitations cannot be eliminated through design enhancements.

### *2.2. Corona Discharge Mechanisms and Thrust Generation:*

Ionic wind propulsion relies on the gradual formation of corona discharge in the surrounding air. Ionization occurs through impact ionization and photoionization when electric fields reach 3–5 MV/m.[17] Thrust generation involves three steps: first, atmospheric air is converted into ions; next, the electric field accelerates these ions; finally, collisions between ions and neutral molecules transfer momentum, creating bulk airflow, as illustrated in Figure 2.

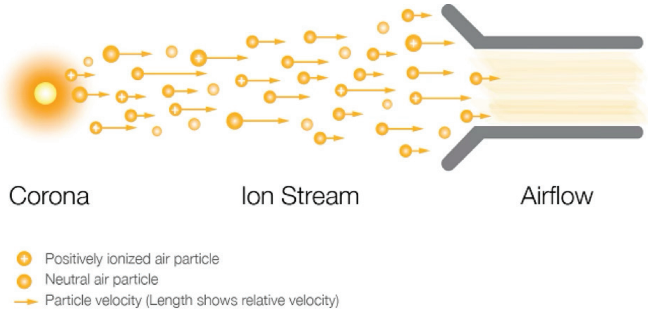

**Figure 2:** Positive ion corona discharge. Adapted from COMSOL Multiphysics Blog (2025).

The corona discharge process imposes key efficiency limits. Ionization requires substantial electrical power that does not directly produce thrust. Each ion pair in air needs approximately 35 eV, with additional energy lost as heat and light.[11] Laboratory tests using wire-to-cylinder electrodes achieved maximum thrust densities of 3.3 N/m$^2$ for parallel arrangements and 110 N/m$^3$ for series setups at 39–40 kV.[5] Air density and composition limit ion generation, capping maximum current and thus maximum achievable thrust. To contextualize this limitation: a conventional jet engine produces thrust densities exceeding 10,000 N/m$^2$ of intake area, meaning ionic wind systems would require electrode arrays over 3,000 times larger than a jet engine's frontal area to match equivalent thrust—an impossibility for any airworthy structure.

Momentum transfer is also constrained by fundamental physics. Corona discharge operates under Maxwell's equations and requires field strengths determined by the ionization potentials of air—15.8 eV for oxygen and 15.6 eV for nitrogen.[18] Positive ion mobility in standard air, limited to

1.5–2.0 cm$^2$/V·s, sets an upper bound on ion acceleration and momentum transfer efficiency.[15]

### 2.3. Power Performance Trade-offs:

Experiments show that ionic wind systems face a trade-off between thrust and efficiency. Higher thrust requires increased current, which demands higher voltage, causing power consumption to rise faster than thrust output. Peak thrust-to-power ratios of 110 N/kW were observed at only 0.35 N of thrust, while standard aircraft engines operate around 2 N/kW.[16] While ionic wind appears 55 times more efficient at this minuscule thrust level, the absolute thrust value is 300,000 times smaller than what a commercial aircraft requires. More critically, efficiency collapses dramatically when attempting to scale up thrust: achieving aircraft-relevant thrust levels would require power-to-weight ratios that far exceed any feasible battery or generator technology, necessitating power supplies weighing more than the entire aircraft structure.

Wire-to-cylinder setups achieved thrust-to-power ratios above 20 N/kW at low voltages in zero airflow, producing minimal thrust.13 At 50 m/s ambient airflow, efficiency dropped to roughly 4 N/kW, still exceeding conventional engines' 2.5 N/kW but remaining insufficient for practical aviation. Environmental factors such as pressure and temperature further limit performance. Plasma actuator effectiveness decreases sharply between 135 and 200 kPa, while higher temperatures can modestly increase the induced force.[19] Combined, these factors make ionic wind performance highly sensitive to flight conditions.

### 2.4. Electrode Interactions and Field Distribution Constraints:

The electric field distribution around electrodes imposes additional limits. Increasing system size introduces irregular fields and low-efficiency zones that cannot be corrected through design. Gilmore and Barrett demonstrated that electrode interactions reduce thrust density to roughly half of the theoretical one-dimensional maxima for 30 mm and 50 mm systems.[5]

Corona discharge requires sharp electrodes to concentrate fields, which conflicts with achieving uniform thrust across large areas. Field intensity depends on proximity to the electrode surface, with breakdown occurring at 3–5 MV/m and decreasing rapidly with distance.[20] These geometric constraints further restrict system scaling and performance. For practical aircraft applications, this means that simply building larger electrode arrays does not proportionally increase thrust. Instead, efficiency degrades as size increases. A passenger aircraft wing-sized electrode array would suffer such severe field non-uniformities that large portions would produce negligible thrust while still consuming power and adding weight, making the weight-to-thrust ratio completely unviable for flight.

## ■ Experimental Evidence

Because research into the feasibility of ionic wind propulsion is still relatively recent, many international institutions have carried out experiments to better understand its performance limits as well. The amount of experimental evidence from these studies demonstrates consistent limitations in ionic wind propulsion, providing much support for fundamental physics constraints. This section combines performance data from research conducted at MIT, NASA, Politecnico Milano, the University of Washington, and other institutions to establish a basis for thrust generation, power efficiency, and scalability.

### 3. Scaling Challenges:

Scaling laboratory demonstrations of ionic wind propulsion to practical aviation faces significant challenges. This part will look at the Airbus A320 and its operational requirements to highlight how they far exceed the maximum performance levels of ionic wind systems, demonstrating that their use in commercial aviation is not feasible.

### 3.1. A320 Scaling Comparison:

Using the Airbus A320-200 as an example commercial aircraft, each CFM56-5A3 engine requires approximately 118 kN, approximately 26,500 lbf, of thrust during takeoff operations.[21] This represents a scaling factor of over 37,000 times compared to the maximum 3.2 N demonstrated by MIT's aircraft and over 236,000 times compared to NASA's maximum practical thrust of 0.5 N.

Power consumption is at an unrealistic level. Using MIT's optimistic 110 N/kW ratio achieved only at minimal thrust levels would require 1.07 GW per engine. For practical thrust densities, realistic performance data indicate 5.8 to 6.3 N/kW, requiring 18.7 to 20.3 GW per engine.[16] A 20.3 GW power supply would weigh roughly 16,900 tons per engine, as current aerospace power electronics achieve 1.2 kW/kg.[22] To put this into perspective, it is clear that it is impossible. The requirements for electrode areas also show challenges. According to MIT's optimized configurations, each engine would need electrode areas of about 35,758 m$^2$, which is the maximum demonstrated thrust density of 3.3 N/m$^2$. This comparison makes it evident how far the electroaerodynamic research community still needs to go to create a practical aircraft powered by ionic wind.

### 3.2. Structural and Control Challenges:

Experiments show significant operational and structural problems that worsen the limitations of ionic wind propulsion, in addition to thrust constraints. According to Beihang University's research on ion propulsion UAV systems, the large, lightweight electrode arrays required for significant thrust generation are prone to significant deformation under flight loads.[23] According to their analysis, when electrode structures undergo elastic deformation, the thrust action point shifts upward by 28.7 mm, and the thrust direction deviates by 2.7° from the horizontal plane while the thrust magnitude decreases by 2.6%. With a 0.014 change in the pitching moment coefficient, these deformations have a major effect on the stability and control of the aircraft, "causing a great impact on the longitudinal trimming of the whole aircraft."

A basic design problem comes from this structural instability: electrode arrays need to be big and light in order to produce enough thrust, but these same qualities render them structurally unsuitable for use in flight. The deformation effects show that additional obstacles would prevent ionic wind systems from being used practically in dynamic flight environments, even if thrust scaling issues were resolved. For real-world aircraft operations, this creates an unsolvable engineering dilemma: making electrodes rigid enough to prevent thrust vector deviation would increase weight to the point where the thrust-to-weight ratio drops below 1.0, meaning the aircraft could not generate enough lift to overcome its own mass. This fundamental constraint exists independently of the thrust scaling problem, creating a second overwhelming barrier to practical implementation.

## ■ Successful Small-Scale Applications

Although there are inevitable barriers to the broad use of ionic wind propulsion in general aviation, the technology has proven remarkably effective in niche small-scale applications where its unique properties offer a distinct advantage. Ionic wind systems offer potential in speciality missions and controlled settings where conventional propulsion is not desired due to their high controllability, lack of moving parts, and quietness.

### *4.1. Indoor Airships and Controlled Environment Applications:*

Ionic wind propulsion works best indoors, where electrode contamination can be reduced, and atmospheric density is constant. One of the most effective uses of ionic wind technology is indoor unmanned airships, which use helium's buoyant lift to augment their limited thrust capabilities. Using dual propulsion systems for total motion control, the design shows an ion-propelled lightweight aircraft that can move in three directions without making any noise, as demonstrated in Figure 3.[24] These systems typically require continuous DC supplies exceeding 20,000 volts to achieve practical flight control and maneuvering capabilities.[25] Improved electrode configurations that exhibit promise for small-scale applications have been investigated in recent optimization studies. Through asymmetrical metal structures, Saiki's study of polarization-effect devices produced force-to-power ratios of up to 15 N/kW, which is a 5.7-fold improvement over simple lifter configurations.[26]

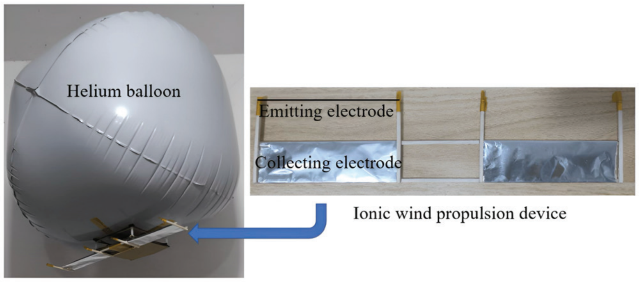

**Figure 3:** Helium balloon test demonstrating ion-propulsion drone setup. Source: Patil Rushikesh, BOHR International Journal of Engineering, 2022.

Many of the problems that afflict outdoor ionic wind applications are resolved by the controlled atmospheric conditions found in indoor settings. Dust and precipitation contamination are removed, humidity can be managed, and atmospheric pressure stays constant. Under these circumstances, ionic wind systems can reliably function at their theoretical peak efficiency. Because the systems don't make any noise that could alert people to their presence, they are particularly useful for indoor surveillance applications.[25]

### *4.2. Centimeter-Scale Microrobots:*

The ionocraft, or centimeter-scale microrobots, offer an environment where the drawbacks of ionic wind propulsion can be leveraged to their advantage. When paired with lightweight construction methods, the modest thrust levels that can be achieved through ionic wind at the centimeter scale become adequate for feasible flight. Taking off at 2000V without load and increasing to 2100V with sensor payload, the demonstrated ionocraft, which measures 1.8cm×1.8cm and weighs 13.6mg, can produce about 1mN of thrust, resulting in a thrust-to-weight ratio of 4.5.[27]

Because of MEMS techniques on silicon-on-insulator substrates, electrodes can now be made with high precision and reproducibility at the microscale. These enhancements resulted in a 20% decrease in takeoff voltage and a 30% decrease in corona onset voltage. The onset voltage was lowered by about 400 V by simply cutting the electrode gap in half, from 500 μm to 250 μm.[27] By creating high-aspect-ratio electrode structures with feature sizes as small as micrometers, deep reactive ion etching (DRIE) makes it possible to achieve the ideal electric field distributions for effective ion generation. Four adjustable thrusters are created by assembling 13 components using mechanical slots and UV-cured epoxy. While uncoated silicon electrodes nearly immediately lost performance, emitter electrodes with TiN coatings remained stable for more than 1000 seconds of continuous use.[27]

The system can carry a 40 mg Flex PCB payload that includes an InvenSense MPU-9250 9-axis IMU and supporting passive components, sized 5 mm by 5.5 mm, mounted in the center of the airframe without affecting thruster performance. Experiments with multiple emitters show that each additional wire increases thrust by about 100 μN while adding only 1.5 mg of mass, resulting in significant gains in thrust-to-weight ratio. The reported efficiency ranges from 1 to 2 mN per watt across the operating voltage range, reflecting current advancements in centimeter-scale ionic wind propulsion.[27]

Because ionic wind propulsion is fully solid state, it avoids mechanical wear and requires almost no maintenance, which is a major advantage for long-term use in microrobotics. Unlike conventional propulsion, which depends on motors, bearings, and moving parts, ionic wind systems only need some electrode cleaning. The ability to carry modern sensors such as 9-axis IMUs while maintaining flight demonstrates the practical potential of this technology at the microscale.[27]

## ■ Successful Small-Scale Applications

The goal for sustainable aviation has led to the development of zero-emission technologies that can grow to meet the demands of mainstream flight, even though ionic wind propulsion faces fundamental limits that keep it from being practical for large aircraft. To reach aviation's environmental goals, it makes sense to focus research and development on solutions that are not blocked by these basic physical constraints, as this paper's analysis of ionic wind shows.

Some alternative technologies have already emerged as candidates. Hydrogen-powered aircraft, for example, have flown successfully and offer some paths to commercial scaling. Of course, sustainable aviation fuels can reduce emissions in the near term while still working with existing planes. Despite both approaches having engineering challenges, unlike ionic wind propulsion, these are problems that can be solved through design and technology rather than being limited by the laws of physics.

### *5.1. Hydrogen Propulsion:*

The most promising solution for zero-emission aviation exists through hydrogen propulsion systems. The specific energy content of hydrogen fuel reaches 120 MJ/kg, which represents three times the energy density of Jet A at 43 MJ/kg.[28] Two distinct technologies have emerged as leaders in this field. PEMFCs operate between 10–100 °C to achieve 50–60% system efficiency while storing compressed hydrogen for 1000 Wh/kg and delivering hundreds of kilowatts of power suitable for regional aircraft operations. The high operating temperature range of 600–1000 °C in Solid Oxide Fuel Cells enables cell efficiencies up to 85%, and hybrid SOFC-gas turbine systems reach 75% overall efficiency at megawatt power levels, which makes them suitable for large commercial aircraft.[28] Hydrogen propulsion systems operate without physical size restrictions, which distinguishes them from ionic wind systems.

The HY4 aircraft (Figure 4) operates as the main demonstration system because it uses an 80 kW electric motor, which receives power from PEMFC systems. The aircraft uses 10 kg of compressed gaseous hydrogen stored at 437 bar to achieve a 1000 km flight range while transporting four passengers at a gross weight of 1.5 tonnes and a cruising speed of 145 km/h.[28] Boeing tested 1.5 MW fuel cell auxiliary power units on the 787-8 to power onboard electrical systems, while ZeroAvia performed successful flight tests on Piper PA-46 aircraft after retrofitting them[28] NASA conducted trade space analysis, which indicates that fuel cell hybrid electric (FCHE) systems match regional aircraft requirements for the 50–100 passenger segment. Airbus announced through its ZEROe program that it will introduce hydrogen-powered commercial aircraft by 2035 with three different concepts that include turbofans and turboprops and fuel cells for 100–200 passenger aircraft with 1,000–2,000 nautical mile ranges. The development of liquid hydrogen storage systems continues to achieve 60–70% gravimetric efficiency and continues to prove its suitability as an aviation fuel.

**Figure 4:** The HY4 aircraft in flight using liquid hydrogen. Source: H2FLY.

The development of hydrogen aviation depends on technological and infrastructure advancements rather than physical limitations because certification standards are already defined. The environmental advantages of hydrogen aviation include a 75% reduction in $CO_2$ emissions, and 90% decrease in nitrogen oxide emissions, and a 16-29% reduction in contrail-related climate effects when compared to traditional aircraft.[28] The development of PEMFC-powered regional aircraft will start in 2035, while SOFC-powered large commercial aircraft will enter service after 2045, when high-temperature fuel cell and cryogenic storage technologies become fully operational.[28]

## ■ Conclusion

This review pulls together theoretical physics, experimental data, and scaling analyses to demonstrate that ionic wind propulsion, despite offering noise reduction and zero emissions, faces unavoidable physical barriers preventing its implementation in commercial aviation. The evidence reveals constraints rising not from engineering insufficiency but from unchangeable electromagnetic and quantum mechanical laws.

Across international research institutions, performance boundaries converge with remarkable consistency. Ion mobility remains fixed at 1.5–2.0 $cm^2/V\cdot s$ in atmospheric air, while corona discharge demands 35 eV per ion pair.[15] MIT achieved maximum thrust densities of 3.3 $N/m^2$.[5] NASA reached 1.5 $N/m^2$,[2] and European institutions replicated these limits across diverse electrode geometries.[6,7] This consistency across wire-to-cylinder setups, pin arrays, and advanced DBD actuators confirms that physical law, not technological limitation, constrains performance. The scaling gap proves insurmountable: an Airbus A320 requires 118 kN per engine,[21] representing 37,000 times MIT's maximum thrust and necessitating 35,758 $m^2$ electrode arrays and 16,900 ton power supplies per engine.[22] Beihang University's aeroelastic analysis compounds this impossibility, revealing that lightweight electrode arrays deform under flight loads, causing 2.7° thrust deviations and destabilizing pitching moments.[23] Electrodes cannot simultaneously satisfy the contradictory requirements of being large enough for thrust yet rigid enough for stability.

However, ionic wind demonstrates legitimate utility in appropriately scaled applications. Indoor helium airships[24] and centimeter-scale microrobots[27] succeed by embracing rather than fighting these constraints, operating where modest thrust suffices. This contrasts sharply with hydrogen propulsion, exemplified by the operational HY4 aircraft, which faces engineering rather than physics barriers and achieves 120 MJ/kg specific energy with demonstrated commercial scalability.[28]

Future research should focus on applications where ionic wind become advantages. In space, for example, studies should prioritize three key things: how efficiently we can generate thrust at super low pressures (under 1 kPa, where it actually takes 40–60% less energy to ionize the air), how fast electrodes wear out in a vacuum (since there's no atmospheric oxygen to cause oxidation), and how much thrust you get for the power you put in when flying above 50 km, where the thin air cuts down drag a lot. Promising hybrid configurations include ionic wind arrays for boundary layer control on conventional aircraft wings, reducing skin friction drag by 5–10% while primary propulsion remains turbofan-based, and dual-mode systems combining ionic wind for low-speed maneuvering with conventional propulsion for cruise flight in high-altitude UAVs. These specific architectures leverage ionic wind's strengths while avoiding its fundamental thrust limitations. By acknowledging fundamental boundaries and pursuing applications aligned with ionic wind's natural characteristics, the aerospace community can tackle its potential while advancing viable, sustainable aviation pathways, particularly hydrogen propulsion, toward zero-emission commercial flight.

## ■ Acknowledgment

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