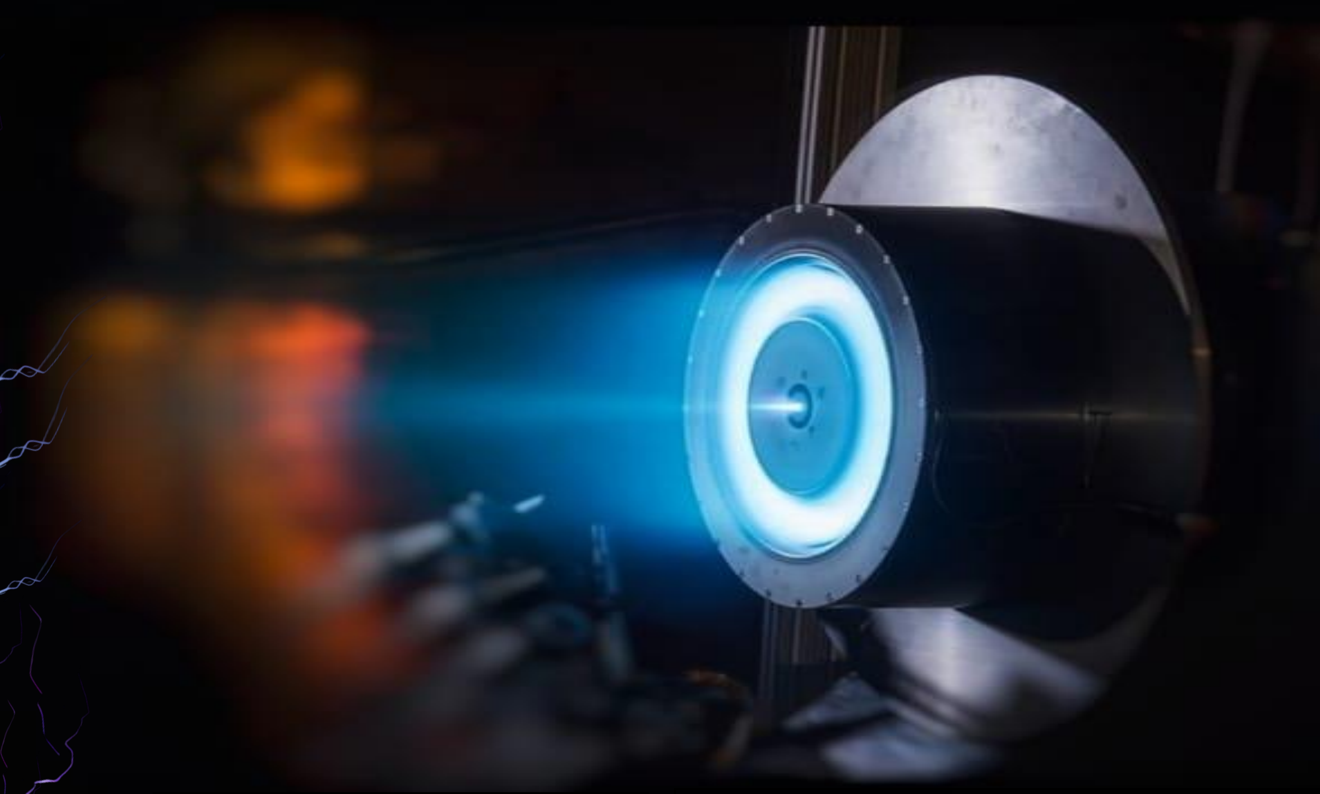
ME-243L- Thermodynamics lab

# Lab Report on Design and Energy Analysis of Plasma Ion Propulsion system

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# Design and Energy Analysis of Plasma Ion Propulsion system

## 1. Abstract:

This study details the construction and **thermodynamic analysis** of a basic **Electro hydrodynamic (EHD) Ion Wind Engine**, utilizing copper and steel wire electrodes mounted on a PVC frame. The primary objective was to quantify the energy conversion efficiency (electrical to kinetic) and analyze the system's energy balance using the **First Law of Thermodynamics**.

The apparatus was powered by a high-voltage 400 kV DC supply to generate measurable thrust through a sustained **corona discharge** and the resulting **ionic wind**.

**Key quantitative findings** revealed an **exceptionally low propulsive efficiency** of approximately $1.345 \times 10^{-4}$%.

The energy balance analysis showed that of the 34.6 kJ total electrical energy input, the **vast majority 34.5 kJ was wasted energy $Q_{loss}$**. This substantial energy dissipation is primarily attributed to **irreversible processes**, including **Joule heating** in the high-voltage circuit, **viscous dissipation** (fluid friction) during ion-neutral collisions, and **acoustic losses**. These mechanisms significantly contribute to the **increase in system entropy**.

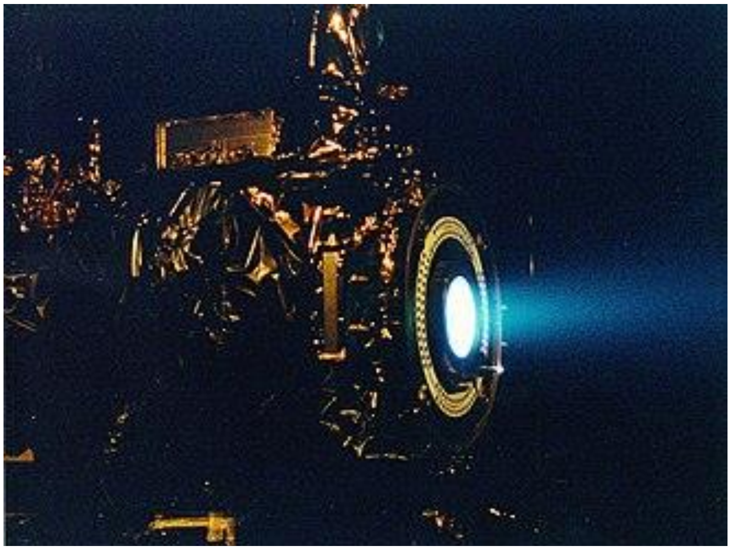

*Figure 1: The 2.3 kW NSTAR ion thruster developed by NASA for the Deep Space 1 spacecraft during a hot fire test at the Jet Propulsion Laboratory (1999)*

In conclusion, the experiment successfully demonstrated the principle of EHD propulsion and confirmed the application of the First Law of Thermodynamics. However, the quantified **exceedingly low efficiency** highlights the inherent challenges of atmospheric EHD propulsion, where losses dominate the system's thermodynamics and only a negligible fraction of input energy is converted into directed propulsive kinetic energy.

# 2. Introduction:

## 2.1. Objective:

The primary objective of this experiment is to construct and test a basic **Ion Wind Engine** using a steel collector electrode, and to analyze its performance through the lens of thermodynamics.

Specifically, the project aims to:

1. Quantify the energy conversion efficiency (electrical to kinetic) of the EHD system.
2. Determine the key operational parameters (voltage, current, power) required to generate measurable thrust.
3. Analyze the Thermodynamics in the Ion Propulsion System.

**Thermodynamic Law Used:** The fundamental principle governing the analysis of this system is the **First Law of Thermodynamics (Conservation of Energy)**. Applied to the thruster, the law is used to track the energy balance:

Electrical Energy Input = Kinetic Energy (Thrust) + Waste Heat (Electrical Losses) + Ionization Energy Loss

Since the system operates at a steady state, the analysis focuses on the **power balance**, where the electrical power consumed is equated to the propulsive power output and various power losses, including heat dissipation.

# 3. Experimental Setup:

## 3.1. Apparatus:

1. Emitter Electrode: Copper wire placed on top of frame.
2. Collector Electrode: Steel wire. Placed beneath the emitter.
3. Frame: PVC pipe.
4. High-Voltage Power Supply: Capable of generating 400kV DC.
5. Button.
6. Battery (Li-Ion 2600mAh,3.7V)
7. Battery Holder
8. Anemometer.
9. Propellant: Ambient Air.

## 3.2. Construction:

The construction of the Ion Wind Engine focuses on creating a rigid, non-conductive frame to securely hold the emitter and collector electrodes at a precise, fixed distance, which is critical for maintaining the necessary high-voltage electric field.

### 3.2.1. Frame Preparation and Assembly:

1. **Frame Material Preparation:** Start by procuring and precisely cutting sections of **PVC pipe** (Polyvinyl Chloride) to form the structural frame. PVC is chosen for its high **dielectric strength** and mechanical rigidity, ensuring it will not conduct the high voltage and will maintain the electrode geometry.
2. **Drilling and Positioning for Electrodes:** Carefully drill small, corresponding holes into the PVC pipe frame to accommodate the electrodes. These holes must be positioned to ensure the electrodes are **parallel** and separated by a specific, uniform gap distance. This distance is a crucial experimental parameter, influencing the required voltage and the efficiency of the thrust generation.

*Figure 2: PVC pipe for frame*

### 3.2.2. Electrode Installation:

1. **Emitter Electrode Installation:** Insert the **copper wire** (the **emitter electrode**) through the designated holes near the top of the frame. The copper wire should be thin, sharp, or pointed to maximize the electric field concentration, which is necessary to initiate the **corona discharge**. Secure the wire firmly to prevent vibration or movement during operation.
2. **Collector Electrode Installation:** Position the **steel wire** (the **collector electrode**) into the holes directly beneath the copper emitter. The collector's geometry is less critical than the emitter's but must be sized appropriately to capture the ionized air stream.

*Figure 3: Steel wire installation*

Ensure the crucial gap distance between the emitter (copper) and collector (steel) is uniform along their length.

*Figure 4: Copper wire installation*

### 3.2.3. Electrical Connections and Control Circuit:

1. **Connecting the High-Voltage (HV) Supply:**
   Connect the **positive terminal** of the high-voltage power supply to the **copper wire emitter**. The positive potential is necessary to create and accelerate positive air ions. Connect the **negative terminal** (ground) of the high-voltage power supply to the **steel wire collector**. This negative potential attracts and neutralizes the accelerated ions, closing the circuit and driving the ionic current.

2. **Low-Voltage Control Circuit Assembly:** Assemble the low-voltage control circuit, which includes the **Li-Ion battery (3.7 V, 2600 mAh)** and the associated **battery holder**. This low-voltage circuit is typically used to power the high-voltage multiplier stage (the internal components that step up the voltage to 400 kV.

*Figure 5: Low voltage control circuit assembly*

3. **Button Installation:** Integrate the activation **button (switch)** into the low-voltage control circuit. This switch serves as the main safety and operational control, allowing the user to safely initiate the power transfer from the battery to the high-voltage power supply, thereby beginning the EHD thruster's operation

*Figure 6: Switch Installation*

## 3.3. Working of Ion Wind Engine:

### 3.3.1. Initiation of High Voltage and Corona Discharge:

1. System Activation: Once the apparatus is fully assembled and the battery is connected, activating the switch closes the high-voltage circuit. This rapidly applies a large potential difference (up to 400 kV DC in this setup) between the emitter and collector electrodes.
2. Electric Field Formation: The geometry of the electrodes—specifically the sharp tip of the copper wire emitter versus the flatter or larger surface of the steel wire collector—creates a highly non-uniform electric field. The electric field is concentrated intensely around the sharp emitter, exceeding the dielectric strength of air in that localized region.
3. Corona Discharge: The intense electric field at the emitter tip initiates corona discharge. This process is characterized by an audible hissing or crackling sound and, in a darkened environment, a visible glow around the emitter.

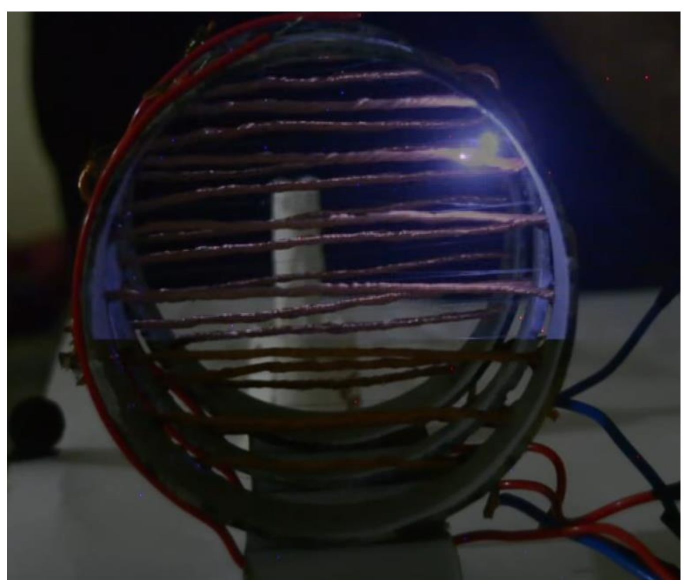

*Figure 7: Corona Discharge*

### 3.3.2. Ionization and Acceleration:

1. **Ion Generation:** Within the corona region, free electrons—naturally present or pulled from ambient air molecules—are accelerated so rapidly that they collide with neutral air molecules (primarily Nitrogen and Oxygen). These collisions strip electrons from the neutral molecules, creating a cloud of positively charged **ions** (e.g., $N^2$ and $O^2$). The copper wire itself acts as the source, continuously providing the necessary energy to drive this ionization.
2. **Ion Migration and Acceleration:** The positively charged ions created near the emitter are immediately subjected to the powerful electric force. They are rapidly and continuously **accelerated** toward the negatively charged **steel collector electrode**.
3. **Momentum Transfer:** As these high-speed primary ions travel across the gap, they constantly collide with the vast number of surrounding **neutral air molecules**. These inelastic collisions transfer momentum from the accelerated ions to the neutral air molecules.

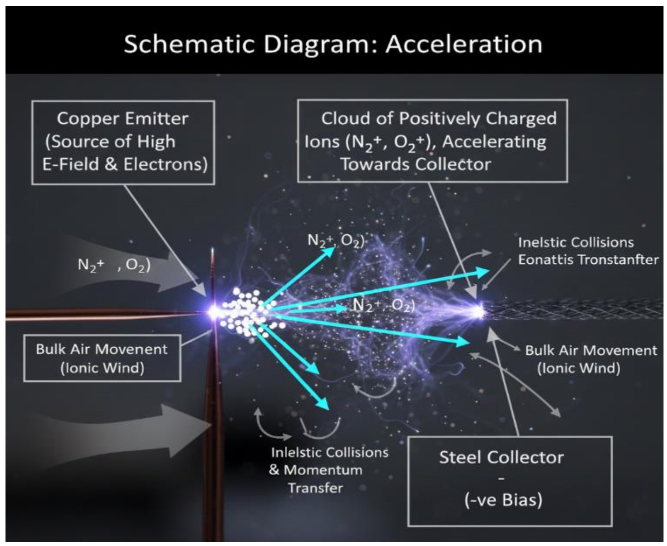


*Figure 8: Ionization and acceleration*

### 3.3.3. Thrust Generation (Ionic Wind):

1. **Bulk Air Movement:** The cumulative effect of these momentum transfer collisions is the **bulk movement of the air** between the electrodes. This directed flow of both charged and neutral air is known as the **"ionic wind"**.
2. **Thrust Production:** The mass flow of the ionic wind in one direction (from emitter to collector) generates an equal and opposite reaction force, or **thrust**, on the entire electrode structure (the EHD thruster itself), in accordance with **Newton's Third Law of Motion**. This thrust is the useful output of the engine.

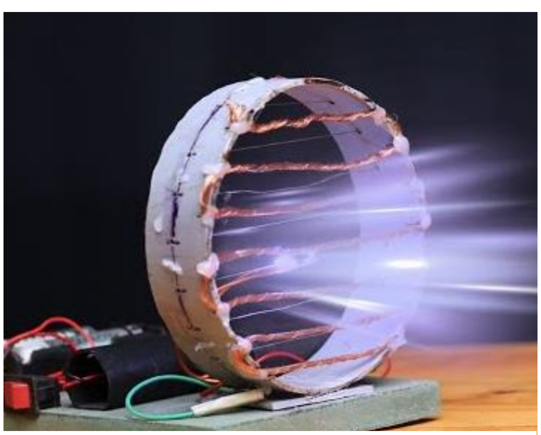

*Figure 9: Bulk air movement*

# 4. Energy Analysis:

Energy Balance and Propulsive Power:

Electrical Input Power = Thrust Power (KE) + Heat Loss Power

1. **Work input:**
   The input provided by the voltage supplier the energy for the ionization and generation of the thrust.

   $W_{in}$: Power (watts) x time (s)

   $W_{in}$: 2600 mah.

   $W_{in}$: 34632w.s.

   $W_{in}$: 34.6 kJ

2. **Work Output:**
   Work output is the useful work the machine does on the object. For the ionic plasma thruster. The useful work is the kinetic energy imparted to the surrounding air, resulting in a thrust force that moves the object.

   $W_{out}$: output force x Distance

   - The air velocity calculated by anemometer is 2 m/s.
   - Dynamic pressure calculated $q= (1/2)\ \rho v^2$, Air density $\rho$=1.225kg/m$^3$, value = 2.45N/m$^2$,
   - Output Force: the force generated by the thruster in newton (N).
   - Force on area F=q A, area = 2cm$^2$. Force =4.9x10$^{-4}$.
   - Distance: the device moved by that force (m).

   $W_{out}$: 0.00049x0.095.

   $W_{out}$: 4.655x10$^{-5}$kJ.

3. **Wasted Energy ($Q_{loss}$):**

   $Q_{loss}$: Electrical Input Power- Thrust Power (KE)

   $Q_{loss}$: 34.6-4.655x10$^{-5}$kJ

   $Q_{loss}$: 34.5 KJ

4. **Propulsive Efficiency:**

   Propulsive Efficiency: Thrust Power output/ Electrical Power Input

   $\eta$: (4.655x10$^{-5}$/34.6KJ)x100%

   $\eta$: 1.345x10$^{-4}$%

# 5. Entropy Analysis:

1. The system operates near **ambient temperature**
2. $T_{amb}$=300K.
3. The system is **steady-state**.
4. The majority of the electrical input energy is dissipated as heat to the surroundings.
5. Changes in kinetic and potential energy of the system are negligible compared to heat loss.

- Electrical input energy:

$$E_{in}=34.6kJ$$

- Useful output energy:

$$E_{out}=4.655\times10-5kJ$$

- Heat loss (wasted energy):

$$Qloss=34.5\ kJ=34500J$$

## 5.1. Entropy Generation Due to Heat Loss:

The entropy increase of the surroundings due to irreversible heat dissipation is given by:

$$\Delta Sgen= Q_{loss}/T$$

Substituting values:

$$\Delta Sgen= 34500/300$$

$$\Delta Sgen =115J/k$$

## 5.2. Entropy Contribution from useful work:

The useful kinetic energy output is extremely small:

$$E_{out}=0.0466J$$

The associated entropy change due to ordered kinetic energy is negligible compared to heat loss:

$$\Delta S_{useful}\approx0$$

Thus, nearly the **entire entropy increase** comes from irreversible losses.

## 5.3. Total Entropy Balance:

For the combined system + surroundings:

$$\Delta S_{total} = \Delta S_{gen} > 0$$
$$\Delta S_{total} \approx 115 J/K$$

This confirms compliance with the **Second Law of Thermodynamics**.

- So total entropy generated is 115J/K.

- Joule heating, ion-neutral collisions, viscous dissipation
- Nearly all input energy becomes unavailable for useful work

# 6. Schematic Diagram:

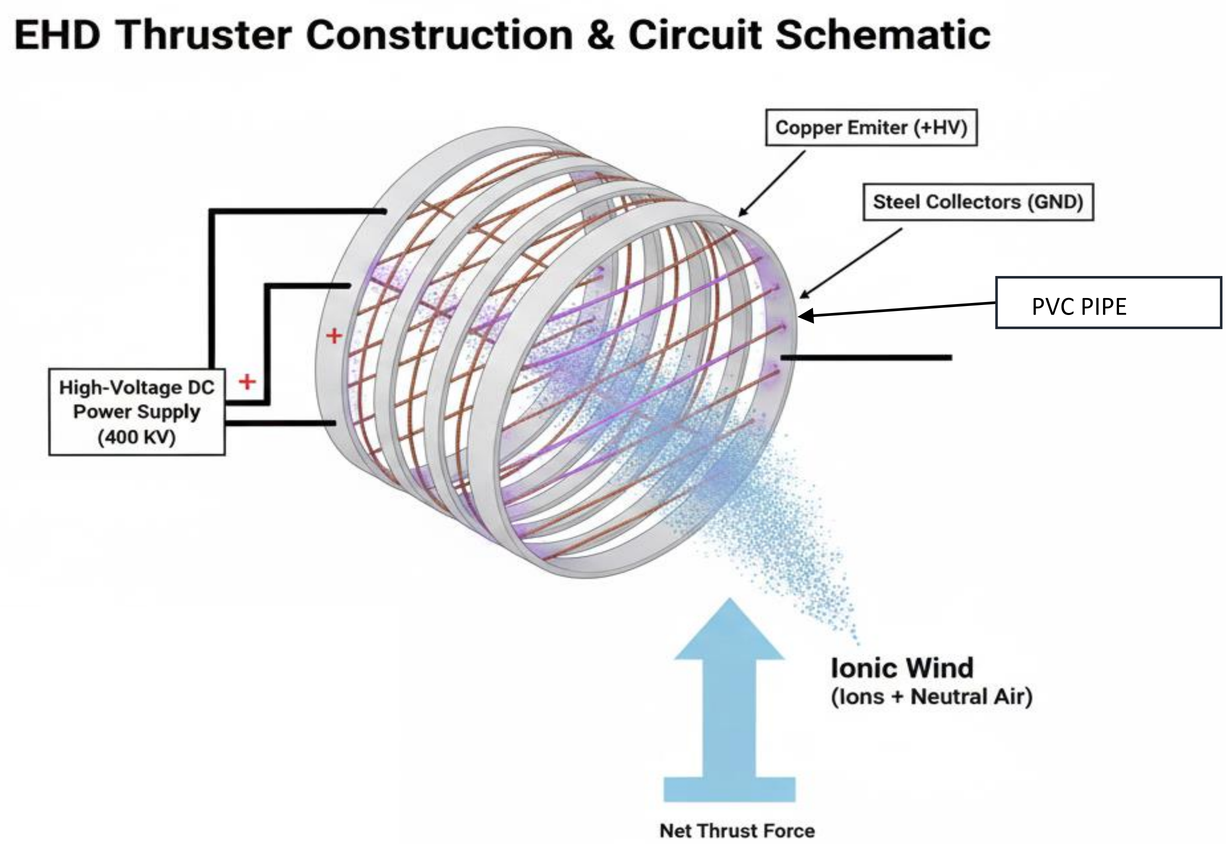


*Figure 10: Detailed Diagram*

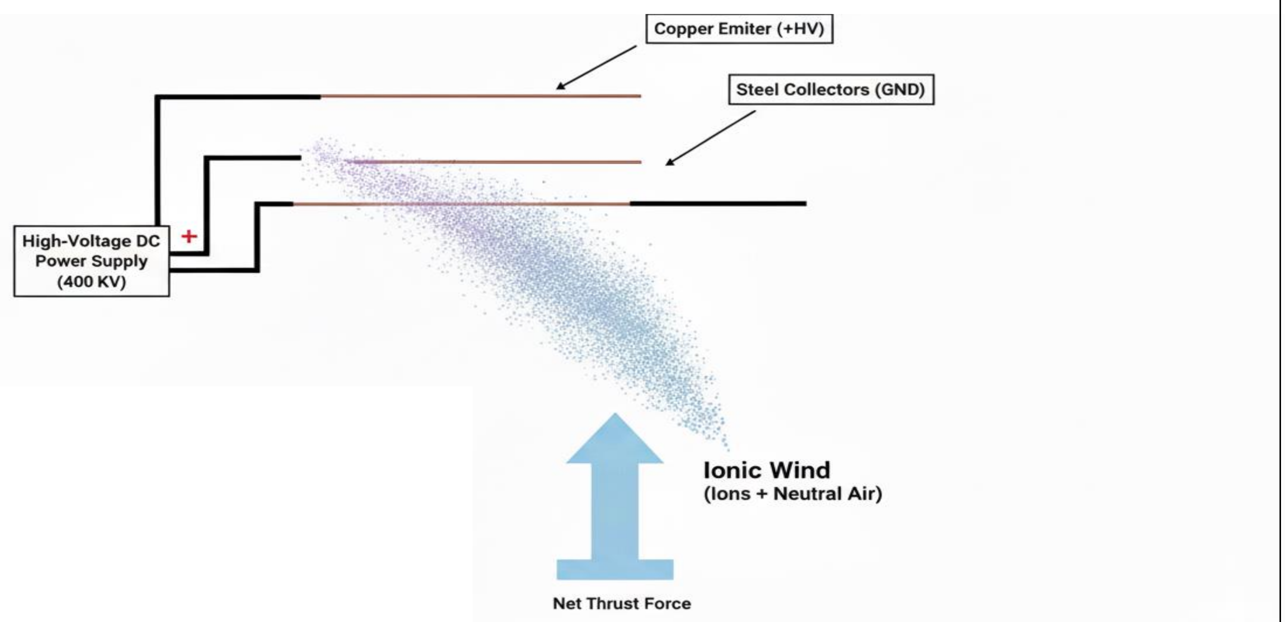


*Figure 11: Schematic Diagram*

## 7. Efficiency and Entropy Discussion:

1. **Efficiency:** Since it is not a heat engine the concept of thermal efficiency based on the Carnot cycle does not apply. The efficiency is an energy conversion efficiency or propulsive efficiency.
2. **Heat loss:** The losses in the high voltage circuit, in the basic small setup the waste heat overcomes (increase in system entropy).
3. **Entropy:** The system entropy increases due to heat losses in the high voltage circuit the mixing of ion wind.
4. **Viscous Dissipation:** As the charged ions collide with and accelerate the surrounding neutral air molecules, there is energy lost increasing the entropy due to **fluid friction** (viscosity). This friction converts ordered kinetic energy into internal energy (heat), further increasing the overall entropy of the system and its surroundings.
5. **Turbulence and Aerodynamic Losses:** The accelerated stream of air causes **aerodynamic drag** on the electrodes and the PVC frame, which reduces the net force the device produces.
6. **High Exhaust Velocity:** Studies show that when you try to maximize thrust, you often increase the air velocity, but this high-velocity jet leaves a large wake of **wasted kinetic energy** (turbulence) behind the device.

## 8. Conclusion:

This experiment successfully demonstrated the principle of **Electro hydrodynamic (EHD)** propulsion, confirming the direct conversion of electrical power into kinetic air flow (thrust) in accordance with the **First Law of Thermodynamics**.

Key findings include

• **Low Energy Conversion Efficiency:** The energy conversion efficiency was quantified as extremely low, at approximately $1.345 \times 10^{-4}$%.This low value highlights the inherent challenges of atmospheric EHD propulsion, where only a negligible fraction of the input electrical energy is converted into directed propulsive kinetic energy.

• **Dominant Energy Loss:** The energy balance showed that the vast majority of the electrical input 34.6kJ was categorized as **Wasted Energy** indicating that nearly all of the energy was lost primarily to **heat**, **acoustic energy (sound)** from the corona discharge, and **inefficient momentum transfer** during ion-neutral collisions.

• **Operational Parameters:** The experiment successfully demonstrated the operational principle of generating measurable thrust via the acceleration of air ions, confirming that the thrust is produced by the resulting **ionic wind**.