Ion-Injected MHD Gas Acceleration: A Hybrid Theoretical Framework for Fully Electric Plasma Propulsion

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Abstract

This paper introduces a hybrid theoretical propulsion concept that combines gas pre-ionization with magnetohydrodynamic (MHD) acceleration inside a duct. Pre-ionization increases the electrical conductivity of the working gas, enabling higher current densities and stronger Lorentz forces for a given electric field. The Lorentz force $\vec{F} = \vec{J} \times \vec{B}$ then acts on the entire gas volume, potentially generating directed exhaust momentum without mechanical moving parts. The framework is presented in a purely theoretical and qualitative manner, without experimental details, and is intended to motivate further analytical and numerical investigations.

1. Introduction

Electric propulsion concepts can be broadly classified into electrostatic, electromagnetic and electrothermal systems. Ion thrusters and Hall thrusters provide very high exhaust velocities but low mass flow rates and thus low thrust per unit input power. Magnetohydrodynamic (MHD) accelerators, in contrast, act on a much larger gas volume but are limited by poor electrical conductivity and high ionization energy requirements.

The present work proposes a hybrid approach, here termed the Ion-Injected MagnetoHydroDynamic Duct Drive (IIMHD-Drive), in which a dedicated pre-ionization stage ('ion injection') is used to enhance the conductivity of the working gas prior to MHD acceleration. The objective is not to claim any immediate practical device, but to define a consistent theoretical framework that can be studied with modern plasma and MHD simulation tools.

2. Background

2.1 Magnetohydrodynamic acceleration

In idealized MHD, the force density acting on a conducting fluid in the presence of electric and magnetic fields is given by the Lorentz force:

$$\vec{f} = \vec{J} \times \vec{B},$$

where $\vec{J}$ is the current density and $\vec{B}$ is the magnetic field. Assuming Ohm's law in moving media, the current density can be approximated as $\vec{J} = \sigma (\vec{E} + \vec{v} \times \vec{B})$, where σ is the electrical conductivity, $\vec{E}$ the electric field and $\vec{v}$ the fluid velocity. For the purpose of this conceptual work, we focus on configurations in which the imposed electric field dominates and approximate $\vec{J} \approx \sigma \vec{E}$.

The total force acting on the fluid in a given control volume V is then:

$$\vec{F}_\text{total} = \int_V \vec{J} \times \vec{B} \, dV.$$

2.2 Conductivity and pre-ionization

In weakly ionized gases the conductivity σ depends strongly on the electron and ion density, their mobility and collision rates. Historically, MHD systems have struggled with low σ at moderate temperatures and pressures, requiring either very high temperatures or seeding with alkali metals or other additives.

Pre-ionization refers to any process that intentionally produces a population of free charge carriers in the gas before it enters the main MHD interaction region. This can be achieved by radio-frequency discharges, microwave ionization, corona-like discharges or other methods. The key theoretical role of pre-ionization in the present framework is to increase σ so that $\vec{J} = \sigma \vec{E}$ can reach values high enough for effective momentum transfer.

3. Hybrid IIMHD-Drive Concept

3.1 Conceptual architecture

The proposed IIMHD-Drive consists of the following conceptual subsystems:

1. Working gas inlet: introduces a selected gas at a controlled mass flow rate.

2. Pre-ionization region: generates a weakly to moderately ionized plasma from the incoming gas, primarily to raise its effective electrical conductivity.

3. MHD duct region: applies an electric field $\vec{E}$ and a transverse magnetic field $\vec{B}$ to the ionized gas, driving a current density $\vec{J}$ and hence a Lorentz force $\vec{J} \times \vec{B}$.

4. Exhaust shaping section: geometrically guides the accelerated gas into a directed exhaust jet.

3.2 Momentum coupling

Neglecting detailed fluid dynamics and back-reaction of the flow on the fields, the net force on the working gas within the duct can be estimated as:

$$\vec{F}_\text{total} \approx \int_V \sigma (\vec{E} \times \vec{B}) \, dV.$$

This expression highlights the central role of conductivity σ: a higher σ directly increases the achievable current density for a given electric field and thus the force density. Pre-ionization is therefore interpreted as a conductivity amplifier that enables stronger electromagnetic coupling without specifying any particular ionization technology.

4. Efficiency considerations

The overall efficiency of any electric propulsion system must take into account: (i) the power invested in generating and sustaining the plasma, (ii) the power invested in driving the current $\vec{J}$, (iii) losses due to radiation, collisions and turbulence, and (iv) the kinetic power of the resulting exhaust stream.

In this theoretical framework, pre-ionization adds a distinct power channel P_{ion}, while the MHD stage consumes power P_{MHD} associated mainly with driving $\vec{J}$ through the plasma. The potential advantage of the hybrid scheme lies in the possibility that a modest P_{ion} can enable a large increase in σ, leading to a disproportionate increase in $\vec{J}$ and thus in useful force for a given P_{MHD}.

A quantitative assessment would require detailed kinetic and fluid simulations and is beyond the scope of this initial conceptual paper. However, the structure of the equations suggests that there exists an optimal regime in which pre-ionization cost and MHD drive power together maximize thrust per unit input power.

5. Applications and limitations

Potential application domains for the IIMHD-Drive framework include high-temperature gas propulsion in environments where mechanical components are undesirable, experimental plasma jets for laboratory studies, or specialized electric propulsion concepts for planetary atmospheres. The concept is not proposed as an immediate replacement for conventional electric motors or turbomachinery.

Major limitations include the technical challenges of generating strong, well-shaped magnetic fields, supplying and controlling high currents in plasmas, and managing thermal loads. Moreover, as with all exhaust-based systems, the achievable thrust per unit input power is constrained by fundamental momentum and energy balances.

6. Conclusion

This paper has outlined a hybrid theoretical framework for plasma-based gas acceleration, combining pre-ionization of a working gas with MHD forcing in a duct. By explicitly identifying pre-ionization as a conductivity amplifier for \vec{J} × \vec{B} coupling, the concept suggests a pathway for revisiting MHD propulsion ideas with modern plasma sources, power electronics and numerical tools. Future work should focus on detailed numerical modeling and on clarifying under which parameter regimes the hybrid approach could be competitive with other electric propulsion concepts.

7. Disclaimer

The present work is purely theoretical and conceptual. It intentionally avoids any construction details, operating parameters or instruction-like content that could be interpreted as practical guidance for high-power plasma or high-voltage experiments. Any future experimental studies inspired by this framework must be carried out only in appropriately equipped laboratories under professional supervision and in compliance with all relevant safety standards.