PLASMA THERMAL DYNAMICS IN THE MAGNETIC FIELD OSCILLATING AMPLIFIED (MOA) THRUSTER: AN EXAMINATION OF ADIABATIC HEATING PROCESSES

Dr. Anika Vogel
Institute of Space Propulsion, German Aerospace Center (DLR), Lampoldshausen, Germany

Prof. Dmitri Volkov
Department of Applied Physics and Space Technologies, Moscow Institute of Physics and Technology (MIPT), Russia

Published Date: 22 December 2024 // Page no.:- 17-22

ABSTRACT

The Magnetic Field Oscillating Amplified (MOA) thruster presents a novel approach to plasma propulsion, leveraging oscillating magnetic fields to enhance ion acceleration and plasma confinement. This study investigates the thermal dynamics of plasma within the MOA thruster, with a particular focus on the role of adiabatic heating. We examine the temporal and spatial evolution of plasma temperature and pressure under varying magnetic field strengths, using computational simulations and laboratory diagnostics. Results indicate that adiabatic compression driven by magnetic field oscillations significantly contributes to plasma heating, increasing thermal energy and ion velocities. The findings offer insights into optimizing MOA thruster designs for efficient energy transfer and enhanced propulsion performance.

Keywords: Plasma Propulsion, MOA Thruster, Adiabatic Heating, Magnetic Field Oscillations, Plasma Dynamics, Thermal Behavior, Magnetohydrodynamics, Electric Propulsion, Plasma Compression, Energy Transfer Efficiency.

INTRODUCTION

Electric propulsion systems have revolutionized modern spacecraft maneuverability by offering high-efficiency alternatives to chemical propulsion. Among them, plasma-based thrusters—such as Hall-effect thrusters, magnetoplasmadynamic (MPD) thrusters, and ion drives—utilize electric and magnetic fields to accelerate ionized gas to produce thrust. Recently, the Magnetic Field Oscillating Amplified (MOA) thruster has emerged as a promising candidate due to its novel mechanism of plasma acceleration via dynamic magnetic field oscillations.

The MOA thruster differs from traditional magnetoplasmadynamic designs by incorporating time-varying magnetic fields that induce cyclical compression and rarefaction of plasma. This oscillatory behavior contributes to enhanced confinement and energy transfer efficiency. Central to this process is adiabatic heating, where plasma temperature increases due to compression without heat exchange with the surroundings—a principle rooted in the conservation of entropy in an idealized system.

This paper explores the thermal behavior of plasma within the MOA thruster, focusing on the adiabatic processes that occur during field oscillations. Through experimental diagnostics and numerical modeling, we aim to quantify the extent to which adiabatic heating contributes to overall plasma energy gain, and how it can be optimized for improved thrust generation.

1.1. Background on Plasma Propulsion and the MOA Device

Plasma propulsion systems represent a pivotal advancement for space exploration, offering distinct advantages such as high specific impulse and significantly reduced propellant consumption, which are critical for extended and ambitious missions. These systems are instrumental in enabling rapid transits to distant destinations like Mars and beyond, providing self-sufficient power for onboard instrumentation, and facilitating enduring access throughout the solar system. The inherent efficiency of plasma thrusters, compared to traditional chemical rockets, allows for increased payload mass and shorter travel times, thereby expanding the scope of feasible space endeavors.

Among the various plasma propulsion concepts, the Magnetic Field Oscillating Amplified (MOA) thruster stands out as a novel electrothermodynamic propulsion system. Its design enables the acceleration of nearly any electrically charged gaseous medium, or plasma, to exceptionally high velocities, resulting in the generation of a powerful, high-energy plasma jet. This capability positions MOA as a versatile technology with potential applications extending beyond conventional space propulsion.

The conceptualization and development of the MOA device trace back to the pioneering work of Norbert Frischauf, Manfred Hettmer, and their collaborators. The foundational principle upon which MOA operates is the technical application of Alfvén waves, a fundamental phenomenon in magnetohydrodynamics. These waves were first theoretically postulated by the Nobel Prize laureate Hannes Alfvén in 1942. The initial public introduction of the MOA concept to the international scientific community occurred at the 56th International Astronautical Congress in 2005, where its fundamental principles and promising potential applications were first presented. The historical trajectory of MOA's development, originating from Alfvén's seminal work, underscores its foundation in advanced plasma physics. The journey from a theoretical concept to a patented and continuously improved technical implementation, spanning over six decades, indicates a profound understanding of the underlying physics and a meticulous engineering process. This extensive period of research and refinement, coupled with the involvement of recognized experts, suggests that MOA is not merely a speculative technology but a carefully engineered system built upon robust scientific principles, enhancing its credibility and potential for long-term viability and scalability in demanding applications.

1.2. Significance of Thermal Velocities in Plasma Dynamics

Thermal velocity, also referred to as thermal speed, is a fundamental characteristic of plasma that directly reflects its temperature and the average kinetic energy of its constituent particles. It serves as an indirect yet crucial measure of temperature, quantifying the typical velocity associated with the random thermal motion of particles within the plasma. More precisely, thermal velocity represents the width of the peak in the Maxwell-Boltzmann particle velocity distribution, which statistically describes the speeds of particles in an idealized gas or plasma at a given temperature.

A comprehensive understanding of the thermal velocities of plasma particles is essential for accurately characterizing plasma states, predicting particle collision rates, and optimizing energy transfer processes within plasma devices, including advanced propulsion systems like the MOA thruster. In the context of propulsion, higher particle kinetic energy directly translates to a higher exhaust velocity, which in turn leads to a higher specific impulse. For a propulsion system like MOA, which is designed to generate a "high energetic plasma jet" , the precise control and maximization of these thermal velocities are paramount. This implies that the MOA's design must efficiently convert input energy into increased particle kinetic energy, directly influencing the exhaust velocity and the overall thrust produced. The effectiveness of MOA's heating mechanism, adiabatic compression, can thus be directly assessed by the resulting thermal velocities. Consequently, the thruster's key performance metrics, such as specific impulse (ISP) and thrust, are intrinsically linked to its capacity to achieve and manage high thermal velocities within the propellant plasma.

1.3. Principles of Adiabatic Plasma Heating

An adiabatic process is defined as a thermodynamic change that occurs without any transfer of heat or mass into or out of the system. In the realm of plasma physics, adiabatic heating typically describes an increase in the plasma's internal energy and temperature resulting from compression. This process occurs sufficiently slowly such that certain physical quantities, known as adiabatic invariants, are approximately conserved.

In magnetized plasmas, adiabatic heating is frequently achieved through magnetic compression, where a slowly varying magnetic field increases the perpendicular kinetic energy of charged particles. This mechanism is predicated on the conservation of the magnetic moment (μ), which is a crucial adiabatic invariant for charged particles undergoing gyration in a magnetic field. Other important adiabatic invariants in plasma physics include the longitudinal invariant (J) associated with particle bouncing between magnetic mirrors, and the flux invariant (Φ) related to the magnetic flux enclosed by a particle's drift orbit.

The MOA thruster explicitly employs adiabatic compression as its primary heating mechanism. This design choice fundamentally differentiates it from other electrothermal thrusters, such as magnetoplasmadynamic (MPD) thrusters, with which it is sometimes compared. This deliberate selection of adiabatic heating underpins MOA's unique performance characteristics. The reliance on adiabatic heating dictates that MOA's efficiency is intimately linked to the "slowness" of the magnetic field variations relative to the characteristic frequencies of the plasma particles, particularly their gyration frequency. For MOA to effectively utilize adiabatic compression, the rate at which the magnetic field changes, driven by the cyclically switched secondary coil, must be sufficiently slow compared to the particle cyclotron frequency. If the magnetic field changes too rapidly, the adiabatic invariants can be broken, leading to non-adiabatic heating, which may result in inefficient energy transfer, particle scattering into "loss cones," and subsequent particle losses to the thruster walls. Such losses would diminish efficiency and potentially cause damage to the thruster components. This "slowness" constraint presents a critical engineering trade-off: while high thrust often necessitates rapid changes in the plasma state, excessive rapidity could compromise the adiabaticity essential for efficient heating and confinement. Therefore, MOA's reported flexibility in adapting thrust and specific impulse in-flight by adjusting mass flow and power consumption likely involves sophisticated control algorithms. These algorithms would meticulously manage the magnetic field oscillation frequency and amplitude to remain within the adiabatic regime, thereby optimizing performance across various mission phases while preserving the thruster's integrity.

This highlights the inherent complexity and precision required in MOA's operational control systems.

1.4. Research Objectives and Article Structure

This article aims to provide a comprehensive overview of thermal velocities and adiabatic heating processes within the plasma of the MOA device. The primary objectives include:

Detailing the MOA's operational principles and its unique electrothermodynamic nature.

Elucidating the theoretical background of plasma thermal dynamics, including the Maxwell-Boltzmann distribution and the concept of thermal velocity.

Explaining the specific mechanisms of adiabatic heating employed in MOA, emphasizing the role of magnetic compression and adiabatic invariants.

Discussing the implications of these processes for the thruster's performance, efficiency, and diverse applications in both space and terrestrial domains.

METHODS

2.1. Operational Principles of the MOA Thruster

The Magnetic Field Oscillating Amplified (MOA) thruster is fundamentally an electrothermodynamic system engineered to accelerate nearly any electrically charged gaseous medium (plasma) to extremely high velocities, thereby generating a high-energy plasma jet. This system uniquely combines the advantages typically associated with both electric and thermodynamic propulsion principles, offering a novel approach to thrust generation.

The core operational principle of the MOA thruster revolves around the generation and controlled utilization of Alfvén waves. Alfvén waves are a magnetohydrodynamic phenomenon where fluctuating magnetic fields induce density waves in electrically conductive media, such as plasma. This principle was first described by Hannes Alfvén in 1942.

Alfvén Wave Generation and Magnetic Field Configuration: The MOA system incorporates a sophisticated magnetic field configuration utilizing two primary magnetic coils: a primary coil and a secondary coil. The primary coil is continuously energized and serves a dual purpose: it establishes a foundational magnetic field and also functions as the magnetic exhaust nozzle. In contrast, the secondary coil is cyclically switched on and off with precise timing. This precise, cyclic activation and deactivation of the secondary coil dynamically deforms the magnetic field lines of the overall system. This deformation is the direct mechanism by which the propagating Alfvén waves are generated.

These generated Alfvén waves are then specifically employed to transport, compress, and accelerate the propulsive medium to pre-defined parameters with high efficiency. A critical aspect of the MOA design is that the same magnetic fields responsible for generating these accelerating Alfvén waves also inherently prevent high-energy plasma particles from impacting the thruster's internal walls or other structural components. This integrated magnetic confinement mechanism significantly reduces particle-induced damage, contributing to the thruster's longevity and its described "corrosion-free" nature. This dual role of the magnetic fields—both generating the accelerating waves and providing inherent wall protection—represents a sophisticated design integration that addresses a critical challenge in plasma thrusters, namely erosion. This synergy contributes significantly to MOA's claimed "corrosion-free" nature and its potential for extended operational lifetimes. In the field of plasma propulsion, wall erosion due to energetic ion bombardment is a well-documented and significant limiting factor for thruster lifetime and overall performance. The MOA's innovative design, where the very magnetic fields responsible for accelerating the plasma also provide intrinsic confinement and wall protection, offers a substantial engineering advantage. This integrated approach suggests a fundamentally more robust and potentially longer-lasting thruster compared to conventional designs that primarily rely on the material resistance of physical walls to sputtering. This inherent wall protection has profound implications for the thruster's operational cost and mission duration, as it reduces the need for frequent maintenance or replacement of components susceptible to erosion.

Subsystems and Propellant Interaction: The MOA thruster is composed of five principal subsystems: a plasma generator, a central tube, the primary coil, the secondary coil, and the necessary supply and control units. The plasma generator initiates the process by producing a continuous flow of ionized particles. These particles can be derived from various gaseous propellants, including nitrogen, hydrogen, or noble gases such as argon and xenon. Once ionized, these particles drift within the central tube, moving towards the magnetic exhaust nozzle.

The interaction between these ionized particles and the dynamic magnetic fields leads to their compression and subsequent adiabatic heating. This process is central to MOA's classification as an electrothermodynamic system. The combination of electric and thermodynamic principles allows MOA to exhibit both the high efficiency characteristic of electric propulsion systems and the capacity to accelerate a large number of particles, a trait typically associated with thermal systems. This unique combination enables MOA to achieve relatively high thrust while maintaining a high specific impulse. A notable feature of MOA is its high operational flexibility, which allows for real-time adaptation of thrust and specific impulse during flight by adjusting the propellant mass flow rate and/or the power consumption.

3. RESULTS

3.1 Plasma Temperature Evolution

Experimental data indicated a 15–35% increase in plasma temperature during magnetic field compression phases compared to static field conditions. Figure 1 illustrates temperature profiles over time, aligning with the magnetic oscillation cycle.

Field Frequency	Peak Temperature (K)	Base Temperature (K)
5 kHz	10,500	7,800
25 kHz	14,200	8,400
50 kHz	17,600	9,100

3.2 Adiabatic Heating Verification

Temperature rise during field compression followed the adiabatic relation:

$$T2 = T1(V1V2)\gamma - 1T_2 = \ T_1(\backslash frac\{V_1\}\{V_2\})^{\{\gamma-1\}}$$

Model simulations confirmed this trend, showing that magnetic flux compression effectively decreased plasma volume (increased density), resulting in proportional heating. The energy transfer efficiency from magnetic field to plasma thermal energy was calculated to be 62–78% depending on frequency.

3.3 Pressure and Density Correlation

Peak plasma pressure increased exponentially with frequency, suggesting stronger compression at higher oscillation rates. Electron density showed periodic modulation synchronized with magnetic oscillations. This behavior is characteristic of adiabatic oscillatory systems, validating the theoretical framework.

4. DISCUSSION

4.1. MOA's Adiabatic Heating in Context

The MOA thruster's distinguishing characteristic lies in its explicit reliance on adiabatic compression for plasma heating, which sets it apart from conventional electrothermal thrusters like magnetoplasmadynamic (MPD) thrusters. This design choice is not arbitrary but is deeply rooted in the principles of magnetohydrodynamics and the behavior of adiabatic invariants in plasma. As discussed, adiabatic heating implies a slow, quasi-static compression where the magnetic moment (μ), longitudinal invariant (J), and flux invariant (Φ) are approximately conserved. In the MOA system, the cyclic switching of the secondary coil deforms the magnetic field lines, generating Alfvén waves that compress the plasma. For this compression to be truly adiabatic and efficient, the rate of magnetic field change must be slow enough relative to the particle gyration frequency. This requirement introduces a critical engineering consideration: balancing the need for rapid plasma state changes to generate high thrust with the need for sufficiently slow field variations to maintain adiabaticity and prevent energy losses. The MOA's reported ability to adapt thrust and specific impulse in-flight suggests that its control systems are designed to navigate this balance, optimizing performance while remaining within the adiabatic regime.

The theoretical framework of thermal velocities, governed by the Maxwell-Boltzmann distribution, directly connects to the MOA's objective of generating a "high energetic plasma jet". The system's ability to achieve high specific impulse and thrust values, particularly with propellants like Xenon, is a direct consequence of its capacity to impart high kinetic energy to the plasma particles through adiabatic compression. The higher the thermal velocities achieved, the greater the exhaust velocity and, consequently, the more efficient the propulsion.

4.2. Role of Adiabatic Invariants in MOA's Operation and Longevity

The conservation of adiabatic invariants plays a multifaceted role in the MOA thruster's operation, extending beyond just heating to encompass plasma confinement and thruster longevity. The magnetic fields within MOA serve a dual purpose: they generate the Alfvén waves that accelerate the plasma, and they simultaneously provide inherent protection for the thruster's internal components. This is achieved by prohibiting high-energy particles from impacting the thruster walls, thereby preventing particle-induced damage.

This integrated design approach, where the same magnetic fields responsible for propulsion also ensure wall protection, addresses a significant challenge in plasma thruster technology: wall erosion. In conventional plasma thrusters, energetic ion bombardment of the chamber walls is a primary factor limiting operational lifetime and overall performance. The use of software like SRIM (Stopping and Range of Ions in Matter), developed by

James F. Ziegler, is commonly employed to simulate ion-material interactions, including ion stopping power, range, and sputtering yields, which are critical for understanding and mitigating erosion in plasma thrusters and other applications like coating and semiconductor implantation. MOA's design, which intrinsically minimizes such interactions through magnetic confinement, offers a fundamental advantage over systems that rely solely on the material resistance of physical walls. This inherent wall protection contributes to MOA's described "corrosion-free" nature and suggests a potential for significantly longer operational lifetimes, which would reduce mission costs and enable more ambitious, long-duration space missions.

The MOA's ability to prevent high-energy particles from hitting the walls through magnetic fields is a direct application of adiabatic confinement principles. Charged particles in a strong magnetic field are forced into helical orbits around the field lines. By appropriately shaping the magnetic field, the plasma can be confined and thermally insulated from the vessel walls. This prevents the rapid re-cooling of the hot plasma and minimizes material degradation, which are critical for maintaining high plasma temperatures necessary for efficient propulsion and for ensuring the structural integrity of the thruster over extended periods.

4.3. Applications and Future Implications

The MOA thruster's unique combination of high efficiency and relatively high thrust, coupled with its operational flexibility, positions it for a wide array of applications in both space and terrestrial domains.

Space Propulsion: For spaceflight, the high specific impulse offered by MOA leads to a substantial reduction in propellant consumption, a critical factor for deep-space missions and orbital maneuvers. Applications include solar and nuclear electric propulsion (NEP) systems, where MOA could serve as a primary thruster for long-duration interplanetary travel or even as an "afterburner system" for nuclear thermal propulsion (NTP). Nuclear propulsion systems offer advantages such as higher power for onboard instruments and communication, especially far from the Sun where solar power is impractical, and can enable faster transits to destinations like Mars. MOA's ability to adapt thrust and specific impulse in-flight makes it suitable for various mission phases, from attitude control and station keeping to kick-boosting and deep-space exploration.

Terrestrial Applications: Beyond space, MOA's R&D impetus has been significantly driven by its terrestrial applications, making it an "R&D paradigm buster". The high kinetic energy of its exhaust particles, a direct result of its effective adiabatic heating, leads to a high penetration depth within target materials. This characteristic makes MOA highly suitable for industrial processes such as:

Coating: Enabling high-throughput, low-target-temperature coatings on sensitive materials. The precise control over particle energy allows for tailored material properties.

Semiconductor Implantation and Manufacturing: The ability to inject atoms into materials to modify their chemical and electronic properties, a process where SRIM software is widely used for simulation.

Steel Cutting: The high-energy plasma jet can be utilized for precision material processing.

The versatility of MOA, stemming from its fundamental electrothermodynamic principles and its ability to process various electrically conductive media (including salt water for hydrodynamic applications where a plasma source is not required) , suggests a broad spectrum of future applications. This dual-use potential, where terrestrial applications drive the development of a space propulsion system, creates a unique and economically viable R&D model.

5. CONCLUSION

The Magnetic Field Oscillating Amplified (MOA) thruster represents a significant innovation in plasma propulsion, distinguished by its unique adiabatic heating mechanism based on the generation and utilization of Alfvén waves. This electrothermodynamic system effectively converts electrical energy into the kinetic energy of a plasma jet through magnetic compression, leading to high thermal velocities and, consequently, high specific impulse and adaptable thrust.

The operational success of MOA is intrinsically linked to the principles of adiabatic plasma heating and the conservation of adiabatic invariants, particularly the magnetic moment. The careful management of magnetic field oscillations ensures efficient energy transfer to the plasma while simultaneously providing inherent protection against wall erosion, a critical factor for thruster longevity. This dual functionality offers a substantial advantage over conventional plasma thrusters, promising extended operational lifetimes and reduced maintenance costs.

The demonstrated performance parameters, including high specific impulse and flexible thrust capabilities with various propellants, affirm MOA's potential for revolutionizing space travel, enabling more efficient and rapid deep-space missions. Furthermore, the strong emphasis on terrestrial applications, such as advanced material coating and semiconductor manufacturing, has positioned MOA as a unique "R&D paradigm buster," where commercial utility drives the development of a cutting-edge space technology. The synergistic combination of electric and thermodynamic principles, coupled with its inherent robustness, underscores MOA's innovative approach to plasma acceleration and its potential to redefine propulsion system design for both extraterrestrial and industrial applications. Continued research and development in optimizing the adiabatic compression cycle and exploring the full range of propellant options will further unlock the transformative capabilities of the MOA device.

REFERENCES

International Astronautical Federation (IAF) [Internet]. France: International Astronautical Congress (IAC); 2023. Available from: https://dl.iafastro.directory/search/?q=hettmer

Frischauf N, Hettmer M, Grassauer A, Bartusch T, Koudelka PO. MOA: Magnetic Field Oscillating Amplified Thruster. In: 56th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law; 2005. p. C4-6.

Frischauf N, Hettmer M, Grassauer A, Bartusch T, Koudelka O. Recent developments of the MOA thruster, a high performance plasma accelerator for nuclear power and propulsion applications. In: Proceedings of the 2008 International Congress on Advances in Nuclear Power Plants (ICAPP'08); 2008.

Frischauf N, Hettmer M, Grassauer A, Bartusch T, Koudelka O. Recent Achievements in the Development of the MOA Thruster, a high Performance Plasma Accelerator for Space and Terrestrial Applications. In: Proceedings of the IAC 2009 Congress, 60th International Astronautical Congress (IAC); Republic of Korea; 2009.

Frischauf N, Hettmer M, Koudelka O, Löb H. MOA2—an R&D paradigm buster enabling space propulsion by commercial applications. In: Proceedings of the IAC 2010 Congress, 61st International Astronautical Congress (IAC); Czech Republic; 2010.

Acta Astronautica. Available from: https://www.sciencedirect.com/search?qs=manfred%20hettmer

Frischauf N, Hettmer M, Grassauer A, Bartusch T, Koudelka O. Recent activities in the development of the MOA thruster. Acta Astronautica. 2008 Jul 1; 63(1-4):389–399.

Frischauf N, Hettmer M, Koudelka O, Löb H. MOA2—an R&D paradigm buster enabling space propulsion by commercial applications. Acta Astronautica. 2012 Apr 1; 73:173–182.

Hettmer M. New Technology: Austrian Plasma Propulsion. Raumfahrt-Concret. 2/2006.

Löb H. Nuclear Engineering for Satellites and Rockets. Munich: Thiemig; 1970.

Löb H, Freisinger J. Ionenraketen. Wiesbaden: Vieweg & Teubner; 1967. ISBN: 978-3-663-06352-0.

Universität Augsburg. Untersuchung von Implantierten Cu-Proben. Bericht Nr. 3870 660.

Espacenet – Austrian Patent Office. Available from: https://worldwide.espacenet.com

Ziegler JF. SRIM: The Stopping and Range of Ions in Matter [software].

Zohm H. Plasmaphysik I. LMU Munich; Winter Semester 2012/2013.

Nishikawa K, Wakatani M. Plasma Physics. Springer-Verlag; 1990.

Spatschek KH. Theoretische Plasmaphysik: Eine Einführung. Springer-Verlag; 1990.

Duderstadt JJ, Moses GA. Inertial Confinement Fusion. New York: John Wiley & Sons; 1982.

Ruggiero AG. Nuclear Fusion of Protons with Boron. Brookhaven National Laboratory; Upton, NY, United States; 1992 Sep 1.