Superconducting Applications in Propulsion Systems

Magnetic Insulation for Plasma Propulsion Devices

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Abstract

One of the greatest problems with plasma engines is unacceptable heat transfer rates due to the contact of the plasma with the walls. If a magnetic field is interposed transverse to the thermal conduction path of the electrons in the plasma flow, there is the potential of magnetically insulating the walls and reduce the losses.

The magnetically driven plasma rocket, also known as magnetic induction plasma engine, is a propulsion concept which allows the plasma to be magnetically insulated from the wall, and thereby eliminates large heat transfer and other damage to the walls.

The purpose of this paper is to review the status of our knowledge of the basic concepts needed to establish design parameters for effective magnetic insulation. The objective is to estimate the effectiveness of the magnetic field in insulating the plasma, to calculate the magnitude of the magnetic field necessary to reduce the heat transfer to the walls sufficiently enough to demonstrate the potential of magnetically driven plasma rockets.

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INTRODUCTION

The rate of progress in space exploration and space technology will be determined by the development of advanced propulsion systems which more effectively can store energy and more efficiently can convert such energy into useful thrust.

For the past thirty years, manned and unmanned spacecrafts have left Earth's confining gravity well via chemical rockets. However, chemical rockets are inadequate for long duration space missions, including manned missions to Mars. Electrical propulsion was suggested a few decades ago as an enticing possibility for reducing the cost of propelling large payloads in space.

Plasma engines, which fall under the category of electric propulsion, have the potential for providing the next generation advance propulsion systems. Their primary attraction lies in their highly efficient utilization of propellant mass. Many years ago, plasma propulsion was advocated as superior to other electrical propulsion systems (Ref. 3, 22).

Magnetic containment, a concept whereby the highly energetic plasma flow is insulated from the thruster's chamber walls, was the focus of several investigations over three decades ago. In 1958, R.M. Patrick (Ref. 12) proposed a magnetohydrodynamic propulsion motor based on his propulsive device which employed a magnetic field to insulate the plasma from the walls. This magnetic accelerator consisted of a shock tube driven by ionized hydrogen. For the proposed MHD propulsor, Patrick recommended the use of lithium vapor instead of liquid hydrogen or deuterium on the basis of their specific gravity which would require larger storage tanks for the latter fuels. From 1958 to 1962, further research in magnetic insulation for MHD propulsion application was conducted (Ref. 1,2,17,28) but thereafter the emphasis was shifted to other areas.

Although the basic theoretical properties of a magnetized plasma were fairly well understood at the outset of plasma propulsion research, it appears as if experimental difficulties and inherent plasma unstable behaviour overshadowed any further interest in magnetic insulation for propulsion systems.

Theoretical efforts directed towards the fundamental understanding of plasma confinement and heating received high priority by the Fusion Reactor programs of the 1960's. By the early 1970's, the theoretical understanding of magnetically confined plasmas had advanced impressively, but by then the focus of the space propulsion program had been shifted to developing the Space Shuttle chemically-propelled Main Engines and there was no experimental basis for the extrapolation of any magnetic-confinement scheme to the conditions of a practical plasma propulsion device. Since plasma fusion research is a long-term, energy-related topic, its support derives mainly from the Department of Energy (DOE) and magnetic-confinement research is oriented towards fusion reactor geometries where the requirements of low weight-to-thrust are irrelevant.

The prospects for success in plasma propulsion research appear better now. The improved understanding of magnetically confined plasmas derived from fusion reactors could be applicable if a good interpretation of the requirements for space propulsion is made. We believe that magnetic confinement will be one of the most important.

CLASSIFICATION OF ELECTRIC PROPULSORS

To achieve the high exhaust velocities required for future planetary missions, high enthalpy heating of an insulated gas stream or direct acceleration of it by applied body forces can be most reasonably accomplished by some form of electrical means. Electric propulsion is defined (Ref. 40) as:

> "the acceleration of gases for propulsion by electric heating and/or by electric and magnetic body forces"

Electric propulsion systems can be classified into three broad categories: electrostatic, electrothermal, and electromagnetic thrusters.

a. Electrostatic propulsion devices use strong electric fields applied by an accelerator grid to extract and accelerate the propellant ions in the discharge. Ion thrusters fall under this category.

b. Electrothermal propulsion systems use electric fields to heat the propellant gas which is then expanded in a suitable nozzle. These systems include resistojets, arcjets, pulsed electro-thermal thrusters, and laser propulsion systems.

c. Electromagnetic propulsion devices are characterized by the use of jxB forces to accelerate the ionized propellant. Under this category we find MPD thrusters, electromagnetic launchers, the MIP engine, and Hall current thrusters.

In spite of their attractiveness, electric propulsors are still insufficiently developed. These systems are characterized by rather complex conversion steps between the energy source and the exhaust jet and the efficiency of the process is very much compromised. This complexity, combined with the resulting high weight-per-unit thrust has slowed the progress of electric systems. In 1981, Garrison (Ref. 23) concluded that the mass of the magnet and fusion trigger systems would limit the application of this technology to large vehicles. However, the exhaust velocities potentially achievable by these mechanisms have been found to be more than adequate to qualify for the long-duration interplanetary missions outlined above (Ref. 40) and as such, electric propulsion systems deserve our attention.

PLASMA CONFINEMENT AND INSTABILITIES

The plasma must be confined for a sufficient time and cannot be in contact with any material wall. The fact that a plasma consists of charged particles makes it possible to confine them by applying a strong external magnetic field. However, despite the magnetic confinement, some of these charged particles escape without undergoing fusion reaction. This particle loss cannot be eliminated completely and it sets an upper limit on confinement time (classical confinement time).

Experimentally, anomalous losses seem to be associated with plasma turbulence. For a fully turbulent plasma, the confinement time is termed the Bohm time, used as a basis for comparing the quality of plasma confinement.

There are other kinds of plasma instability which cause the hot plasma to be lost before it has reached the required temperature:

a) MHD instability - plasma is a diamagnetic material and will always move to the weaker magnetic field.

b) Stream instability - a condition arising from the presence of a directed beam of energetic particles in a plasma.

c) Hydromagnetic instability arising from imposed currents within the plasma itself producing jxB forces.

d) Other instabilities arising from density gradients, velocity gradients, etc.

Confinement studies have been conducted in several magnetic-field configurations for fusion reactor applications. A plasma can become unstable in many ways, including both macroscopic and microscopic instabilities. In a macroscopic instability there is a gross motion of the plasma to the wall. Gross motions can be controlled by magnetic wells and by magnetic shear configurations (Ref. 7). The microscopic instabilities are more akin to fluid dynamic turbulence. The result of these instabilities is increased diffusion to the walls. They may be caused by density and temperature gradients in the plasma or by non-Maxwellian velocity distributions of the ions or electrons. All these instabilities derive from the fact that the plasma is not in a state of thermodynamic equilibrium. If the plasma relaxes to the equilibrium state, it can release free energy that can drive the instabilities. To avoid this, we must either eliminate the non-equilibrium conditions or prevent the plasma from relaxing to the equilibrium state.

The magnetic-well concept is a means of preventing the plasma from relaxing to the equilibrium state. Magnetic wells have proved completely effective in eliminating macroscopic instabilities in open-ended systems.

The other way to control macroscopic instabilities in a torus is by application of magnetic shear. The Tokamak T-3, a Russian toroidal machine with magnetic shear is the best known example.

Because of the relatively simple geometry of the open-ended systems, the theoretical understanding of microscopic instabilities in such systems is fairly complete. The theory also suggests ways of eliminating most of the instabilities.

In 1975, Papailiou (Ref. 5) reviewed the energy transfer process occurring between a fluctuating magnetic field and the velocity field of a conducting fluid in turbulent motion. He referred to the analysis by Batchelor (Ref.149) on the similarity between the fluid dynamic vorticity equation and the equation for the rate of change of the energy in the fluctuating magnetic field. Papailiou concluded that a hydromagnetic dynamo, in which energy flows from the velocity field to the magnetic field can only operate under the condition where is the magnetic diffusivity and is the kinematic viscosity of the fluid. Based on this energy exchange scheme, he recommended ionized hydrogen as the working fluid. Further, Papailiou diffusion equation indicated that the magnetic field decays into the conducting fluid of conductance , with decay time several order of magnitude higher than the interaction time with the turbulent fluid; this prohibits the complete annihilation of the magnetic field and therefore causes a reduction in the amount of energy transferred to the conducting fluid. In spite of this problem, the application of this concept in propulsion was believed to be promising so Papailiou recommended the conducting of a theoretical-experimental effort to examine the mechanism of decay of a fluctuating magnetic field in an electrically conducting fluid in turbulent motion.

MAGNETIC INSULATION

One of the greatest problems with plasma engines is unacceptable heat transfer rates due to the contact of the plasma with the walls. In 1960, Clauser (Ref. 1) estimated the reduction of the heat transfer rate by using a magnetic field transverse to the thermal conduction path of the electrons. Clauser theorized that the ratio of the electron collision frequency to the electron cyclotron frequency determined the extent of decrease of the thermal conduction. At the same time, Janes from the AVCO-Everett Labs (Ref. 2) predicted that the level of magnetic field strength necessary for magnetic confinement of the plasma was a fraction of the magnetic field for plasma acceleration. Janes' work focused on the application of plasma insulation for the Magnetic Induction Plasma (MIP) engine, which is an electrodeless device.

In a separate program, Fowler and Turner (Ref. 17) demonstrated experimentally how a magnetic field could effectively insulate the hot plasma from the walls of a shock tube. They found that when the cyclotron frequency of the electrons is greater that the frequency of collision, which cause diffusion across the field lines, this effect could be observed.

Studying plasma containment for control of thermonuclear reactions, stability of the plasma and magnetic field seem to preoccupy us. Clauser (Ref. 1), in 1960, observed that for a short shock tube, such instabilities would not have time to grow since the time required for the instability to develop is of the order of the time required for a particle or sound wave to transverse the tube and return.

The next paragraphs will describe the type of analysis that have been conducted to demonstrate the feasibility of using magnetic forces to insulate the plasma.

In 1959, Camac, et al (Ref. 14) proposed the use of magnetic fields to keep the electrically conducting plasma from the walls and thus minimize heat losses. Their analysis was based on the assertion that electrical propulsion devices operate at lower power levels as compared with conventional chemical rockets; this results in lower gas densities and lower Reynolds numbers which in turn produce thicker boundary layers on the walls and therefore greater energy losses. They related the boundary layer thickness to specific impulse and thrust power and concluded that magnetohydrodynamic containment would be more efficient at high specific impulses and for fully ionized gases. Electrode losses in the form of dissipated potential drop were also believed to be reduced by the use of magnetohydrodynamic forces.

Clauser (Ref. 1) later developed a relationship for the depth of penetration, or skin depth, primarily dependent on the magnetic Reynolds Number, assuming a plasma Beta of one. The (rf current) skin depth is the distance to which the electromagnetic field is able to penetrate in a cycle. For typical shock tube conditions, Clauser concluded that the skin depth was small enough that the interface between the magnetic field and the plasma could be thought of as a surface rather than a volume.

Confinement of plasma at fusion temperatures makes use of the fact that charged particles tend to gyrate in tight spirals along the lines of force in a magnetic field. However, the plasma has a kinetic pressure p that is large enough to depress the magnetic pressure of the confining magnetic field by a factor Beta (β)

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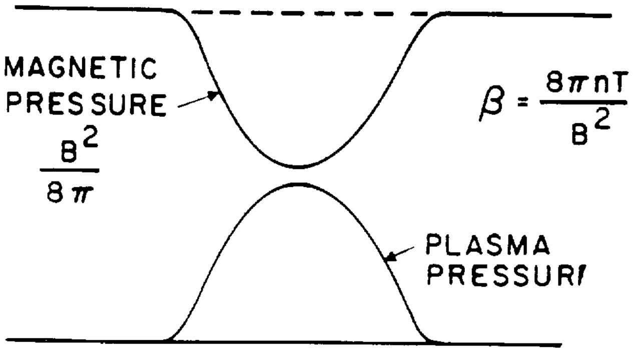

FIGURE 4.4 Illustration of the depression in the magnetic pressv the kinetic pressure nT of a confined plasma. Here, B is the field sv of electrons and ions, and T the plasma temperature. The ratio of t = $8\pi nT/B^2$.

The attainable value of Beta depends mainly on the geometry of the magnetic confinement. (For fusion reactor design, typical magnetic field strengths of 50 kilogauss and Beta values of 6 percent provide plasma pressures of about 6 atmospheres , Ref.60)

The heat conduction coefficient of a gas at very high temperature is much greater for a fully ionized gas. If a magnetic field is interposed transverse to the thermal conduction path of the electrons, the thermal conduction is decreased. To obtain an estimate of the effectiveness of the magnetic field in insulating the plasma, Clauser calculated the strength of the magnetic field necessary to reduce the conductivity 100 fold.

MAGNETIC NOZZLE CONCEPT

Plasma thrusters produce high speed flows in a diverging magnetic field. The acceleration mechanism is due to the diverging magnetic field which acts as a nozzle. Axial acceleration occurs as a result of both the magnetic pressure exerted by the nozzle and the conversion of thermal motion into axially directed motion.

In 1971, Walker and Seikel (Ref. 8) studied the axisymmetric expansion of a plasma in a magnetic nozzle. Their analysis considers the flow near the axis of the nozzle including the electron thermal conductivity. They assumed that the ion temperature is negligible and that the Hall parameter ( ) is a constant near the nozzle's axis. Chubb (Ref. 9), on the other hand, included the effects of unequal electron and ion temperatures and electron thermal conductivity.

NUMERICAL MODEL

A magnetically confined plasma may be represented by ideal MHD equations. The MHD model treats the plasma as a charge-neutral fluid that is in local thermodynamic equilibrium and thus neglects most of the physics of plasmas. The physics retained, however, describe the transfer of momentum and energy between the plasma and the magnetic field. Thus, the MHD model provides the simplest model by which the effect of the geometry on the gross equilibrium and stability of a high-beta plasma can be studied. The MHD equations must be coupled with initial and boundary conditions to obtain a complete evolutionary system.

SUMMARY

Because of the complexity of physical phenomena involved, our discussion of plasma magnetic insulation has been rather qualitative. Without experimental research, little can be said about the validity of the argument that magnetic fields can be used to insulate plasmas in propulsion devices.

We are particularly interested in the possibility of developing a mathematical scheme which can adequately model the extent to which a given magnetic field can insulate a plasma from the walls.

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