Analysis of Electromagnetic Propulsion of Nonionized Dipole Gases

Michael M. Micci*
The Pennsylvania State University, University Park, Pennsylvania

A means by which the thrust-producing electromagnetic acceleration of a nonionized gas could be achieved was suggested recently. This acceleration is accomplished through the interaction of an alternating polarization in the exhaust medium with a synchronized alternating magnetic field. Two derivations of this force are presented along with quantitative experimental evidence of its existence. The thrust produced by such an interaction is proportional to the product of the polarization amplitude, the magnetic field strength, and the frequency of the field oscillation. Estimates of the thrust obtainable with naturally occurring atoms and molecules proved too small to provide for a variable thruster concept, therefore, artificial means of increasing the dipole moment were examined. Electronically excited or Rydberg atoms and molecules provide a proven means of obtaining increased polarization amplitudes; however, the decreased ionization potential negated their use as potential propellants. Comparison of alternating polarization thrusters with other electric propulsion concepts indicated that this method is not a viable advanced propulsion scheme at this time.

Nomenclature

a = acceleration
B = magnetic field strength
d = dipole charge separation distance
E = electric field strength
f = frequency
F = force
I = current
k = Boltzmann constant
K_1, K_2 = high-frequency ionization constants
L = length
m = mass
n = principal quantum number
p = pressure
q = charge
r = radius
$\vec{r}$ = position vector
T = temperature
u_e = exhaust velocity
v = velocity
Z = nuclear charge
α = polarizability
ϵ_0 = vacuum permittivity
μ = dipole moment
ω = circular frequency

Introduction

A MEANS by which the electromagnetic acceleration of a nonionized working fluid could be utilized for space propulsion was suggested by Cox[1] in 1980. This method obtains thrust through the interaction of a nonsteady magnetic field with an alternating polarization in the exhaust medium. The alternating polarization would be obtained by inducing the rotation of permanent or induced dipole moments by alternating electric fields. In 1981, Cox proposed the utilization of the method in a Shuttle-type vehicle using atmospheric gases as the exhaust media.[2] The use of a dipole gas in an electromagnetic accelerator has invoked some interest due to the desirability of avoiding ionization of the working fluid and the resultant energy loss. There is also considerable concern as to the effects of ion or plasma exhausts on space communications and charging. However, several physical phenomena exist (collisions, ionization, etc.) that could interfere with the achievable performance of a nonionized dipole thruster. Also, at the time this investigation was initiated there was doubt as to whether this force existed at all. Therefore, a detailed analysis of the physical processes involved in the electromagnetic acceleration and the applicability of this method to space propulsion was undertaken.

Presented as Paper 83-1395 at the AIAA 19th Joint Propulsion Conference, Seattle, Wash., June 27-29, 1983; submitted Aug. 19, 1983; revision submitted March 21, 1985.

*Assistant Professor of Aerospace Engineering. Member AIAA.

Force Derivation

Cox[1] derived the force acting on a rotating dipole as follows (see Fig. 1). A dipole is an atom or molecule with a net charge separation. The dipole moment is simply the charge multiplied by the separation distance, d. Molecules such as water can possess permanent dipole moments and both atoms and molecules can have dipole moments induced in them by an electric field. Under the influence of an electric field, the dipole will experience a torque which will act to align the dipole with the electric field. If the polarization of the electric fields is rotating, as in for instance a circularly polarized electromagnetic wave, then the dipole can be induced to rotate. When a magnetic field which is normal to the instantaneous velocity of the rotating dipole charges is applied, Lorentz body forces in the same direction are generated on each charge constituting the dipole. The direction of the Lorentz forces is such that the dipoles are accelerated normal to their plane of rotation. The Lorentz force is given by

$$\vec{F} = q(\vec{v} \times \vec{B}) \tag{1}$$

The velocity of each charge is simply the rotational frequency multiplied by the radius, thus,

$$\vec{F} = [(\vec{d}/2)\omega \times \vec{B}] \tag{2}$$

The dipole moment was defined to be

$$\mu = qd \tag{3}$$

Thus if the magnetic field is always perpendicular to the instantaneous charge velocity the force on one charge is

$$F = (\mu/2)\omega B \tag{4}$$

and the sum of forces on the two charges is

$$F = \mu\omega B \tag{5}$$

If the magnetic field is unidirectional and varies sinusoidally with time at the same frequency as the dipole rotation, then the integral of the force on the entire dipole averaged over one revolution is

$$F = \tfrac{1}{2}\mu\omega B \tag{6}$$

The thrust developed by such a device is simply the sum of the forces acting on all of the dipoles within the interaction region.

An earlier derivation of the forces acting on a dipolar gas was published by Penfield and Haus.[3] Their derivation differs from Cox's in that it considers any general motion of the dipole, not just rotation. The position of the negative end of the dipole is given by $\vec{r}$ (see Fig. 2). The dipole is acted on by electric, $\vec{E}(\vec{r})$, and magnetic, $\vec{B}(\vec{r})$, fields which can be functions of the position. The negative end of the dipole is moving with velocity $\vec{v}$ and the dipole moment vector extending from the negative to the positive charge is labeled $\vec{d}$. The force acting on the negative end is

$$-q\vec{E}(\vec{r}) - q\vec{v}\times\vec{B}(\vec{r}) \tag{7}$$

The positive end of the dipole is located at the point $\vec{r}+\vec{d}$ and is traveling with velocity $\vec{v}+\mathrm{d}\vec{d}/\mathrm{d}t$, thus the force acting on the positive end is

$$q\vec{E}(\vec{r}+\vec{d}) + q\left(\vec{v}+\frac{\mathrm{d}\vec{d}}{\mathrm{d}t}\right)\times\vec{B}(\vec{r}+\vec{d}) \tag{8}$$

The sum of the two expressions is the net force on the dipole.

$$\vec{F} = q[\vec{E}(\vec{r}+\vec{d}) - \vec{E}(\vec{r})] + q[\vec{v}\times\vec{B}(\vec{r}+\vec{d}) - \vec{v}\times B(\vec{r})] + q\frac{\mathrm{d}\vec{d}}{\mathrm{d}t}\times\vec{B}(\vec{r}+\vec{d}) \tag{9}$$

When taken to first order the expression for the force becomes

$$\vec{F} = q\vec{d}\cdot\nabla\vec{E} + q\vec{v}\times(\vec{d}\cdot\nabla\vec{B}) + q\frac{\mathrm{d}d}{\mathrm{d}t}\times\vec{B} \tag{10}$$

Since the dipole moment is given by $q\vec{d}$, the last term represents the cross product of the time rate of change of the dipole moment with the magnetic field, giving the same magnitude as derived by Cox [Eq. (5)]. In spatially uniform electric and magnetic fields only the final term remains.

This force has been experimentally measured in solid dielectric crystals by Walker and Walker[4] and Walker et al.,[5] and agreement within 4% of the Penfield and Haus derivation was obtained. The experiment, described in detail in Ref. 5, involved the production of an alternating radial polarization induced by an alternating radial electric field. A steady axial magnetic field was applied and the resultant force produced an alternating torque on the crystal. The crystal was suspended such that it was free to rotate and the torque-induced rotation was measured by optical means. Walker and Walker[4] and Walker et al.[5] were looking for a force derived by Abraham (hence called the Abraham force) and given by

$$q\frac{\mathrm{d}\vec{d}}{\mathrm{d}t}\times\vec{B} + q\vec{d}\times\frac{\mathrm{d}\vec{B}}{\mathrm{d}t} \tag{11}$$

but only found a force due to the first term. Penfield and Haus showed that the second term does not exist and that Abraham's derivation was in error. Thus the derived force does exist and can be experimentally measured. However the solid crystal possessed a dipole moment larger than that of any gas suitable for propulsion and yet the forces produced in the crystal were of microscopic scale.

Propellant Survey

Looking at Eq. (5), the force is simply equal to the dipole moment time the magnetic field strength times the rotational frequency. A large dipole moment can increase the available thrust or reduce the required magnetic field strength and rotational frequency. In order to obtain an acceptable exhaust velocity (and, therefore, specific impulse) in a realistically sized thruster, the dipole acceleration must be above a minimum value. For a zero initial velocity the acceleration required to obtain a given exhaust velocity u_e is

$$a = u_e^2/2L \tag{12}$$

where L is the acceleration length. Assuming that a specific impulse of 1000 s would be required to make this a viable concept, and assuming an acceleration length of 20 cm, the required acceleration is 10^8 m/s^2. The dipole acceleration is the force divided by the mass or

$$a = (\mu/m)\omega B \tag{13}$$

Thus for a high specific impulse a large dipole moment to mass ratio would be required. Atoms do not exhibit permanent dipole moments but nonsymmetric molecules do. A permanent dipole moment is one that exists even in the absence of

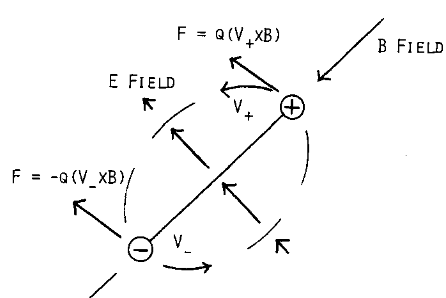

Fig. 1 Rotation of dipole molecule is induced by the electric field. Lorentz force on each charge is in the same direction and their sum accelerates dipole normal to the plane of rotation.

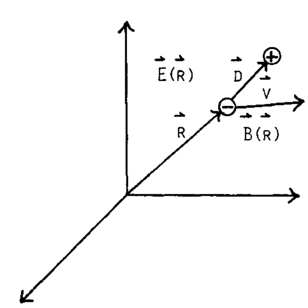

Fig. 2 Dipole representation in Penfield and Haus force derivation.

electric fields. Water (H_2O) has the highest permanent dipole moment to mass ratio of any naturally occurring molecule, 2.07×10^{-4} C·m/kg. Thus, to obtain an acceleration of 10^8 m/s^2, ωB must equal approximately 5×10^{11} T/s. The production of high-strength, high-frequency magnetic fields will be considered in the next section, however, due to the large magnitude of the required ωB, means of obtaining larger values of μ/m were examined.

Both atoms and molecules exhibit induced dipole moments when placed in an electric field. This dipole moment is given by

$$\mu=\alpha\epsilon_0 E \tag{14}$$

where ϵ_0 is the vaccuum permittivity. The induced dipole moment is proportional to the electric field strength with the proportionality constant called the polarizability, α. The polarizability has the dimensions of volume and is indeed proportional to the atomic or molecular volume. However, induced dipole moments have magnitudes less than the permanent dipole even at high electric field strengths. For example, water at a field strength of 10^6 V/m, the field ionization limit, has an induced dipole moment which is five and one-half orders of magnitude less than the permanent dipole moment.

There are various processes which can increase or decrease the dipole moment of a gas. Collisional processes will decrease the effective permanent dipole moment by disrupting the alignment of the dipoles with an electric field but do not affect induced dipoles which are not dependent on atomic or molecular orientation. The effect of collisions is described by the Debye equation,

$$\mu_{\text{eff}}=\left(\alpha\epsilon_0+\frac{\mu^2}{3kT}\right)E \tag{15}$$

where μ denotes the permanent dipole moment and μ_{eff} is the effective dipole moment due to induced and collisionally diminished permanent dipoles. For example, water vapor at room temperature in an electric field of 10^5 V/m will possess an effective dipole moment to mass ratio of 1.04×10^{-8} C·m/kg, four and one-half orders of magnitude less than the collisionless case. On the other hand, at high gas pressures the influence of electric fields generated by neighboring dipoles becomes comparable to the externally imposed electric field and the dipole alignment reinforces itself, increasing the effective dipole moment. However, the increase for gases as one goes to extreme pressures ($>10^8$ Pa) is less than a factor of 2.[6]

Since the polarizability α is proportional to the atomic or molecular volume, both macromolecules and small solid particles were considered. The problem with larger molecules is that the volume increases at the same or slightly lower rate than mass, and the ratio of dipole moment to mass decreases. The polarizability of a conducting sphere is equal to its volume but since the mass of a solid body will increase at the same rate as the volume solid particles will not produce increased dipole moment to mass ratios. Hollow spheres where the mass will increase as the square of the linear dimension were examined. It was found that a hollow aluminum sphere with a 0.01-μm shell thickness would have to be on the order of 1 cm diameter to equal the dipole moment to mass ratio of water. Hollow glass microballoons with a diameter of 300 μm gave results equivalent to a hollow alumium sphere of the same diameter.

In his 1981 paper,[2] Cox suggested the use of Rydberg atoms or molecules to obtain greatly increased dipole moments. A Rydberg atom or molecule is one where a valence electron is excited to a high energy level just below the ionization limit.[7] The lifetimes of such excited states are remarkably long ($>100\mu$s) and typically the principle quantum number of the excited electron $n>10$. Rydberg states are usually created by tuned laser absorption or electron collision excitation. In the presence of a weak electric field the excited electron will orbit exclusively on one side of the nucleus, forming a large permanent dipole moment. This contrasts with the induced polarization of an unexcited atom or molecule where an electric field simply causes a slight shifting of the entire electron cloud. The magnitude of the Rydberg-produced permanent dipole moment can be calculated from the quantum mechanics of hydrogen-like atoms (which Rydberg atoms are) and is given by Ref. 8.

$$\mu=\frac{3n(n-l)}{Z} \tag{16}$$

where Z is the net nuclear charge. Experimental evidence for the existence of these large permanent dipole moments for the alkali metals was published by Zimmerman et al.[9] Thus, it would appear that a means of increasing the dipole moment by a factor of 100 or more was available. However, as will be discussed subsequently, the maximum value of the product ωB which can be utilized in a rotating dipole thruster is limited by the ionization of the gas by induced electric fields which are proportional to ωB. For Rydberg atoms the field ionization potential decreases by $1/16n^4$. Thus the force on the dipole increases with n^2 while the maximum allowable electric field is proportional to $1/n^4$ with the result that the maximum acceleration which can be achieved by an alternating polarization thruster is reduced as the gas is electronically excited.

Rydberg states, although long lived, are easily destroyed either by collisions with other particles or by the absorption of electromagnetic radiation and resultant ionization. The energy needed for ionization is proportional to $1/n^2$ and the collisional cross section is proportional to n^4. Therefore, in order to avoid collisional ionization, operation at cryogenic temperatures would be required. The decreased ionization potential also gives Rydberg atoms the ability to be photoionized by backgroung infrared and submillimeter radiation, frequencies which are approaching the operating frequency of the alternating polarization thruster. Beiting et al.[10] demonstrated that Rydberg sodium atoms were photoionized by 300-K background radiation and that a thermal shield was required to prevent unintentional photoionization in experiments. Thus, an alternating polarization thruster utilizing a Rydberg gas would have to be thermally shielded from the remainder of the spacecraft.

As mentioned previously, the maximum acceleration that can be achieved with an alternating polarization thruster is limited by the value of ωB which will cause ionization of the propellant gas. The two ionization processes examined were field ionization and high-frequency ionization. The ionizing electric field can come from two sources: the electric field used to generate the alternating polarization or the electric field induced by the alternating magnetic field. The magnitudes of these two fields which can be generated in realistic devices will be discussed in the next section. Field ionization occurs when the electric field exerts a stronger force on the valence electron than the nucleus, and is able to remove the electron either directly or through tunneling.[11] This field strength is usually the higher of the two processes considered. High-frequency ionization occurs when stray electrons absorb energy from the alternating electric field and transfer it to the neutral particles through collisions. The transferred energy ionizes the neutral particle providing another stray electron to absorb energy. For the case where secondary emission from chamber walls does not occur the electric field strength required for ionization is given by[12]:

$$E=K_1\cdot p \tag{17}$$

for high pressures ($p>10^4$ Pa) and

$$E=\frac{K_2\cdot f}{p\cdot L} \tag{18}$$

for low pressures ($p < 10^3$ Pa) where K_1 and K_2 are constants, p the pressure, L a characteristic length, and f the frequency of the electric field. Thus operation at very high and very low pressures will discourage high-frequency ionization. In these cases field ionization will impose the maximum limit on the dipole acceleration.

Field Generation

The operation of an alternating polarization thruster requires the generation of alternating electric and magnetic fields. The electric field generates an alternating polarization and the magnetic field accelerates the dipole producing thrust. If the electric field is used only to induce permanent dipole rotation then it need not be very strong. However, if it is also used to induce a usable dipole moment in the gas large field strengths are required. The principle that an alternating magnetic field generates an alternating electric field can be used to avoid the necessity of separate means of generating electric and magnetic fields. For a unidirectional sinusoidally varying magnetic field which possesses radial symmetry such as the field produced within a solenoid, a tangential electric field is generated with maximum amplitude

$$E_{\max} = (r/2)\omega B_{\max} \tag{19}$$

where r is the distance from the axis of symmetry. This circumferential electric field can be used to induce dipole moments and rotation which can couple with an alternating radial magnetic field to produce gas acceleration in the axial direction. Current circulating in a pancake coil will produce a magnetic field with both radial and axial components (Fig. 3) and should theoretically produce a force on a dipolar gas. The most efficient means of providing a large current to the pancake coil would be through a tuned LC circuit, which has a natural frequency of $1/\sqrt{LC}$.

Let us recall the field strengths and frequencies required for a viable thruster concept. Neglecting collisions water requires a product ωB equaling 5×10^{11} T/s. If the magnetic field strength is assumed to be 1 T, this requires a frequency of 500 GHz. The magnetic field inside an ideal solenoid is given by

$$B = \mu NI/L \tag{20}$$

where μ is the magnetic permeability, N the number of turns, I the current, and L the solenoid length. Generating a field of the order of 1 T requires currents on the order of 10 kA circulating in a coil with a diameter on the order of 1 cm. The circumferential induced electric field would have a magnitude of 2.5×10^9 V/m which is larger than the field ionization potential of water (approximately 10^6 V/m). Thus water would be ionized and accelerated by plasmadynamic forces before the rotating dipole acceleration can occur. Smaller thruster dimensions which would decrease the required currents and the associated electric fields are not practical. Thus the use of water as a propellant does not produce acceptable acceleration levels.

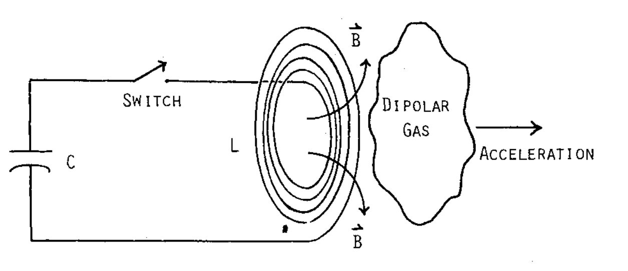

Fig. 3 Capacitor connected to pancake coil forming LC network and generating radial and axial magnetic fields. Alternating axial field induces dipole rotation which couples with radial magnetic field to accelerate dipolar gas.

Since the electric field ionization strength is the physical process limiting the acceleration of water, which is the naturally occuring molecule with the highest permanent dipole moment to mass ratio, light gases with high ionization energies were examined. Helium has an electric field ionization limit of approximately 10^{12} V/m, giving it the highest ionization energy per mass of any atom. The dipole moment for helium must be totally induced by an electric field since it possesses no permanent dipole moment. Taking this into account, the acceleration of helium atoms in a rotating dipole thruster is given by

$$a = 2.66 \times 10^{-16} E\omega B \tag{21}$$

Using the alternating magnetic field to induce the electric field, Eq. (18) can be substituted for the product of the frequency times the magnetic field strength to obtain

$$a = 5.33 \times 10^{-16}(E^2/r) \tag{22}$$

For the minimum required acceleration of 10^8 m/s^2 and a characteristic radius of 0.1 m the electric field strength is 1.37×10^{11} V/m, which is less than an order of magnitude lower than the field ionization limit and the ωB product is 2.74×10^{12} T/s. Thus helium appears to be marginally acceptable as a propellant if high-frequency ionization can be avoided before field ionization can occur. Reducing the thruster dimensions has the effect of decreasing the necessary electric field strength while increasing the required ωB. Once again the physical design is directed toward small size and large circulating currents.

The pancake coil shown useful for a rotating dipole thruster concept also has been utilized in the pulsed inductive thruster.[13] In that application the induced circumferential electric field is used to ionize the argon propellant gas. The gas then becomes conducting and the induced current interacts with the radial magnetic field generated by the coil to accelerate the gas away from the thruster. Since the pulsed inductive thruster is an extensively tested device capable of specific impulses of 2240 s and peak thrusts of 4.5×10^4 N, a comparison was made of the thruster performance while operating in the plasma and alternating polarization modes. Operating in the plasma mode the thruster produces an average gas acceleration of 2.5×10^9 m/s^2. The measured radial magnetic field strength was approximately 0.35 T at a radius of 0.35 m. The oscillation frequency was approximately 50 kHz. Using helium as the propellent gas, Eq. (21) gives an acceleration for operation in the alternating polarization mode of 5.6×10^{-7} m/s^2, 15 orders of magnitude less than when operating in the plasma mode. Comparison of the alternating polarization thruster with the metallic induction reaction engine[14] which also utilizes a pancake coil yielded similar results.

Conclusions

Alternating electric dipoles, either atomic or molecular, can interact with a synchronized alternating magnetic field to generate a force to accelerate the dipoles and produce thrust. The magnitude of this force, although small, has been derived for any dipolar substance and experimentally verified in a solid dielectric crystal. Estimates of the force obtainable utilizing naturally occurring substances as the exhaust medium proved too small for a viable thruster concept. Electronically excited or Rydberg atoms and molecules provide a proven means of increasing dipole moments. However, because the electric field ionization limit is decreased faster than the dipole moment is increased use in a rotating dipole thruster would not prove beneficial. When compared with current thruster concepts utilizing alternating magnetic and electric fields, the alternating polarization thruster produces accelerating forces many orders of magnitude less. The conclusion is that although the alternating polarization force exists its magnitude is too small to provide a viable thruster concept.

Acknowledgments

This work was sponsored by The Pennsylvania State University through its Provost Revolving Research Fund (PRRF) and by the Air Office of Scientific Research under Grant AFOSR-82-0196, Amendment A.

References

[1]Cox, J.E., "Electromagnetic Propulsion Without Ionization," *Journal of Spacecraft and Rockets*, Vol. 18, Sept. – Oct. 1981, pp. 449-456.

[2]Cox, J.E., "Shuttle Propulsion Using Electromagnetic Force Fields," AIAA Paper 81-1535, July 1981.

[3]Penfield, P. and Haus, H.A., *Electrodynamics of Moving Media*, Research Monograph 40, The M.I.T. Press, Cambridge, Mass., 1967, Chap. 3.

[4]Walker, G.B., and Walker, G., "Mechanical Forces of Electromagnetic Origin," *Nature*, Vol. 263, Sept. 30, 1976, p. 401.

[5]Walker, G.R., Lahoz, D.G., and Walker, G., "Measurement of the Abraham Force in a Barium Titanate Specimen," *Canadian Journal of Physics*, Vol. 53, Dec. 1975, pp. 2577-2586.

[6]Bottcher, C.J.F. and Bordewijk, P., *Theory of Electric Polarization, Vol. 1: Dielectrics in Static Fields*, Elsevier Scientific Publishing Co., New York, 1973, Chap. 5.

[7]Kleppner, D., Littman, M.G., Zimmerman, M.L., "Highly Excited Atoms," *Scientific American*, Vol. 244, May 1981, pp. 130-149.

[8]Bethe, H.A. and Salpeter, E.E., *Quantum Mechanics of One and Two-Electron Atoms*, Springer-Verlag, Berlin, 1957, Chap. IIIb.

[9]Zimmerman, M.L., Littman, M.G., Kash, M.M., and Kleppner, D., "Stark Structure of the Rydberg States of Alkali-Metal Atoms," *Physical Review A*, Vol 20, 1979, pp. 2251-2275.

[10]Beiting, E.J. et al., "The Effects of 300 K Background Radiation on Rydberg Atoms," *Journal of Chemical Physics*, Vol. 70, April 1979, pp. 3551-3552.

[11]Littman, M.G., Kash, M.M., and Kleppner, D., "Field Ionization Processes in Excited Atoms," *Physical Review Letters*, Vol. 41, July 1978, pp. 103-107.

[12]Brown., S.C., *Introduction to Electrical Discharges in Gases*, John Wiley & Sons, New York, 1965, Chap. 10.

[13]Lovberg, P.H. and Dailey, C.L., "Large Inductive Thruster Performance Measurement," *AIAA Journal*, Vol. 20, July 1982, pp. 971-977.

[14]Mongeau, P. and Kolm, H., "Metallic Induction Reaction Engine," AIAA Paper 82-1279, June 1982.