A COMPARISON OF TWO APPROACHES TO AN ELECTRIC PROPULSION SYSTEM*

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INTRODUCTION

Interest in high-velocity, high-current ion beams for injection into particle accelerators and attempts to solve the heating and containment problems, associated with controlled thermonuclear reactors, have led recently to considerable experimental work on the production of high-velocity matter. In the course of this work, results have been obtained which may be of significance to those interested in the possibility of very high specific impulse thrust devices.

This paper will review briefly two electrical systems for obtaining high-velocity directed mass motion of plasmas which, for convenience, may be arbitrarily referred to as thermal-plasma and magneto-plasma systems. Since both methods involve transfer of electromagnetic energy to a gas, they necessitate either prime sources of electricity or the conversion of other types of power into useful electrical power.

However, this paper will not discuss sources of energy as such.

GENERAL PROPERTIES OF AN IONIZED GAS

An ionized gas can be considered a plasma if it is electrically neutral; i.e. for a singly-ionized gas the number of ions in any macroscopic region is equal to the number of free electrons. For the purpose of comparison, it is convenient to think in terms of either a fully-ionized or slightly ionized plasma. The best criterion for distinguishing between the two is the electrical conductivity of the gas or, what is the same thing, the electron mobility among the heavy particles, i.e. ions and atoms.

For a fully-ionized, electrically-neutral gas in which the electron mobility is governed by coulomb encounters with ions, Spitzer and

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Härm⁽¹⁾ give the following expression for the dependence of the conductivity σ on temperature and electron density*:

$$\sigma = \frac{6{\cdot}5 \times 10^{-13}(kT)^{3/2}}{m_e^{1/2}e^2 \ln(l/b)} \text{ mhos/cm} \tag{1}$$

where k is the Boltzmann constant, m_e and $\dot{e}$ are the mass and charge of the electron l is the Debye shielding length and b is the impact parameter for a 90° deflection of an electron in a gas at temperature T. The Debye length is roughly the distance in the plasma over which ion and electron densities may differ due to thermal agitation of the particles. Spitzer⁽²⁾ gives:

$$l = 6{\cdot}90 \frac{T^{1/2}}{n_e} \text{ cm}$$

where n_e is the electron number density. The impact parameter b is given by:

$$b = e^2/3kT$$

For a partially- or slightly-ionized gas in which the electron mobility depends on electron-atom (close encounter) collisions rather than electron-ion (distant encounter) collisions, Chapman and Cowling⁽³⁾ give for the conductivity:

$$\sigma = \frac{5{\cdot}5 \times 10^{-13}e^2 \alpha}{(m_e kT)^{1/2}} \frac{1}{Q} \text{ mhos/cm} \tag{2}$$

where Q is the collision cross-section between electrons and neutral atoms and α is the fractional degree of ionization of the gas. For a gas in thermal equilibrium, α can be obtained from the Saha equation which relates the degree of ionization of a gas to the gas temperature, density and the particle-partition functions. If the measured conductivity agrees with equation (1), then one may call the gas "fully" ionized, whereas if the conductivity agrees with equation (2), then the gas can be classed as slightly ionized.

Lin, Resler and Kantrowitz⁽⁴⁾ have shown experimentally that the conductivity of *argon* is correctly given by equation (1) for $\alpha \geqslant 10^{-3}$; i.e. the distant, or coulomb, encounters between electrons and ions predominate over the close encounters between electrons and atoms. It seems reasonable, then, to assume that the electrical conductivity of any gaseous plasma which is more than 0·1% ionized can be calculated from the Spitzer–Härm expression, while equation (2) should be used when $\alpha < 10^{-3}$. When using equation (1) to calculate the conductivity, care must be taken to select the appropriate temperature. Usually, the *electron* temperature must be used since conduction is governed by electron mobilities.

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* Quantities in equations (1)–(4) are expressed in cgs–esu units.

For a plasma in thermal equilibrium $T_e = T_i = T_a$, where T_e, T_i and T_a are the electron, ion and atom temperatures, respectively. Under certain conditions of disequilibrium, however, T_e may differ significantly from T_i for times of laboratory interest because the exchange of energy between electrons and ions is inefficient due to the great disparity in masses. Thus, a large number of collisions is necessary between electrons and ions in order to reach thermal equilibrium. Generally, T_i is equal to T_a in all cases of practical importance, inasmuch as a Maxwellian distribution is produced after only a few collisions for two sets of particles of the same mass.

The case of $T_e < T_i$ occurs, for example, in the region behind a strong shock wave in a plasma because the shock front gives both the ions and electrons roughly the same velocity increment and hence the ions receive most of the energy. The energy is then redistributed to the electrons by collisions. This difference in temperature is also an important consideration when a plasma is accelerated by a magnetic field in a time short compared with the relaxation time for thermal equilibration between electrons and ions. On the other hand, in an electric arc or a spark discharge $T_e \geqslant T_i$. In this case the electric field exerts the same force on both the electrons and singly-ionized ions. The lighter electrons gain more speed between collisions than do the ions which can result in an electron temperature higher than the ion temperature. The ions are heated by collisions with the hot electrons. Any temperature difference between ions and electrons will decay with a characteristic time which depends upon the collision frequency between electrons and ions and the amount of energy which is transferred in each collision. It can be shown that the equilibration time t_{eq} between electrons and ions is:

$$t_{\text{eq}} = \frac{m_i}{m_e} t_{c,e} \text{ sec} \tag{3}$$

where $t_{c,e}$, the collision time of electrons with other electrons, is approximately:

$$t_{c,e} = 0{\cdot}025 \frac{T^{3/2}}{n_e} \text{ sec} \tag{4}$$

There are several reasons why the gas conductivity has such an important role in plasma physics. First, the interaction between a magnetic field and a plasma depends upon the currents in the plasma, which in turn are governed by the gas conductivity. Also, the skin depth to which an electromagnetic wave of given frequency can penetrate into the surface of a conductor, and the magnetic Reynolds number, which indicates the relative importance of magnetic and flow effects, both depend on gas conductivity.

In the absence of special constraints, the interior of a quiescent plasma cannot support a charge separation or an electric potential over distances much larger than the Debye length. Thus, assuming no currents and no instabilities, the forces which tend to expand a plasma are only gas-pressure forces. These are usually small compared to the electrical forces which arise if a region in an ionized gas is not electrically neutral. However, in recent work on containment of high-temperature plasmas in connection with controlled fusion research, it was noted the "micro" electric fields can exist in a plasma over distances considerably larger than the Debye length. The meaning of this electrical turbulence phenomena for plasma stability is not clear at the present time.

FLOW OF AN IONIZED GAS

In order to obtain an idea of the importance of hydromagnetic forces relative to ordinary hydrodynamic forces in the flow of an ionized gas, it is instructive to write the conservation equations, including hydromagnetic terms, in non-dimensional form. This transformation to non-dimensional quantities can be carried out for Euler's equation as follows. Including electromagnetic effects, Euler's equation is:

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + q\mathbf{E} \tag{5}$$

where ρ, $\mathbf{v}$, and p are the gas density, velocity and pressure; and $\mathbf{j}$, $\mathbf{E}$, and $\mathbf{B}$ are the current density, electric and magnetic fields, respectively. Assuming that charge separation cannot occur over a macroscopic region, q is zero and the last term vanishes. Letting the subscript zero refer to conditions at some reference position and primed quantities represent dimensionless ratios; i.e. $\mathrm{B}' = B/B_0$, $x' = x/L$ etc.; then equation (5) can be rewritten in the following non-dimensional form:

$$\rho \frac{\mathrm{D}v'}{\mathrm{D}t'} = -\frac{p_0}{\rho_0 v_0{}^2} \nabla' p' + \left[(\mu\sigma v_0 L)\frac{(B^2/2\mu)}{p_0}\right] j' \times B' \tag{6}$$

where μ and σ are the gas permeability and conductivity, respectively, and L is a length characteristic of the system. The quantity $\mu\sigma v_0 L$ is called the magnetic Reynolds number and $B^2/2\mu$ is the magnetic energy density or so-called "magnetic pressure", both expressed in the MKS system of units. For appreciable magnetic forces to be exerted on an ionized gas, the quantity in brackets of equation (6) should be on the order of or larger than the value of the coefficient of the gas pressure term $p_0/\rho_0 v_0{}^2$. Experiments performed in a shock tube⁽⁵⁾ with ionized argon have shown that a magnetic field will noticeably alter the luminous flow pattern if the bracketed quantity is greater than 0·4. In general when the product of the magnetic Reynolds number times the ratio of "magnetic pressure" to gas pressure is greater than unity, hydromagnetic effects will occur in a plasma.

THERMAL-PLASMA SYSTEM

Thermal-plasma systems refer to devices in which the enthalpy of a gas is increased by conversion of electrical energy into random particle energy by means of internal ohmic heating. If the heated gas is expanded through a nozzle into a region of lower pressure, the energy in random particle motion and the internal degrees of freedom, such as dissociation and ionization, can be recovered as useful thrust. Unlike ordinary chemical combustion in which the enthalpy added by the reaction is limited to the energy of the chemical bond, the enthalpy of the gas in a thermal-plasma system is limited only by the rate at which energy can be transferred to the moving gas by means of an electric field. In a practical device, ablation effects at material surfaces such as electrodes are a limiting factor.

The electric arc is the main example of a thermal-plasma device. The water stabilized arc⁽⁶⁾ has been extensively investigated in the past few years and more recently methods have been devised for stabilizing an arc by means of a gas flow⁽⁷⁾. The following discussion will be based on results obtained with gas-stabilized arcs at the Giannini Research Laboratory. These experiments were mainly concerned with the thrust characteristics of such devices and the results are similar to results obtained elsewhere with gas-stabilized arcs.

A diagram of a typical arc chamber is shown in Fig. 1. The gas is fed tangentially into the chamber, it is ionized and heated as it passes through the arc and then escapes through an orifice in one of the tungsten electrodes. Pressure gradients in the gas vortex tend to stabilize and constrict the arc. The constriction serves to increase the temperature above that obtainable with an ordinary arc. In these gas-constricted arcs, the temperature can be high enough so that at equilibrium the gas is 20% ionized. As discussed above the heavy particles in the gas, atoms and ions, are heated primarily by collisions with the energetic electrons which gain more energy from the electric field between collisions than do the ions. The rate at which thermal energy is transferred from electrons to the ions in these arcs can be estimated from equations (3) and (4). By manipulation of the gas density in the arc region, it is possible to have the gas temperature lower than the electron temperature, or the density can be high enough (gas pressure in the arc above 0·1 atm.) so that the electron and gas temperatures are essentially equal. In general, it is advantageous to have equilibrium between electrons and ions when the arcs are used as thrust generators.

The specific enthalpy of a monatomic gas in equilibrium is given by:

$$h = \frac{\gamma_0}{\gamma_0 - 1}(1 + \alpha)RT + \alpha I + \text{(elec. excitation)} \tag{7}$$

where γ_0 is equal to 1·67 and I is the specific ionization energy. The first term in equation (7) accounts for random particle motion of all the gas components (i.e. electrons, atoms and ions) and the pv work. The αI term represents the contribution of the ionization energy to the enthalpy. At the temperature usually obtained in arcs, the electronic excitation accounts for no more than 1 or 2% of the total enthalpy and can be neglected. Equation (7) can be generalized to include diatomic gases by the addition of a term giving the energy in dissociation.

A certain fraction of this enthalpy can be converted into useful directed mass motion if the gas in the arc region is expanded through a suitable nozzle. Assuming that the pressure in the jet at the nozzle exit is equal to the gas pressure outside of the jet, the specific impulse S.I. is related to the change in enthalpy across the expansion in the following manner:

$$\text{S.I.} = \frac{\sqrt{(2\Delta h)}}{g}\ \text{sec} \tag{8}$$

where h is expressed in mechanical units and g is the acceleration of gravity. This expression gives the most optimistic case for the specific impulse. Thus, a $\Delta h = 2 \times 10^8$ J/kg can ideally result in a specific impulse of 2000 sec. If the collision rate in the expanding gas becomes low enough due to the density and temperature decrease, the recovery of enthalpy is limited. For efficient recovery of the enthalpy during the expansion, the αI portion of equation (7) must also be recovered, but for sufficiently low density the recombination rate between electrons and ions becomes very small. This lowered rate leads to long recombination distances and effective nozzle lengths may become impractical. The problem is even more severe for hydrogen which will be dissociated as well as ionized by the arc.

Some experiments(7) have been conducted on the thrust characteristics of gas-stabilized arc devices. Enthalpy values of the gas were determined from the measured net power balance (i.e. the electrical input power, P_{in}, minus the power carried away by the cooling water, $P_{\text{H}_2\text{O}}$) and the mass flow rate $\dot{m}$:

$$h = \frac{P_{\text{in}} - P_{\text{H}_2\text{O}}}{\dot{m}} = \frac{P_{\text{gas}}}{\dot{m}} \tag{9}$$

Average stagnation enthalpy values of $8{\cdot}0 \times 10^7$ J/kg have been obtained experimentally in helium at a mass flow rate of 0·6 gm/sec without excessive burning of the tungsten electrodes. A reasonable upper limit for the enthalpy value of helium in the arc is perhaps three times this value. Aside from the question of atom recombination in the nozzle, hydrogen would appear to be a more desirable working gas than helium; because, for the same chamber conditions, hydrogen has a lower mass flow rate than helium. For the same power input, this results in a higher enthalpy. However, initial experiments show that severe electrode burning problems arise when pure hydrogen is used in the arcs. Table 1 gives some representative values of pertinent quantities from the thrust measurements in helium and argon. The thrust of the jet was determined by mounting the arc on a calibrated, cantilivered beam and measuring the deflection with and without the arc turned on. The specific impulse was determined from the measure thrust F and mass flow rate,

$$\text{S.I.} = \frac{F}{\dot{m}g}\ \text{sec} \tag{10}$$

Measurements of the radiant energy from the arc jet indicates that less than 5% of the total energy input to the gas is lost as radiation and hence radiation was neglected in the analysis of the data. It was noted in these tests that, in order to achieve the predicted value of gas exit velocity based on equilibrium gas flow considerations, it was necessary to add a constant-area nozzle after the front electrode as indicated in Fig. 1. At present the process occurring in the nozzle is not clearly understood; however, it is believed that the gas enthalpy is originally much higher along the central core of the nozzle than near the outside, as shown in Fig. 2. As the gas flows through the nozzle, the energy diffuses radially outward from the hot core until it intersects the growing boundary layer.

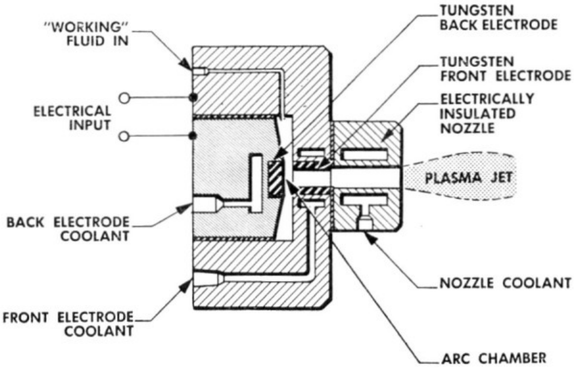

FIG. 1. A typical arc device for producing a high-temperature plasma jet.

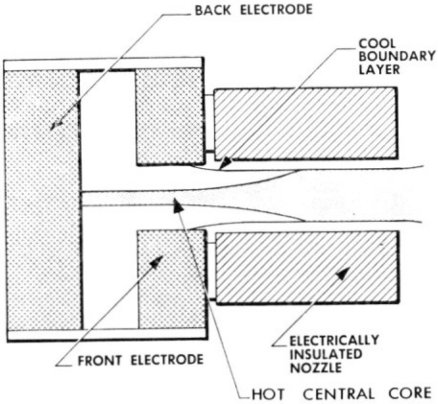

FIG. 2. Schematic diagram illustrating the outward radial diffusion of enthalpy as the gas flows through the nozzle.

TABLE 1

Typical results of thrust experiments using a continuous arc plasma jet

	Gas				
	Argon			Helium	
Electrical power input (P_{in}) kW	40	61	46	80	80
Mass flow rate (m) $\times$ 10^3 kg/sec	1·6	3·0	4·66	1·29	0·70
Specific enthalpy (h) $\times$ 10^{-6} J/kg	14	10	4	47	76
Thrust (F) Newtons	2·2	6·3	8·9	7·5	3·7
Thermal efficiency ($P_{\text{gas}}/P_{\text{in}}$)	0·55	0·52	0·41	0·75	0·66
Specific impulse (S. I.) sec (S. I. $= F/\text{mg}$)	140	214	195	590	535
Length of nozzle, in.	None	1	1	1/2	None

If the nozzle is long enough so that the gas is heated uniformly by this radial diffusion, then the value of specific impulse is expected to be a maximum for that particular set of arc parameters. Measurements under similar conditions with different length nozzles show that the specific impulse as determined from equation (10) and the gas exit velocity do increase to an asymptotic value as the length of the nozzle increases. These results agree with the consequences of the above model.

If the present jets were expanded into a low-vacuum region, the measured specific impulse would approximately double. Thus, specific impulse values of about 1200 sec should be possible at present with helium for a mass flow rate of about 1–2 gm/sec. Taking the factor of 3 mentioned above as a limit for increasing the enthalpy in helium, would indicate that thermal-plasma devices as they now exist are limited to specific impulses of about 2000 sec with a thermal efficiency $P_{\text{gas}}/P_{\text{in}}$, of 50 to 70%.

Missions analyses for trips to the Moon and nearby planets clearly indicate that the most advantageous range of specific impulse is 3000 to 5000 sec. These figures are based on values for the ratio of power plant mass to power plant output of 1–10 kg/kW, depending on the power level to be sustained. Thus, the thermal-plasma systems appear to be of definite interest for this range of specific impulse.

The disadvantages and problems associated with arc devices, aside from the present difficulties of obtaining a suitable source of electric power, mainly center around the heat lost to the arc container and ablation of electrodes and nozzle due to the extreme temperatures. For the most optimistic case the power lost to the container will be at least 25% of the input electrical power. The important parameter when considering electrode and nozzle burning or ablation rates is the power input/unit area of the front electrode orifice. There are reasons why it is advantageous to push the maximum power through the smallest hole possible, but unfortunately, this is incompatible with long electrode and nozzle life. At present it is possible to run arc jets with power densities of about 250 kW/cm^2 without lowering the specific impulse of the jet due to excessive metal ablation.

A possible practical method of reducing material ablation and heat transfer, especially along the nozzle walls, may be to use magnetic fields to channel the gas through the nozzle. For practiced nozzle dimensions the magnetic Reynolds number can be expected to be much less than unity because of the low velocity and conductivity of the gas (on the order of 10^3 m/sec and 1–10 mhos/cm) after it leaves the arc region. Therefore, in order to obtain appreciable effects, the "magnetic pressure" would have to be very high compared with the gas pressure. With present techniques, 3 Wb/m^2 (30,000 G) is an upper limit to the B field which can be obtained in a steady-state system over reasonable volumes without elaborate means for cooling the coils. In practice, the current which produces the magnetic field could be the same current which flows through the arc. The power dissipated through ohmic losses in the coil may be larger than the reduction in heat transfer to the nozzle walls. However the reduction in material ablation may still make such a scheme desirable,

MAGNETO-PLASMA SYSTEM

This term refers to methods of accelerating plasma by the interaction of currents in a gas with magnetic field produced by currents in fixed external conductors. The experiments described here all depend on transient rather than steady state interactions. These experiments separate into two groups: those in which the electric field producing the currents is applied directly between electrodes in the gas, and those in which the electric field is induced by a time rate of change of the magnetic flux in the gas. Three examples of the first group are shown schematically in Figs. 3, 4, and 5, and discussed below.

In the first example[8], illustrated in Fig. 3, a spark is drawn between two conductors in a vacuum on the order of 1 micron Hg pressure or

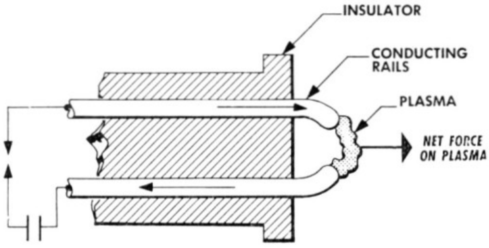

FIG. 3. An example of a magneto-plasma device utilizing electrodes.

less. The spark produces a plasma column consisting mainly of metallic ions and electrons. During the build-up of the current, magnetic forces exist in the plasma in a direction such as to increase the inductance, i.e. expand the circuit; and these forces project the metallic ions and electrons in the spark out from the electrodes. Velocities as high as 20 cm/μsec have been measured. In order to confine the plasma to motion in the axial direction, it is desirable to add a magnetic field parallel to the axis(9). This inhibits motion of the particles in the radial direction while the velocity in the axial direction is unchanged. In a similar experiment(10), a wire of about 0·02 mm diameter is placed on two parallel conducting rails and then vaporized and ionized by a sudden surge of current. The resulting metallic plasma is accelerated along the rails by the magnetic forces. In this work it was found that the self-pinching forces were not sufficient to confine the plasma, i.e. $B^2/2\mu \ll nkT$; so there is a rapid radial expansion of the vapor together with an acceleration of the center of gravity of the "wire" along the rails.

In a second example which has been studied extensively, the electrodes and the discharge region are arranged in a T-geometry as shown in Fig. 4(11). The return conductor is then placed directly behind the discharge region so that the spark plasma is accelerated out the side arm of the tube by the magnetic forces. The tube contains gas at a pressure on the order of 1 mm Hg. As the spark plasma moves into the gas, a shock wave develops on the leading edge of the spark. This shock wave is sufficiently strong to fully ionize the gas through which it passes, and essentially all of the gas can be ionized and expelled from the tube with velocities comparable to the shock wave velocity. Measurements indicate that shock velocities of 20 cm/μsec can be produced in this manner.

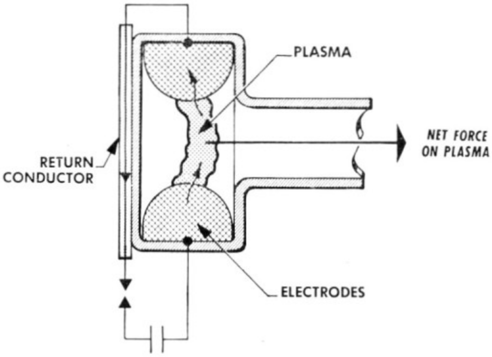

FIG. 4. A T-tube arrangement which uses the Lorentz force from the return conductor to accelerate the spark plasma.

Another geometry(12) which may have several advantages over the first two methods is indicated in Fig. 5. A uniform radial current sheet is drawn between the two coaxial conducting cylinders at the instant of discharge. A current sheet, instead of current filaments, can be assured by

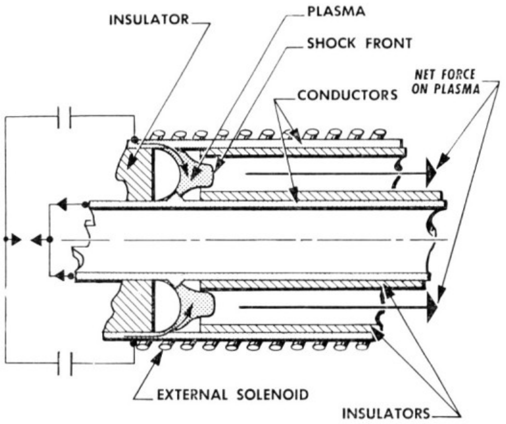

FIG. 5. A co-axial magneto-plasma device utilizing electrodes.

adjusting the value of the axial magnetic field produced by currents in the external solenoid, so that the electrons during the breakdown process have a large component of velocity in the $E \times B$, or θ direction. Thus, the electron cascade process does not appear to lead to bunching of the current. The current sheet, which is pushed down the tube by the increasing azimuthal magnetic field, acts as a piston and forms a shock wave in the gas. The axial magnetic field, trapped between the plasma and the conducting walls, keeps the particles from touching the walls of the tube. By this method gas velocities of 10–20 cm/μsec have been achieved.

Even though these gas velocities are very high and appear attractive from specific impulse considerations, sputtering of the electrodes results in serious practical difficulties for their use in a propulsion device. Sputtering of the metal roughens the electrode surface and leads to erratic breakdown behavior. This sputtered electrode material can also deposit on insulators and cause deterioration of the high-voltage insulation properties.

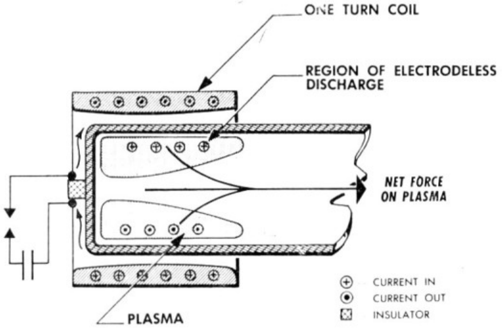

FIG. 6. An electrodeless magneto-plasma device.

These difficulties can be largely eliminated by inducing an electrodeless discharge in the gas and then adding energy by means of ohmic heating and work through electromagnetic forces. The method illustrated in Fig. 6 has been investigated at the Giannini Research Laboratory and elsewhere(13, 14). A low-inductance condenser system is discharged through a circular single-turn conductor. The rapid build-up of the magnetic field due to the current surge through the ring induces an electric field which breaks down the gas in the tube and produces circular current loops in the gas. These current sheets are in the opposite sense to the currents in the external conductor. The magnetic field is confined to the region between the external conductor and the plasma current sheets and the magnetic pressure implodes the ionized gas inwards towards the axis. After the implosion reaches the center, the gas expands symmetrically outward along the axis from the coil region. Measurements of the plasma shock front by streak cameras show that velocities as high as 10 cm/μsec can be produced. For use as a thrust device, the coil and insulating tube can be so arranged that the expansion can take place in one direction only. So far the percentage of gas accelerated to this shock velocity has not been determined; but the average directed velocity of all particles during one pulse is probably much lower than this value of 10 cm/μsec. Thus, the effective specific impulse of such a device is likely to be considerably less than the 10,000 sec which would be calculated on the basis of a velocity of 10 cm/μsec.

For transient magneto-plasma experiments, the quantity

$$\left(\frac{B^2/2\mu}{p_0}\right)(\mu\sigma v L)$$

is much larger than 1. Typical values for the magnetic fields produced are above 5 Wb/m^2 (50,000 G), which corresponds to a magnetic presure of about 100 atm; the gas pressures are usually on the order of 1 atm or less. The conductivity of the ionized gas can be calculated from equation (1). For hydrogen at a kinetic temperature of 10^{5}°K, the electrical conductivity is over 10^3 mhos/cm. Even though the linear dimensions of the device are small, the value of the magnetic Reynolds number may exceed 10^2. It follows that the hydromagnetic effects are the dominant accelerating mechanism in these experiments.

This brief review of magneto-plasma experiments gives a description of laboratory devices and the range of plasma velocities which have been produced by such devices. A more careful look must be taken in order to determine the possible usefulness of such techniques in a propulsion system. All of the experiments discussed utilize a condenser system essentially as a power transformer; i.e. a condenser is charged slowly at low-power levels and then discharged in a time short compared to the charging time. By this technique, power levels up to 10^{12} W can be put into the gas during the discharge. Condensers would add greatly to the mass of any propulsion device using a magneto-plasma accelerator. However, it is difficult to give an accurate estimate of this additional mass inasmuch as the mass of the condenser system, relative to the mass of the electric power plant, depends greatly on the type of power source to be used and on the thrust level to be maintained.

An even more serious limitation is the short lifetime of the high-current switches, such as spark gaps, which would be necessary for pulsing current through magneto-plasma accelerators. Spark gaps, due to sputtering of electrodes, have a very short lifetime in terms of the number of reliable discharges. Although use of ignitrons can give a factor of 100 or so in reliability over spark gaps, they still fall short of the necessary requirements for propulsion systems (i.e. a service life of $10^6 - 10^{10}$ pulses) by a factor of at least 10^3.

In addition, the thermal efficiency of these pulsed magnetic accelerators is still unknown and may be very low.

Some rough experimental determination of thermal efficiency should certainly be made before serious consideration is given to such devices as useful propulsion systems. Finally, measurements are needed of the thrust and specific impulse which are attained.

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