ELECTROHYDRODYNAMICS

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"Proposal to Develop Practical Military, Space and Research Applications of Electrohydrodynamics as related to

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Energy Conversion - electrical to mechanical
Fluid Pumping - no moving parts
Hard Vacuum Pump - 10^{-1} mm. Hg, or better
Continuous Particle Gun - 120,000 fps meteorite simulator
Electric Power Generator - flame-jet generator

(Prepared by Seabrook Hull & Associates, March 4, 1960)

Supplement B

"Theory of an]on Wind Device" by Robert F. Seaton, Capt, USAF
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ELECTROHYDRODYNAMICS

(EHD)

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ELECTROHYDRODYNAMICS

PART I

DEFINITION

The term "electrohydrodynamics" has come into use recently to distinguish a certain class of phenomena from the more general regime of "magnetohydrodynamics". The term may be considered to be synonymous with the rather elaborate term "electrostrictive hydrodynamics".

In general, the phenomena relate to the conversion of electrical energy into kinetic energy and vice versa.

In the first instance, shaped electrostatic fields create hydrostatic pressure (Or motion) in dielectric media. When such media are fluids, a flow is produced. The flow can be directed against the electrodes, generally to move the electrodes. In such case, the moving structure acts as a "motor".

In the second instance, the converse takes place. A powered flow of medium within a shaped electrostatic field adds energy to the system which is picked up as a potential difference by electrodes. In such case, the structure acts as a "generator".

THEORY

The theory underlying these phenomena is not entirely clear. An appropriate reference *1 discloses the following:

"The system of stresses in dielectric media ... may be supposed to consist of

(I) A tension $\frac{KR^2}{8\pi}$ per unit area in the direction of the lines of force;

(ii) A pressure $\frac{KR^2}{8\pi}$ per unit area perpendicular to the lines of force,

(iii) A hydrostatic pressure of amount $\frac{KR^2}{8\pi} \tau \frac{2K}{2\tau}$ in all directions."

*I The Mathematical Theory of Electricity and Magnetism, Sir James Jeans, Cambridge University Press, 1951; p. 177

Sir James Jeans further notes:

> "(this) system of stresses... was first given by Helmholtz. The system differs from that given by Maxwell by including the pressure
>
> $$-\frac{KR^2}{8\pi}\tau\frac{2K}{2\tau}$$
>
> "The neglect of this pressure by Maxwell, and by other writers who have followed him, does not appear to be defensible."

It is to be pointed out that in (iii) a hydrostatic pressure results from an electric field which, if the term $\frac{2K}{2\tau}$ is negative, acts outwardly "in all directions",

A gradient in plasma density and, hence, a gradient in unquestionably exists throughout the shaped electric fields present in these experiments. This may be sufficient to account for a part, at least, of the observed forces. Polarization of certain molecules of the fluid must also be considered where dielectrophoresis is involved, but these forces are generally contra-directional . Additional direct acting forces, not represented in the above, result from the transfer of momentum from ions to the host medium .

ELECTRODE GEOMETRY

Regardless of the adequacy of the theory at this stage,, the experimental results show the need of a unique geometry in the "shape" of the electrostatic field,

These fields must be non-uniform, such as those created by arcuate or annular electrodes of differing size, for the specific purpose of causing maximum electrostriction in the fluid medium.

NEW PRINCIPLE OF LIFT

In applying the principles of electrostrictive hydrodynamics (electrohydrodynamics) it is immediately clear to the aeronautical engineer that a large electrode area is required. Just as a sailboat uses a sail, any vehicle utilizing electrohydrodynamic propulsion must employ a large ballistic electrode to integrate the pressure of plasma "winds" to provide lift or forward thrust.

These so-called "electric winds" are ion flows, moving at relatively high velocity. The flows may take various patterns determined by

1) The manner in which the flows are generated, and
2) The curvature of the surfaces which confine them.

In the case of a large arcuate electrode with small axial electrode near its focus, the flow pattern is a toroidal vortex, like a whirling smoke ring. This is an effective aerodynamic pattern to produce the desired results.

Hydrostatic pressure (Or aerodynamic pressure, if one prefers) is exerted against the entire inner surface of the large arcuate electrode, and the integrated pressure creates a mechanical force which propels the entire structure in one direction.

MAY BE OPERATIVE IN SPACE

It is conceivable that the electrohydrodynamic drive will be effective wherever an ambient plasma Is present. Hence, according to latest concepts, this includes a great part of outer space where the attenuated solar corona is believed to extend. In every case,, momentum is transferred to the surrounding medium however tenuous. The surrounding medium would be Influenced for some distance on all sides of the proposed craft and would be propelled in the opposite direction. Thus it may be concluded that, In outer space, momentum is conserved without the expenditure of a working fluid.

ELECTROHYDRODYNAMICS

PART II

A PROPOSAL FOR SPACE PROPULSION

RECENT ADVANCES:

Recent advances In plasma dynamics have revealed a number of methods for accelerating regions of highly ionized gas, Such methods usually involve electric and magnetic coupling operating for extremely short periods of time. Pulses or "bursts" of plasma, produced by an electrical discharge, pass through an accelerating region and are ejected at high velocity,

Examples of these methods are the button or rail-type gun and the magnetohydrodynamic shock tube, Although the plasma velocities from such devices may be of the order of Mach 100, the mass of the individual plasmoids Approximately 10^{-9}grams) is extremely small . Hence,, the momentum of the individual plasmoids and the reactive thrust upon the system is small, For space propulsion, such systems have the intrinsic disadvantage that the weight of the magnetic structure is ordinarily so great as to make the device unattractive as an ultimate solution.

For the last several years, exploratory work has been carried forward by WHITEHALL-RAND in the related field of electrostrictive hydrodynamics, It is perhaps more accurate to refer to this field as the regime of electrohydrodynamics, for the reason that it is distinguished from the regime of magnetohydrodynamics by the virtual elimination of magnetic elements. It must be recognized, of course, that in the electrostrictive reactions substantial currents are flowing; hence, magnetic fields are present, but the hydrodynamic consequences are largely of electric rather than of electromagnetic origin,

Studies were first undertaken of electric field shaping for the production of forces and motion in fluid dielectrics. These studies were extended to cover in a more general way the stresses developed in dielectric media and their dependence upon density, dielectric constant, dipole moment., et cetera, It was shown that ionized gases or plasma behaved as dielectric media developing hydrostatic pressures upon the electrode structure In a way which would appear to indicate that the dielectric constant of the plasma was directly related to its ion density.

EFFECTS IN VACUUM:

Studies were then undertaken of various electrode shapes, both of the cathode and anode, to obtain:

1) Highest plasma densities in air (and other gases) in the -pressure range from 1 atmosphere to .001 microns

2) Greatest net hydrostatic pressures upon both electrodes in the same direction

It became clear at this stage that the idealized electrode structure included an anode of bi-arcuate or tri-arcuate shape; in other words, helmet shaped. The cathode, much smaller in size (preferably annular or ring-shaped) is positioned concentrically within the helmet anode and aligned with its rim. Heating the cathode to incandescence greatly increases the plasma density in the region between the two electrodes. Bleeding alkali vapor into the region near the cathode further increases the plasma density. The anode and the cathode are mechanically tied together by a ceramic spacing member.

When electrically energized to the limit, just under electrical breakdown, high density plasma is generated in the region immediately adjacent to the incandescent cathode where the electric field density is greatest, By highly effective electrostriction due to the unique geometry of the field, the plasma is accelerated toward all portions of the concave anodic surface, creating hydrostatic pressure against said surface. It is within this region, extending outward to the periphery of the anode, that the plasma receives its principal acceleration. It is then driven beyond the rim and flows with high velocity in a circuit back to the cathode. The flow pattern takes the form of a toroidal vortex. Contact by conviction with the ambient plasma forces the ambient in direction opposite to that of the hydrostatic pressure acting upon the surface of the anode. This is required for conservation of momentum.

It has thus become clear that the arcuate anode experiences a net thrust due to what may be equivalent to aerodynamic pressure; hence, it becomes a type of airfoil capable of lift.

Tests in a vacuum chamber up to .001 microns have revealed a remarkable constancy of this lift with diminishing pressure. Two inter-related possibilities may provide an explanation:

1) The ion density of the plasma, as represented in terms of dielectric constant, does not decrease with pressure, and

2) The plasma velocity increases with the mean free path.

Static pressures at various points on the concave side of the arcuate anode are readily measured by manometers. A pressure profile for any given anode shape can thus be obtained. It is noted that the integrated pressure derived from any profile agrees remarkably well with the observed static thrust, With an arcuate anode or so called "canopy" 80 cm. diameter, the thrust at 250 KV and 2 ma, is of the order of I 10,000 dynes.

110% COUNTERBARY

This thrust, acting as lift, causes a tethered model weighing about 100 grams to hover in the air, lifting not only its own weight but supporting a "payload" of 10 grams.

ADVANTAGES

The apparent advantages of electrohydrodynamic drive over magnetohydrodynamic drive for space propulsion are:

1) Greater thrust by several orders of magnitude

2) Propulsion structures lighter in weight because of the elimination of magnetic components.

3) Steady-state operation

4) When utilized in conjunction with a flame-jet electrostatic generator and cesium-seeded fuels, a tolerable electrical efficiency and a substantial reduction in power plant weight

Flame-jet electrostatic generators should therefore be considered a necessary companion development.

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PART III
A VEHICLE EMPLOYING ELECTROHYDRODYNAMIC PROPULSION

AS AN AERO-MARINE VEHICLE

Before flights through the plasma of space can be seriously considered, many problems must be solved which are beyond the scope of the present proposal . In the early stages of this particular development, much may be learned from flights in the atmosphere at low altitudes. An experimental prototype is suggested which has a good chance of being made operational in surprisingly short time.

For a clearer understanding of the vehicle illustrated, the following description is limited to its operation at a height of 35 to 50 feet above the surface of water.

To begin with, such a vehicle when not in operation would rest upon its spherical pontoons. Takeoff would be accomplished in two stages:

1) Using the flame-jet alone (without electrical excitation), sufficient positive pressure would be built up under the canopy to make the craft airborne and to lift the pontoons out of the water. This provides the additional air-gap needed when the high voltage is later applied. During this stage the action of the flame-jet is similar to that of a ducted fan.

2) The flame-jet is then electrically excited by energizing the needle cathode. This produces an Intense electrostatic field and initiates the plasma vortex, as will be described in detail later. Motion of the plasma provides additional positive pressure which results in further lift.

The craft is then made to rise to a height, let us say, of 35 to 50 feet bul no higher. This can be readily controlled because lift at these levels diminishes with elevation. In other words, lift is a function of vortex velocity which, in turn, is inversely related to elevation at these lower levels. Hence, for a given applied power, a craft will hover at a given height. Horizontal stability is automatically provided for the same reason. Horizontal thrust in any direction is provided by canting the conic sections of the flame-jet generator.

THE ELECTRICAL GENERATING SYSTEM

The so-called flame-jet Generator operating by the electrohydrodynamic (EHD) principle, is the converse of the propulsion system. In the generator, kinetic energy (from the high velocity flame plasma) is converted into electrical energy. In the propulsion system the electrical energy is converted back Into kinetic energy. This is done by accelerating to high velocity the toroidal vortex which produces pressure against the canopy. This results in lift and propulsion.

The flame-jet generator is positioned in the axis of the anode canopy. In this position the conic electrodes of the flame-jet,, together with the main body and outer reaches of the flame plasma, constitute the "total cathode" of the propulsion system.

The flame may be powered in any one of several ways; such as by kerosene or other liquid fuels, solid rocket propellants and - perhaps ultimately - by thermonuclear plasmas. In any case, the flame issues from an orifice and passes through a series of collector electrodes which are electrically insulated one from the other.

The generator is initially excited by emitting electrons into the flame plasma near the orifice. This is done by means of an incandescent needle cathode, maintained at about 30 KV, centrally located in the axis of the flame stream. As the high density plasma with its net negative charge passes through the orifices of the frusto-conical collector electrodes, negative charges are imparted to these electrodes so that an electric gradient is developed upon these electrodes. The electrical potential increases with distance downstream, conceivably reaching limits of several million volts. This high negative potential appears not only upon the collector electrodes but in the outer reaches of the main body of the flame plasma itself. Adequate current to meet the power demands of the vehicle even at these high potentials is provided from the kinetic energy of the high density flame plasma.

To increase the plasma density, not only in the flame-jet but also in the propulsion syste m associated with it, the liquid fuel may be "seeded" with powdered cesium, or alkali vapor may b e "bled" into the combustion chamber or introduced thru louvers from the anode canopy.

MAIN PROPULSION SYSTEM

Due to the unique geometry of the anode canopy with relation to the axial placement of the incandescent high potential cathodes surrounding the flame, a second flow of high density plasma is created toward the entire under surface of the (anode) canopy.

The force which accelerates this plasma operates within the region between the principa l electrodes and is spread throughout all of the space under the canopy, Within this region a larg e volume of plasma is accelerated to very high velocity, The momentum of the plasma then carries it beyond the periphery of the canopy and outward (as much as three diameters) into the -ambien t plasma, It then veers downward and back to the cathodic axis, where it is again accelerated. Thi s flow pattern is essentially that of a very large toroidal vortex, It is to be noted that the canopy, in effect, is riding upon the vortex with aerodynamic pressure acting at all points against the underside of the canopy to lift and sustain it. There is, of course, a reactive force resulting from the mechanical action of the flame-jet itself, and this force tends to lift the vehicle. A further contribution to lift comes about because the flame-jet acts as a ducted fan, creating static pressures on the underside of the entire canopy. Additional static pressure against the canopy results from the fact that the axial (downward) flow of the flame-jet bucks the upward axial flow of the toroidal vortex. The net result of these bucking flows is to further increase the static pressure under the canopy.

FLIGHT CONTROLS

One of the principal advantages of this form of propulsion is its simplicity of control. Fuel is valved as needed to lift the craft to a given altitude. Horizontal thrust in any direction is provided, as stated before, by canting the cathodes. At low altitudes horizontal stability is self-maintaining after the plasma vortex has been established. Soft vertical landings are accomplished by gradual reduction in the rate of fuel supply.