

Colloidal Electrohydrodynamic Energy Converter

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The colloidal EHD energy converter changes the random, thermal energy of a slightly ionized, superheated vapor to directed kinetic energy and then to electrical energy at high potential. A high conversion efficiency is theoretically possible if the working fluid, and conditions are chosen so that the neutral atoms condense on the ions. The neutral flow thus increases the momentum of the ions that are being pushed against a retarding electrostatic field. Some of the energy of the flow reverts to heat in the condensation process and must be radiated by the growing, colloidal ions. The transit region between the nozzle and the high-potential collector of this generator is also its radiator. Experimental study of the formation of colloidal ions by this controlled-growth process indicates that colloid energy conversion is feasible. Power losses will occur if expansion and condensation of the vapor are poorly regulated, if radiation is too slow, or if space charge is not controlled. With proper design and selection of the working fluid, the colloid power generator should achieve 2.5 lb/kwe at comparatively low temperatures. This generator is well suited for operation of electrostatic propulsion engines, since it directly produces high-voltage electric power.

Introduction

HISTORICALLY, numerous studies of fluid-carrier, charge-transport generators have been conducted during the past 50 years.¹ The more recent efforts have centered their attacks on two fundamental problems: 1) friction losses due to slip between the main gas flow and the charged particles; and 2) beam expansion resulting from space charge.

The first problem can be solved by employing heavy ions or a carrier gas at high pressure.² These approaches reduce ion mobility, thereby increasing the efficiency of use of the kinetic energy of the fluid carrier. Unfortunately, the reduction of ion mobility aggravates the space charge problem, because the lower ion velocities effectively increase the ion concentration associated with a given current density.

One method of reducing the space charge problem is to operate with a very short transport region.³ In this way, the ions can reach the collector before ion losses from beam expansion become too severe. Such a short transport region does not permit the development of very high voltages in a single stage (<50 kv). In this case, the power consumed in ion production may become significant. Also, the higher total currents that must be carried for a given power level either will incur greater space charge due to the higher current density or require a large number of generating units.

It has also been suggested that the effects of space charge may be counteracted by means of focusing fields.⁴ The requisite field effects depend on the ion velocities and current densities.

The requirements of a power converter for use in space are even more stringent than for terrestrial applications because of the importance of high specific power for the total power system and the enhanced need for long-term reliability. For the operation of electrostatic propulsion engines, the power system must also deliver power at high voltage. Most EHD power converters operate with few moving parts and should, therefore, provide reliable performance for a long period of time. High-voltage power is the direct output of EHD generators. To avoid internal electrical breakdown, however, high pressures or very low pressures are necessary. High pressures in space operation require heavy container construction in the transit region and for the radiator, thus

reducing the specific power of the system. An EHD power conversion unit operating at low pressure appears admirably suited to space power needs, if a lightweight system can be devised.

The specific power of a space power system depends principally on the efficiency of the conversion process, the power density delivered, and radiator requirements. In the following sections, the operation of a colloidal EHD energy converter is described and then discussed with a view to achieving high specific powers.

General Concept

The colloidal EHD energy converter is based on the principle of the conversion of thermal energy to directed kinetic energy and then to electrical energy at high potential. Such an energy transformation can be performed with a comparatively high efficiency by a controlled-growth colloid generator. In this device, a condensible vapor passes through a supersonic nozzle under conditions that produce a high degree of supersaturation in the expanded flow. If a small portion (10^{-2} to 10^{-7}) of the vapor is ionized before entering the nozzle, these ions act as highly effective nuclei for condensation of the expanding, supersaturated vapor. The charged nuclei grow as a result of collisions with uncharged molecules which result in condensation. This growth occurs in the region between the throat and an insulated collector. As the charge on the collector builds up, it retards the oncoming colloidal ions so that they remain in the transit region a longer time and experience more condensing collisions. The greater number of collisions increases the momentum of the charged particles, driving them against the increasing retarding field. When practically all of the high-speed gas atoms in the growth region are condensed by collisions with the decelerated charged particles, the generator has reached its operating voltage. Further increase in voltage would cause a reduction in the current of colloidal ions, since there is no more gas to augment the momentum with which the charged particles approach the collector. The voltage and current that the controlled-growth colloid generator can produce are thus determined by the charge-to-mass ratio of the vapor issuing from the throat of the nozzle.

In the process of condensation, heat is produced. This heat increases the temperature of the growing colloidal particles. If the temperature becomes so great that the vapor pressure of the colloids is greater than that of the surrounding gas, the particles will re-evaporate. Cooling, resulting from an isentropic expansion, can balance the heat produced by

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condensation of only about 40% of the gas flow. If the particles in the growth region of the generator can radiate the remaining heat of condensation, they can condense virtually all of the vapor in the vicinity of the collector. Since colloidal particles have high ratios of surface area to mass, they are able to radiate heat effectively.

Performance of the Controlled-Growth Colloidal Ion Source

The concept of the controlled-growth colloidal ion source has been considered for application in electrostatic propulsion engines, and a detailed theoretical analysis of its method of operation was developed.⁵ A brief summary of this analysis is presented in the following paragraphs, along with experimental data obtained using the apparatus represented schematically in Fig. 1.

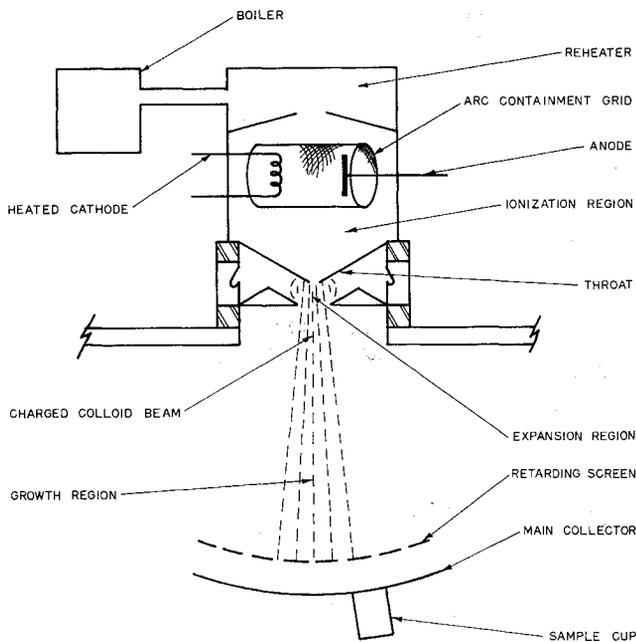


Fig. 1 Experimental controlled growth colloid source.

The mass flow rate is governed by the area of the throat of the supersonic nozzle. To provide sonic flow at the throat, the throat temperature must satisfy the following equation:

$$T_t = p_t^2 A_t^2 \gamma M / \dot{m}^2 R \quad (1)$$

where

- T_t = gas temperature in the throat, °K
- p_t = gas pressure in the throat, dyne/cm²
- A_t = cross-sectional area of the throat, cm²
- γ = heat capacity ratio = C_p/C_v
- M = molecular weight of vapor, g/mole
- \dot{m} = mass flow rate, g/sec
- R = molar gas constant = 8.32×10^7 erg/°K-mole

Since a very low temperature is desired after expansion from the throat, the lowest possible vapor temperature, the temperature of the saturated vapor, should be employed at the throat. This condition provides a unique value, given by the vapor pressure relation, for the most favorable temperature and pressure at the throat for any given substance.

In the preliminary experiments that have been performed, mercury was used. Its vapor pressure is given by the following equation:

$$\log p = 13.498 - (3308/T) - 0.8 \log T \quad (2)$$

Using Eqs. (1) and (2) and selecting 2×10^{-2} cm² for the

throat area and 2.27×10^{-3} g/sec for the mass flow rate in the experiments, the temperature and pressure at the throat were predicted.

The flow conditions in the arc chamber, preceding the throat, are given by the laws applicable to adiabatic, isentropic flow:

$$T_c = T_t [(\gamma + 1)/2] \quad (3)$$

$$p_c = p_t [(\gamma + 1)/2]^{\gamma/(\gamma-1)} \quad (4)$$

where

- T_c = gas temperature in the arc chamber, °K
- p_c = gas pressure in the arc chamber, dyne/cm²

For the given experimental setup, the temperature and pressure of the gas in the arc chamber should be 520°K and 2.18×10^3 dyne/cm² (1.64 mm Hg).

If the average current experimentally measured on the main collector (1×10^{-9} amp) is regarded as the total ion current flowing from the throat, the charged particle flow rate can be calculated, assuming the particles to be singly charged. This value is 6.2×10^9 particles/sec. Since the current issues from a 2×10^{-2} -cm² throat, the current density at the throat is 5×10^{-8} amp/cm². The nozzle provides a 100:1 area ratio for the expansion, and if the nozzle governs the total expansion, the cross-sectional area of the beam will be 2 cm². On this assumption of perfect beam collimation, the current density in the beam should be 5×10^{-10} amp/cm². The particle mass and radius, calculated from the charged particle flow rate and the mass flow rate, are 3.6×10^{-13} g/particle and 1.86×10^{-5} cm, respectively, and the charge-to-mass ratio of the particles is 4.4×10^{-4} coul/kg.

If one assumes a condensation coefficient of one, the minimum time required for sufficient collisions to cause a particle to grow to a radius of 10^{-5} cm is 0.26 sec, as computed from the following equation:

$$t_f - t_i = \frac{9A_e Q_p}{24a_x^2 \pi I_b} \left[\ln \frac{a_x^2 + a_x r + r^2}{(a_x - r)^2} + \frac{6 \tan^{-1} (2r + a_x)}{3^{1/2} a_x^{3/2}} \right]_{r_i}^{r_f} \quad (5)$$

where

- a_x = $(3\dot{m} Q_p / 4\pi \rho_{\text{con}} I_b)^{1/3}$
- t_f = final time at end of transit through growth region, sec
- t_i = initial time at start of transit through growth region, sec
- A_e = cross-sectional area of beam, cm²
- Q_p = charge on a particle, coul
- I_b = beam current, amp
- r = radius of particle, cm
- r_f = final radius of particle, cm
- r_i = radius of critical sized nucleus, cm
- \dot{m} = mass flow rate, g/sec
- ρ_{con} = density of condensed phase, g/cm³

The time required to eliminate sufficient heat for the particles to be in equilibrium with the vapor at the final pressure of 5×10^{-5} mm Hg (average pressure in vacuum tank in the region of the retarding potential electrode) was evaluated. The following equation was employed to compute the amount of material which should have condensed as a result of the temperature drop due to the isentropic expansion:

$$S_e = S_c = \int_0^{T_s} C_s \frac{dT}{T} + \frac{\Delta H_f}{T_s} + \int_{T_s}^{T_{\text{eq}}} C_m \frac{dT}{T} + n_g \frac{\Delta H_{\text{vap}}}{T_{\text{eq}}} - n_g R \int_{P_s}^{P_{\text{eq}}} d \ln p \quad (6)$$

where

S_e	= entropy of the exhaust material, cal/deg-mole
S_c	= feed entropy, cal/deg-mole
T_s	= standard temperature = 298°K
C_s	= molar heat capacity of solid phase, cal/deg-mole
ΔH_f	= molar heat of fusion, cal/mole
T_{eq}	= equilibrium temperature, °K
C_m	= molar heat capacity of the melt, cal/deg-mole
n_g	= fraction remaining uncondensed, mole
ΔH_{vap}	= molar heat of vaporization, cal/mole
R	= molar gas constant = 1.98 cal/deg-mole
p_{eq}	= equilibrium pressure, dyne/cm ²
p_s	= standard pressure = 760 mm Hg = 1.012×10^6 dyne/cm ²

Approximately 50% of the material would condense from this effect alone. Further cooling and condensation must then depend on the rate of heat elimination by radiation, as given by the Stefan-Boltzmann equation

$$-dE/dt = 4\pi r^2 \epsilon \sigma T^4 \quad (7)$$

where

dE/dt	= rate of change of energy content of a particle, joule/sec
r	= radius of particle, cm
ϵ	= emissivity of a particle
σ	= Stefan-Boltzmann constant = 5.7×10^{-12} joule/cm ² -sec-deg ⁴
T	= absolute temperature, °K

Using an emissivity of 0.1 for mercury indicates that about 1 sec would be required for each particle to eliminate enough heat to grow to a radius of 10^{-5} cm and exist in stable equilibrium with the vapor at 5×10^{-5} mm Hg. Since some evaporation probably occurred simultaneously with the growth of these large particles, resulting in convective cooling, the actual time required for the growth process should be between 0.3 and 1.0 sec. To keep the particles in the growth region for this period of time would require a much higher retarding field than the 2500 v applied. Either the space charge of the particles produced a potential hill greater than the applied field, or the actual growth and radiation processes are more rapid than indicated by this simple analysis.

Electron microscope examination of particles collected in a shuttered sample chamber (Fig. 2) show an average particle mass of 3.4×10^{-13} g and an average charge-to-mass ratio of 4.8×10^{-4} coul/kg, if singly charged particles are assumed. These values agree well with the results obtained from the current and mass flow rate data.

The performance just described was obtained with the arc geometry shown in the schematic representation of the experimental device (Fig. 1). Other methods of ionization and other nozzle designs can be used. A different arc geometry produced currents of 10 μ a and charge-to-mass ratios of 5 coul/kg with the same flow conditions. On the basis of the thermodynamic calculation of the energy conversion, operation at this current and mass flow level should develop a potential of about 50 kv on a collector. The experimental studies have employed a screen with an applied retarding potential rather than allowing the particles to establish their own potential on an insulated collector. This technique permits measurement of the current delivered against the retarding field. Potentials up to 12 kv were applied to the retarding screen without reducing the current reaching the collector.

Evaluation of the Colloid Power Converter

The thermodynamic analysis of the conversion of thermal energy of a gas to the directed kinetic energy of condensed

particles follows the treatment developed for chemical rocket propellants that produce products in the condensed state.⁶ This calculation provides conversion efficiencies approaching the Carnot efficiency. On this basis, the theoretical performance of several possible working fluids is summarized in Table 1 and in the graphs of Figs. 3-6. The various working fluids show little difference in theoretical conversion efficiency but differ markedly in temperature range of operation and power density. However, these ideal values do not provide a sufficient basis for comparison of the working fluids.

For an accurate evaluation of the capabilities of the colloidal EHD energy converter, the probable modes of power loss will require detailed investigation. The following processes in-

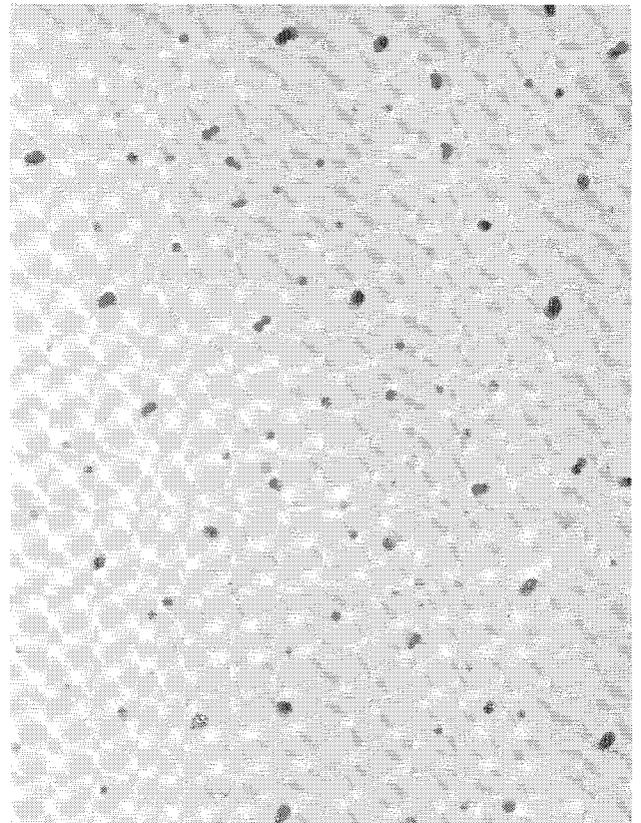


Fig. 2 Electron micrograph of mercury colloid (3200 \times).

involved in operation of the power converter must be examined for loss mechanisms.

a. Ionization

The power consumed in ionization must be small in comparison with the output power. This should be possible, since output potentials ≥ 50 kv are expected.

b. Expansion and Beam Collimation

The vapor must undergo the calculated expansion and maintain mass collimation throughout the growth region. Since the pressure in the nozzle is in the slip-flow regime, its behavior is not entirely predictable. Failure of the nozzle to perform the theoretical conversion of thermal energy to directed kinetic energy would represent a loss and increase the amount of energy which must be radiated. If beam collimation is poor, some of the vapor atoms will strike the walls surrounding the growth region. The gas kinetic energy would be converted to heat on the walls, which would also become coated. Both of these effects would hinder radiation from the growing particles.

c. Nucleation

Ionic nucleation must be effective, and the rate of formation of uncharged nuclei must be much slower than the rate of formation of charged nuclei. Although the theory of ionic nucleation has been accepted under the conditions effective in a cloud chamber, the validity of the theory for high-velocity flow has not been confirmed. Since very high supersaturation is developed in the controlled-growth colloidal ion source, most nonmetallic substances will form uncharged nuclei at an appreciable rate. Calculations indicate that mercury cannot form uncharged nuclei even at the very high supersaturations used in the experimental studies described in the

Table 1 Calculated performance of various working fluids

Working fluid	Flow rate, ^a mg/sec	Temperature, °K		Conversion efficiency, %	Power density, w/cm ²	Energy converted per gram of working fluid, kjoule/g
		Feed reg.	Radiator ^b			
Mercury	0.271	484	221	53	0.049	0.18
	1.135	529	221	56	0.22	0.20
	2.00	545	221	57	0.40	0.20
	2.71	556	221	58	0.55	0.20
Potassium	0.271	795	336	53	0.31	1.3
	1.135	870	336	56	1.6	1.4
	2.00	902	336	57	2.9	1.4
	2.71	923	336	57	4.0	1.5
Sodium	0.271	938	398	54	0.75	2.8
	1.135	1027	398	56	3.4	3.0
	2.00	1069	398	57	6.1	3.1
	2.71	1085	398	58	8.4	3.1
Lithium	0.271	1380	580	53	4.1	15
	1.135	1509	580	55	18	16
	2.00	1571	580	56	33	16
	2.71	1605	580	56	45	17

^a The flow rate is based on a collector area of 1 cm² and an expansion area ratio of 100:1.
^b A final equilibrium pressure of 10⁻⁶ Torr was assumed.

previous section.^{5,7} Therefore, mercury should form only charged nuclei. Although the alkali metals can provide greater power densities, as shown in Table 1, they may give uncharged nuclei in appreciable quantities, when expanded at area ratios as low as 5:1. Mercury should not form un-

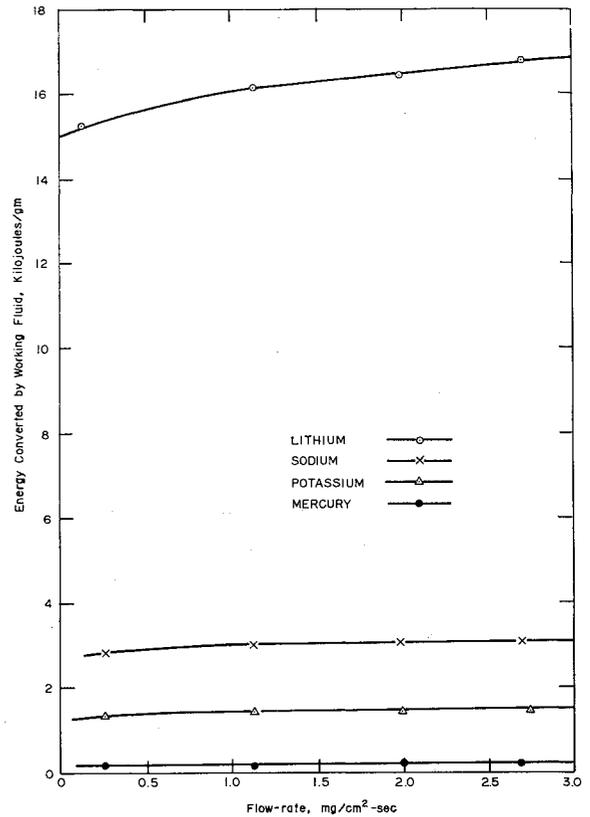


Fig. 4 Energy conversion by working fluid.

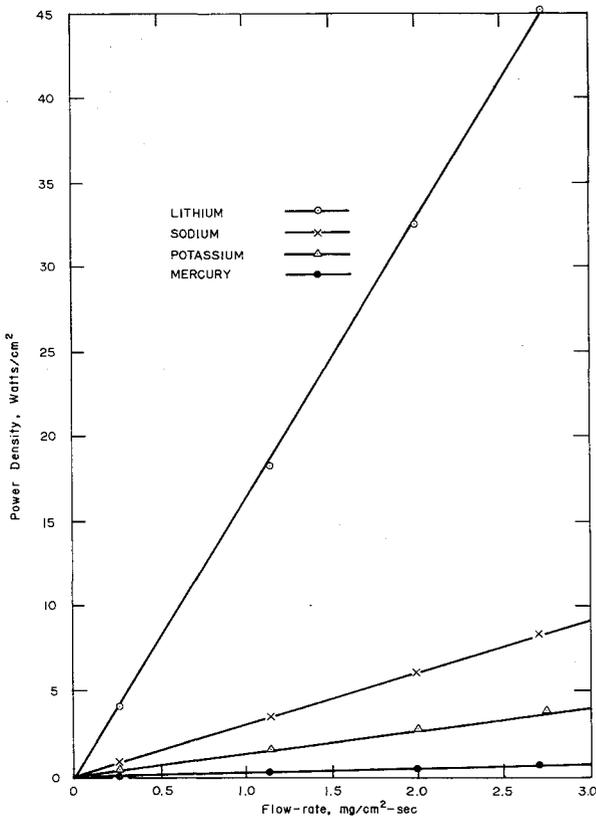


Fig. 3 Power density as a function of flow rate.

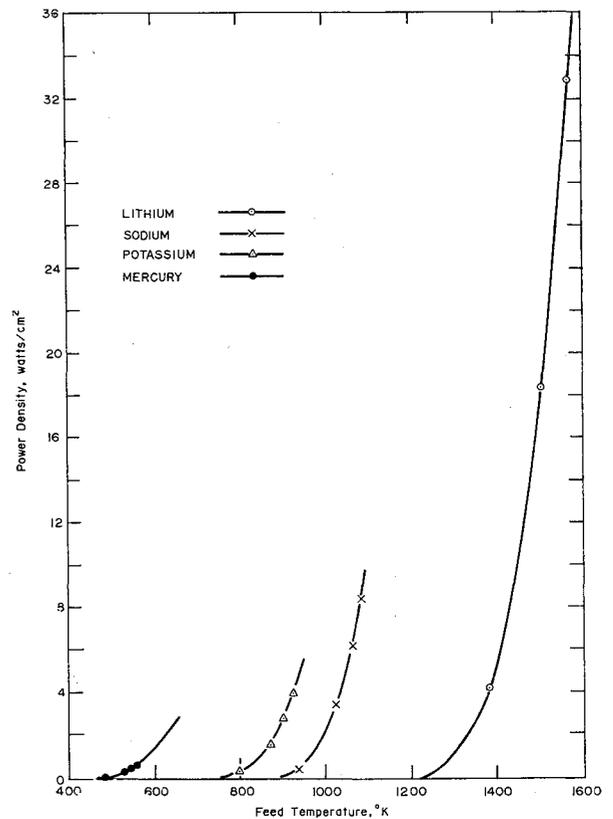


Fig. 5 Power density as a function of temperature.

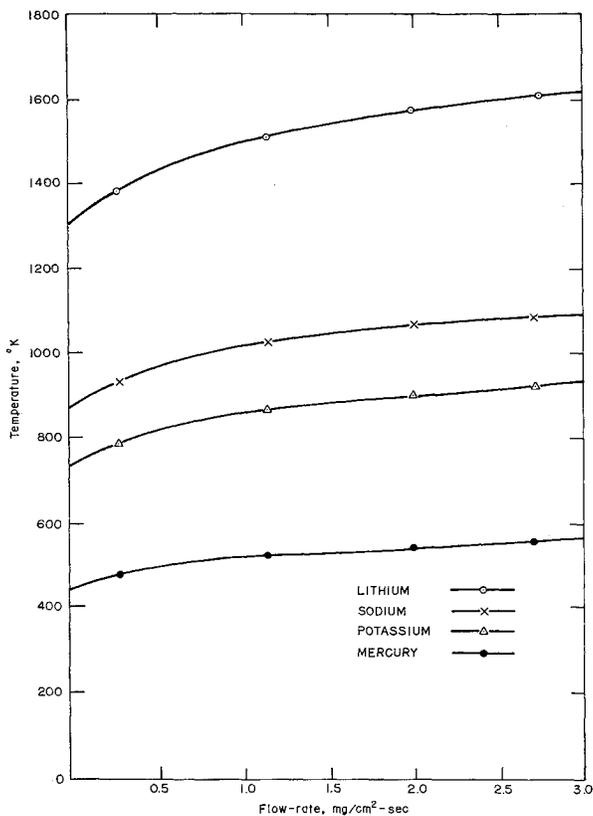


Fig. 6 Feed temperature as a function of flow rate.

charged nuclei but should readily undergo ionic nucleation at area ratios down to 20:1. At the 20:1 area ratio, the same nozzle flow rates would provide power densities five times as large as those given for mercury. If uncharged nuclei become stable and grow, they do no work against the retarding field but simply deliver kinetic energy to the collector, causing its temperature to rise.

d. Radiation

If the rate of heat rejection, in the form of infrared radiation from the particles, is too slow, condensed material will re-evaporate. Much of the re-evaporated material will deposit on the walls of the growth chamber, coating and heating them and thereby further hindering particle radiation. The skin required to prevent loss of the working fluid does not have to possess great impact strength, but it must be transparent to infrared radiation of the wavelength corresponding to the temperature of the particles in the growth region. Unless this skin transmits the radiation effectively, the particle temperatures will increase, and condensed material will re-evaporate from the colloids.

e. Growth and Particle Motion

The particles must accumulate virtually all of the gaseous atoms before reaching the collector, or the uncondensed gas will deliver kinetic energy to the collector. Too high a gas pressure in the region of the collector might also increase the likelihood of electrical breakdown. Furthermore, the charged colloids should all attain the same charge-to-mass ratio on reaching the collector. Particles with too much mass for the prescribed retarding potential would reach the collector with some residual kinetic energy. The retarding potential should be capable of controlling the velocities of the charged particles, so that they all attain the same charge-to-mass ratio. To collect the particles when their residual kinetic energy is almost zero, the collector should be located where the space charge of the particles reaches its maximum.

If the fields in the growth region are unable to counteract the lateral spreading or turn-around of the ions, ions will be lost from the beam, causing a loss of charge and energy. It may be necessary to achieve most of the particle growth before permitting much retardation of the particle velocities. Less deceleration during growth would also reduce the velocity difference between the colloids and the gas. If this velocity difference is large, some of the energy involved in a collision may revert to heat rather than contributing to the kinetic energy of the growing particle.

An evaluation of these energy loss mechanisms will determine the optimum working fluid and strongly influence the design of the colloidal energy converter. Even if the device could achieve only one-fourth of the theoretical conversion efficiency, it would be competitive with other conversion methods. Since radiation is an integral part of the process of formation of the colloidal ions and occurs in a region of low pressures and directed velocities, large radiators with heavy meteoroid protection are unnecessary. In many power generator systems, the radiator contributes almost half of the total weight of the system.

Applications

The colloidal EHD power converter can be employed with solar or nuclear heat sources. It can supply power for electrostatic propulsion engines or for the operation of instruments in a satellite. It can be used as the sole power generator in a system, or it can be used in conjunction with a standard turbogenerator, thermionic generator, thermoelectric generator, or MHD generator, replacing the condenser or radiator with a radiating, high-voltage generating unit. On the basis of the idealized thermodynamic calculations described in a previous section, examples of some possible applications of the colloidal EHD power converter are presented:

1) With a solar collector heat source, the colloidal EHD power converter could produce power for propulsion or instrumentation in space. Figure 7 is a pictorial representation of such a system being employed to operate instrumentation in, for example, a communications or weather observatory satellite. The 10-ft reflector could fit, without folding, into the

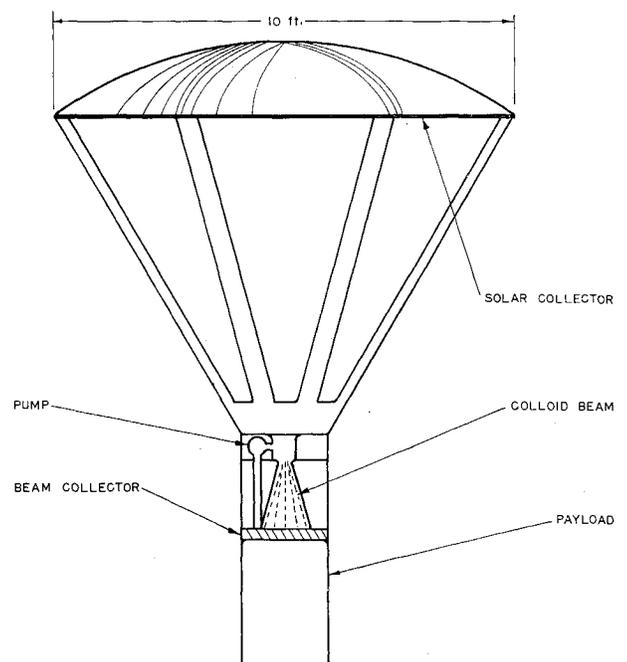


Fig. 7 Solar-colloid powerplant for satellite instrumentation.

payload compartment of a booster. By concentrating solar energy on a small region of the generator, the working fluid could be vaporized and heated to a very high temperature. Assuming a solar power density of 0.135 w/cm^2 and 60% effectiveness of energy collection and concentration, 10 kw of thermal power should be available to the power converter. This heat could be converted to 5.6 kwe with lithium as the working fluid heated to 1600°K at a flow rate of 0.33 g/sec. The total weight of the power generating system would be about 30 lb, including 16 lb for the solar collector (0.2 psf),⁸ 1 lb of working fluid, 1 lb of piping, 7 lb for structure, and 5 lb for the pump.

2) As a powerplant for space vehicles propelled by electrostatic engines, the colloidal EHD power generator can supply the high-voltage requirements of engines using atomic or colloidal ion propellants. Figure 8 is a schematic representation of a space vehicle propelled by an electrostatic propulsion engine with power supplied by a nuclear-colloid conversion system. If the engine uses colloidal ions as the

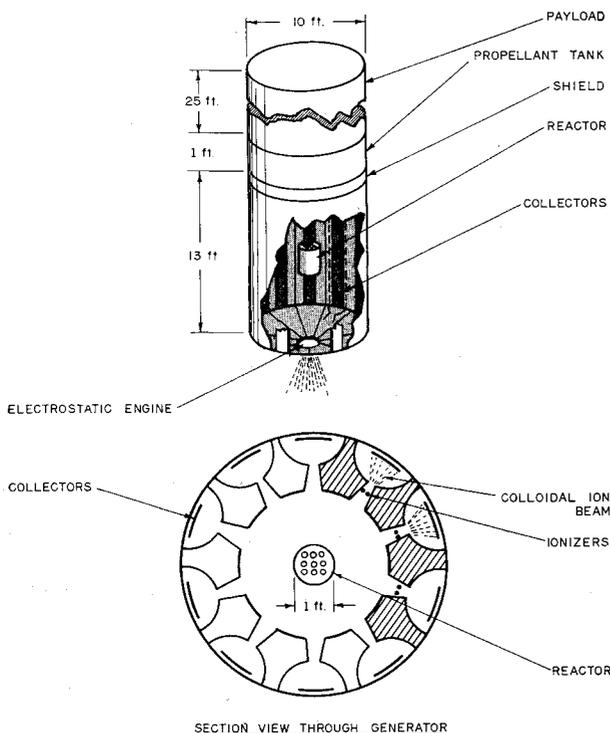


Fig. 8 Colloid power generation and propulsion system.

propellant, it can operate from the same feed region as the power generator, but with more intense ionization. With sodium as the working fluid and propellant material, the power system, at 2.5 lb/kwe, could deliver 570 kw to operate the engine at a specific impulse of 10,000 sec with a thrust of 2.5 lb. The vehicle would require 8000 lb of propellant to operate for one year. Estimated weights of the various components are indicated in Table 2. The skin indicated in this table would be a thin cover to prevent loss of working fluid. Penetration of the skin by micrometeoroids would cause little loss of working fluid, since the working fluid is in a directed flow in the growth region and is in a condensed state when it reaches the collector. The skin would have to be transparent to the infrared radiation of the particles.

3) When used in conjunction with a standard turbogenerator, thermionic generator, thermoelectric generator, or MHD generator, the colloidal EHD power converter would replace the conventional condenser or radiator. This application would increase the over-all efficiency of the power system, since the controlled-growth colloid generator produces electrical power during the condensation process. Such an arrange-

Table 2 Estimated component weights for colloid power generator and propulsion system

Component	Weight, lb
Reactor, 1 Mw thermal	300
Pumps	25
Cylinder walls and collectors	1,000
Skin	125
Weight of power unit	1,450
Shield	400
Propellant tank	500
Propellant	8,000
Payload housing and structures	2,000
Payload	13,000
Total initial vehicle weight	25,350

ment would be useful for generators operating on earth or in space. The advantage is particularly significant in space operations, since additional power output is obtained by replacing the radiator with a unit that weighs less. Also, the high-voltage power produced by the controlled-growth colloid generator can be employed directly for operation of an electrostatic propulsion engine.

In one example of a combination of turbogenerator with a controlled-growth colloid generator, the efflux from the turbogenerator would serve as a heat source for a separate working fluid operating in a controlled-growth colloid generator cycle. As an example, a turbogenerator obtaining 2 Mw of thermal energy from a reactor could produce 300 kw of electrical power and a saturated vapor.⁹ In the case of a rubidium working fluid in the turbogenerator, the efflux from the turbine is 6.1 lb/sec of saturated vapor at 989°K and 20 psi. Condensing and cooling this vapor to 756°K is accomplished by the removal of 1.2 Mw of heat energy which cannot be used by the turbogenerator. Removal of this heat requires an 1800-lb radiator. If the efflux from the turbogenerator is cooled and condensed by heat exchange with a potassium working fluid in a controlled-growth colloid generator, the degenerate heat could produce 680 kw of high-voltage electrical power. Since the particles in the controlled-growth colloid generator are more effective in a radiative heat elimination than a standard radiator, this high-voltage generator unit would weigh less than the radiator it replaces. The reactor and turbogenerator unit would weigh 1800 lb and produce 300 kw. The controlled-growth colloid generator unit would weigh 1200 lb, including heat exchanger, and produce 680 kw at high voltage. The net conversion efficiency of such a combination would be 49%, and the specific weight would be 3.3 lb/kw unshielded or 3.9 lb/kw with shielding.

Conclusions

Considerable investigation is required before the capabilities of the colloidal EHD power system can be properly assessed. Potentially, the system has the following advantages:

- 1) It directly produces electrical energy at high voltages.
- 2) It employs a minimum number of moving parts.
- 3) It converts heat energy to electrical energy at high efficiencies.
- 4) It can operate efficiently at low temperature.
- 5) It incorporates an effective radiator of waste heat requiring no additional radiator.
- 6) The weight of the system could be as low as 2.5 lb/kwe, unshielded (including reactor) at the 500-kwe level.
- 7) Such a system can be employed as the sole power supply for propulsion or for the operation of auxiliary equipment. It can also be used in combination with another type of generator, eliminating the need for a primary radiator for the entire system.

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Plasma Behavior in an Oscillating-Electron Ion Engine

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The behavior of the plasma within an oscillating-electron ion engine was investigated in detail. It was found that certain conditions of gas pressure, magnetic field strength, and cathode emission current are required to maintain the accelerating electrostatic field in the plasma within the engine. In addition, the investigation revealed two types of transient phenomena in the discharge which can occur under certain conditions. The first is a pulsing or fluctuating mode of operation which appears to be caused by depletion of gas within the engine due to the pumping action of the discharge. The second is an azimuthal rotation of plasma perturbations in the range of frequencies of 10 to 50 kc as a result of $E_r \times B_z/B^2$ drifts. There is a possibility that this rotation may result in an enhanced diffusion of electrons across the containing magnetic field and hence contribute to engine power losses.

Nomenclature

B	= magnetic flux density
D	= diffusion coefficient
E	= electric field
I	= current
M	= molecular weight
\dot{m}	= mass flow
P_c	= probability of collision
p	= pressure
T	= temperature
V_{pE}	= exhaust beam plasma potential
ω	= cyclotron frequency
τ	= mean free time

Subscripts

a	= anode
i	= ion
r	= radial direction
s	= solenoid
x	= axial direction
θ	= azimuthal direction
\perp	= perpendicular to magnetic field

Introduction

THE oscillating-electron ion engine^{1,2} is a bombardment-type ion engine in which ions are generated and then electrostatically accelerated in an intense gaseous discharge. Although the geometry of this engine is simple (Fig. 1), the ion acceleration mechanism is quite complex, as it involves the establishment of axial electrostatic potential gradients in an essentially neutral plasma. Theoretical analyses as reported in Refs. 3 and 4 have shown that these potential gradients are supported by the reflection of trapped electrons having a nonthermal energy distribution. Some preliminary experiments had shown that these potential gradients were not present in the plasma under all operating conditions of the oscillating-electron discharge. Therefore, a more detailed investigation was undertaken to determine the effect of external operating parameters such as voltage, current, magnetic field strength, and mass flow on the behavior of the plasma within the engine. The results of this investigation which show the effects of these parameters on both steady-state and transient behavior of the plasma in the engine environment are reported herein.

Apparatus

Experiments with the oscillating-electron ion engine were performed in a 6-in.-diam Pyrex glass vacuum system that was connected to a 4-in. oil diffusion pump backed by a mechanical forepump. A schematic diagram of the vacuum envelope with the engine and external solenoids drawn to scale is shown in Fig. 2. Two sets of separately excited solenoids were used, the main solenoid and the downstream sole-

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