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Collection of Liquid Propellants in Zero Gravity with Electric Fields

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Liquid propellants can be collected in a zero-*g* environment by use of the concept of dielectrophoresis, i.e., the induced motion of electrically neutral bodies in a nonuniform electric field. A brief analysis of the field forces is presented, and liquid collection experiments in simulated and actual zero-*g* environments are described, including tests in aircraft flying ballistic trajectories. Two dielectrophoretic propellant collection systems for a 250,000-lb liquid-hydrogen/liquid-oxygen space vehicle are described and compared with a typical auxiliary propulsion system for propellant settling. Results indicate that the dielectrophoretic systems are lighter and will provide collecting forces of nearly the same magnitude. The use of the high voltages (10^6 v) required for a dielectrophoretic system on a large vehicle is discussed, and additional applications of the concept are considered. This system appears to offer a lightweight, low-power method of collecting propellant in zero *g* with forces on the order of 10^{-4}–10^{-2} *g*. Propellant boiloff losses can be decreased by $\frac{1}{5}$ by collecting the propellant off the tank walls with dielectrophoretic forces.

Nomenclature

b = barometric pressure, cm Hg
T = absolute temperature, °K
E = electric field intensity, v/m
F_v = force/unit volume, newton/m^3
K = dielectric constant
P = pressure, newton/m^2
r_1 = inner electrode radius
r_2 = outer electrode radius
r_3 = tank radius
ϵ_0 = capacitivity of space, farad/m
ρ = mass density, kg/m^3
ρ_e = electric charge density, coul/m^3
σ = conductivity, mho/m
ω = surface free-charge density, coul/m^2
α = surface tension, newton/m

Introduction

To insure proper engine restart of a liquid rocket in a zero-*g* environment, a reliable system for orienting the propellant over the tank outlet and providing vapor-free liquid is a necessity. With cryogenic propellants, some means of providing gas venting with no loss of liquid propellant is required, and in some cases the propellants must be continuously supplied to auxiliary systems during zero-*g* coast phases. We have investigated liquid collection in zero-*g* environments by dielectrophoresis, which is defined as the induced motion of electrically neutral bodies in a nonuniform electric field. The results of an analysis and some experiments are applied to the design of two hypothetical dielectrophoretic propellant collection systems for a liquid-hydrogen/liquid-oxygen (LH_2/LO_2) space vehicle weighing approximately 250,000 lb. Comparisons with an auxiliary propulsion system suggest that the dielectrophoretic system offers a lightweight, low-power solution. The two systems described consist of thin-walled, cylindrical metal electrodes in the LH_2 and LO_2 tanks with 0.5–1.0 Mv applied. The power dissipated through the liquid propellant by resistance heating is only 0.01–0.05 w. Both systems weigh approximately $\frac{1}{10}$ that of the reference auxiliary propulsion system designed for one restart and 15 vent cycles at 0.01 and 0.001 *g*, respectively. These systems can also be used to decrease propellant boiloff losses by $\frac{1}{5}$ by positioning the liquid off of the tank walls. Problems associated with the use of high voltages are discussed, and additional applications of the system are considered.

Theory and Analysis

A continuous, dielectric liquid in a nonuniform electric field experiences forces resulting from free charges and from gradients in the field intensity and liquid dielectric constant. The total volume force on a dielectric liquid with no discontinuities in an electric field is[1]

$$\bar{F}_v = \rho_e\bar{E} - (\epsilon_0/2)E^2\nabla K + (\epsilon_0/2)\nabla[E^2\rho(\partial K/\partial\rho)] \quad (1)$$

The first term is the force exerted on free charges, the second term is the force exerted because of inhomogeneity of the liquid, and the last term denotes the dielectrophoretic effect of force on a body in a nonuniform electric field. A rela-

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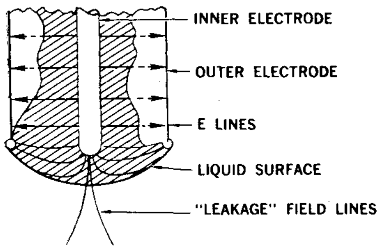

Fig. 1 Method of minimizing surface free charge.

tionship between the dielectric constant K and the density ρ that holds well for most dielectric liquids is the Clausius-Masotti equation

$$C\rho = (K - 1)/(K + 2) \tag{2}$$

where C is a constant for the liquid. Upon substituting Eq. (2) into Eq. (1), the volume force becomes

$$\bar{F}_v = \rho_e\bar{E} - (\epsilon_0/2)E^2\nabla K + (\epsilon_0/6)\nabla[E^2(K - 1)(K + 2)] \tag{3}$$

In our analysis we will be concerned primarily with the ideal case for which the free charge is negligible, $\rho_e = 0$, and the liquid is homogeneous. Then the only electric field force on the liquid is the dielectrophoretic force

$$\bar{F}_v = \{[\epsilon_0(K - 1)(K + 2)]/6\}\nabla E^2 \tag{4}$$

which depends upon the gradient of the square of the electric field intensity, and is in the direction of increasing field strength. Because of the ∇E^2 term, this force is independent of the field polarity, and ideally the force vector will be in the same direction for an a.c. or d.c. field. These effects were noted by Pohl et al.[2-4] in studies of separation of suspensions by dielectrophoresis.

There is a pressure difference between a field-free region and the region of a high field which is given by[5]

$$\Delta P = [\epsilon_0(K - 1)/2](KE_N^2 + E_t^2) \tag{5}$$

In two concentric, cylindrical electrodes of radii r_1 and r_2, the net pressure difference between the liquid outside the electrodes and inside the electrodes will be given by

$$\Delta P = \epsilon_0(K - 1)V^2/2r^2 \ln(r_2/r_1) \tag{6}$$

If the average of the square of the electric field intensity is used,

$$\langle\Delta P\rangle = \epsilon_0(K - 1)V^2/(r_2^2 - r_1^2) \ln(r_2/r_1) \tag{7}$$

This pressure difference will cause the liquid to rise in the electrodes until the field-induced hydrostatic pressure rise is balanced by gravity. The average height to which the liquid will rise because of the electric field is then

$$h_{\text{field}} = \frac{\langle\Delta P\rangle}{\rho g} = \frac{\epsilon_0(K - 1)V^2}{\rho g(r_2^2 - r_1^2) \ln(r_2/r_1)} \tag{8}$$

Surface tension would also cause the liquid to rise between the cylinders to an approximate average height of[6]

$$h_{\text{cap}} = 2\alpha(r_3 - 2r_2 + r_1)/\rho g(r_2 - r_1)(r_3 - r_2) \tag{9}$$

Compared with surface tension effects in the same geometry, the ratio of field force to capillary force is

$$\frac{\bar{F}_v}{F_{\text{cap}}} = \frac{\epsilon_0(K - 1)(r_3 - r_2)V^2}{2\alpha(r_2 + r_1)(r_3 - 2r_2 + r_1) \ln(r_2/r_1)} \tag{10}$$

For two concentric, cylindrical collecting electrodes in LH_2 with the inner radius $r_1 = 0.1$ m, the outer radius $r_2 = 0.5$ m, the voltage $V = 10^6$ v, and the surface tension $\alpha = 2.5 \times 10^{-3}$ newton/m, the dielectrophoretic force acting on the LH_2 in the collector is approximately 460 times greater than the average capillary force. Although capillary forces will aid collection in nearly all of the electrode designs, the effect is usually small as compared with the dielectrophoretic forces. In addition, capillary effects result from surface forces and, because they are essentially passive, are determined, only by the design of baffles, screens, standpipes, etc. A capillary system has the disadvantage that vapor bubbles generated within the collected liquid will not be forced out. Also, surface tension decreases as temperature increases, and thus collection forces will be decreased in areas of high heat transfer such as are likely at the bottom of propellant tanks close to the rocket engines.

Dielectrophoretic forces, however, are body forces and can be controlled by varying the magnitude of the applied voltage or by varying the electric field configuration used for collection or venting, i.e., by charging or discharging selected electrodes. Furthermore, the dielectrophoretic force increases as the temperature of the liquid decreases because of the temperature dependence of the dielectric constant. Thus, free convection currents will be set up within a liquid with variable temperature in zero g, which will attract the colder liquid into areas of higher field intensity.[7] Any vapor bubbles formed will be displaced by the attracted liquid.

The derivation of Eq. (5) for the forces acting on the liquid assumed that the Gaussian displacement vector is continuous at the interface; that is, there is no free charge, and the media are perfect insulators. This is a good assumption for LH_2 and LO_2 with specific resistivities of 10^{18} and 10^{17} ohm-cm, respectively. However, any media will have a finite resistivity, and there will be some current flow. Then the boundary condition at the dielectric free interface is given by the continuity equation for the current flow $\bar{J} = \sigma\bar{E}$ across the interface, and the surface charge density at the interface is

$$\omega = \epsilon_0[(K_2/\sigma_2) - (K_1/\sigma_1)]\bar{J}\cdot\hat{n} \tag{11}$$

According to Eq. (11), the surface free-charge density is maximum when the current flow is normal to the surface, and it is zero when the current flow is tangential to the surface. In some electrode configurations for propellant collection, liquid boundaries occur with $\bar{E}$, and thus $\bar{J}$, normal to the surface. The liquid in this case is subjected to repulsive pressures at the boundary because of the free charge. If an electrode geometry is used in which $\bar{E}$ is substantially tangential to the dielectric interface (except at the boundaries of the conductors), the free-charge density will be minimized. This approach is of limited value since the electric current in the fluid induces electroconvection effects that disrupt the interface.[26] However, the fluid disturbances and repulsion are not as great as with field lines normal to the interface.

The surface free-charge density and the resulting disruptive pressure forces can also be minimized by having as much of the liquid surface as possible bounded by an electrode surface. A "standpipe" electrode design, which we have found to work fairly well with d.c. voltage is shown in Fig. 1. The $\bar{E}$ lines are approximately parallel to the free-liquid surface, and the liquid is bounded by the electrode surfaces at all of the other points. We have obtained collection of liquid with this device by using a laboratory model of two immiscible, equidensity liquids to simulate zero g. In addition, we have obtained good results with this device in the aircraft zero-g tests. However, the collection in both cases showed fluid stirring and electroconvection effects induced by free charges. Thus, even for a design in which field lines are initially parallel to the liquid surface and the liquid is bounded by electrode surfaces at all of the other points, completely stable collection cannot be achieved by a d.c. field.

The most general approach for minimizing free-charge repulsive pressure in a dielectric liquid is the use of alternating fields to decrease the effective surface charge. The surface free-charge density ω given by Eq. (11) is the equilibrium value. The relaxation time necessary to build up this surface charge or to neutralize it is dependent upon the ion and electron mobilities, dielectric constants, and electric conductivities of the particular liquids. We have found in our experiments,[8-10] and it is reported in Ref. 11, that frequencies of the order of 60 cps are sufficiently high to inhibit formation of appreciable surface free charges at the interfaces of good dielectrics. Reference 11 states that, if the field frequency is large as compared to the reciprocal of the relaxation time (σ/ϵ) of the liquids, the interface can be stable. With a propellant such as LH_2 or LO_2, the relaxation time is of the order of 10^3 to 10^4 sec, and it would seem that a field frequency as low as 10^{-2} cps would be sufficient. Experiments on a large scale have yet to be performed to verify this hypothesis.

Electrode Configurations

The collecting forces for particular electrode configurations are difficult to determine, except in the ideal case of perfectly insulating, homogeneous, isotropic liquids with no surface discontinuities and with simple electrode geometries, such as cylinders, spheres, wedges, etc. In the ideal case, the dielectrophoretic force per unit volume acting throughout the liquid, expressed in terms of the equivalent g level for convenience, is given by

$$a/g = \epsilon_0(K - 1)(K + 2)\nabla E^2/6\rho g \qquad (12)$$

Ignoring end effects, two coaxial cylindrical electrodes have a voltage distribution of

$$V(r) = V[\ln(r/r_2)]/\ln(r_1/r_2) \qquad (13)$$

From Eq. (13) the force or g level becomes

$$\frac{a}{g} = \frac{\epsilon_0(K - 1)(K + 2)V^2}{3\rho g[\ln(r_2/r_1)]^2 r^3} \qquad (14)$$

which is the force acting throughout the liquid between the electrodes and radially directed toward the inner electrode. For radii of $r_1 = 0.1$ and $r_2 = 0.5$ m, and an applied voltage of 10^6 v, the force acting on LH_2 varies from 1.35 g's at the inner cylinder to approximately 0.01 g at the outer cylinder.

The average integrated collecting force throughout the cylinder is

$$\frac{a}{g} = \frac{2\epsilon_0(K - 1)(K + 2)V^2}{3\rho g[\ln(r_2/r_1)]^2(r_1 + r_2)r_1 r_2} \qquad (15)$$

For two concentric spheres of radii r_1 and r_2, the voltage distribution is

$$V(r) = Vr_1[1 - (r_2/r)]/(r_2 - r_1) \qquad (16)$$

The dielectrophoretic force at any point of the liquid is

$$\frac{a}{g} = \frac{2\epsilon_0(K - 1)(K + 2)r_1^2 r_2^2 V^2}{3\rho g(r_2 - r_1)^2 r^5} \qquad (17)$$

and is directed toward the inner sphere. Again, for $r_1 = 0.1$ m, $r_2 = 0.5$ m, and $V = 10^6$ v, the force on the LH_2 varies from 10.4 g's at the inner electrode to 0.0033 g at the outer electrode.

The maximum dielectrophoretic force for the sphere is much greater than for the cylinder because the electric field intensity is more nonuniform. However, breakdown will occur for the sphere at a lower voltage than for the cylinder, and therefore the voltage safety factor (ratio of corona discharge voltage to applied voltage) is less for the sphere than for the cylinder.

Experimental Work

Our first experiments were performed with cylindrical electrodes, and demonstrated collection of water drops suspended in an equidensity mixture of carbon tetrachloride and benzene. The collection forces and collection times were in good agreement with theoretical values. Later experiments with equidensity mixtures of FS-1265† in carbon tetrachloride and benzene demonstrated stable configurations of the collected liquid in complex electrode shapes. Tests[8-10] were then performed in a catapult tower, which provided approximately 1 sec of low g. These tests were performed with 250-ml flasks having a transparent, metallic coating as the outer electrode, and an aluminum rod for the inner electrode, with voltages varied between 35 and 50 kv a.c. During the 1 sec of low g, the liquid (carbon tetrachloride) flowed up the rod and into the neck of the flask under the influence of the applied field. Figure 2 shows the liquid position at the end of a typical test sequence. Capillary attraction was negligible in these tests as compared to the dielectrophoretic forces, although the testing periods were too short to study equilibrium configurations.

We have performed tests over extended periods (8–10 sec) by using an Aerocommander aircraft flying ballistic trajectories; the g level varied between ± 0.05 g for tests in calm air. Tests were first performed with a cylindrical electrode 2.5 in. in diameter inside a 1-gal jar 6 in. in diameter which formed the outer electrode. The jar was $\frac{1}{4}$ full of a dielectric liquid, DC-200,‡ 5 cstoke. The DC-200 climbed the inner electrode in low g when the voltage was applied. The tests were designed for an operating voltage of 90 kv d.c., but because of difficulties with the power supply, only 30 kv were obtained. Since the dielectrophoretic force is proportional to V^2, only $\frac{1}{9}$ the force desired was achieved, and hence the inner electrode was covered by a thin sheath of liquid only $\frac{3}{8}$ in. thick. No stirring effects were observed, because the field intensity was low and the test period was shorter than the relaxation time ($\sim$100 sec) necessary for an equilibrium free charge distribution to build up in the DC-200.

In one series of tests, a "standpipe" electrode was used to compare collection with a.c. and d.c. fields. The electrode assembly and typical test results are shown in Figs. 3 and 4, which are taken from a film of the test. The inner electrode is a 0.5-in.-diam aluminum rod; the outer electrode is a 2.5-in.-diam glass tube with a transparent, electrically conducting vacuum-deposited coating of nichrome. The assembly is in a 1-gal, 6-in.-diam jar, $\frac{1}{4}$ full of DC-200. The a.c. tests were limited to 10–12 kv. Figure 3 shows the liquid rising between the electrodes. The field force was approximately twice the capillary force, as obtained from Eq. (10), but no collection was achieved when the voltage was not applied. The collection was stable, with no stirring motion, even at the liquid-gas interface.

More liquid was collected in the d.c. tests because the voltage was higher by a factor of 2 or more (20 to 25 kv), thus quadrupling the collection force. Free charges in the liquid

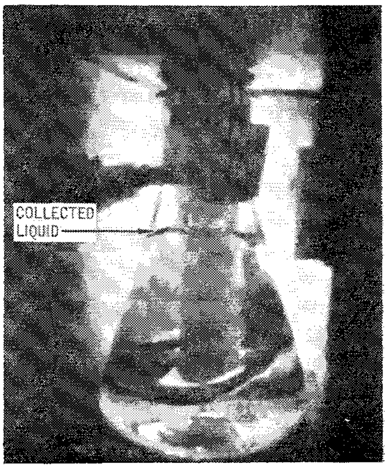

Fig. 2 One-second zero-g catapult test sequence.

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† Dow-Corning fluorpropyl silicone fluid.

‡ Dow-Corning silicone oil.

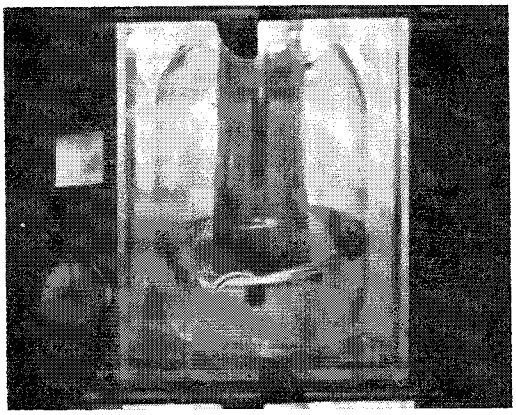

Fig. 3 Alternating current collection; V $\simeq$ 10,000 v.

resulted in a stirring motion, especially at the liquid surface, but the collected liquid was retained between the electrodes for the entire test period, and in fact liquid was continually collected into the electrode during the test. In Fig. 4, the liquid between the electrodes rose 3–5 in. because of the combined surface tension and field forces. From Eq. (10), the field forces at 20 to 25 kv are 5.6 to 9 times greater than the capillary forces.

Liquid collection in the "standpipe" electrode with d.c. voltages indicated that, even with electrode designs in which the lines of electric field intensity are substantially parallel to the liquid surface initially, and in which the liquid is bounded by electrode surfaces at all of the other points, there is appreciable stirring of the liquid. Therefore, a.c. fields must be used for stable collection of liquids, and a.c. fields will be assumed as a primary design requirement.

Dielectrophoretic Propellant Control System for a 250,000-lb LH_2/LO_2 Space Vehicle

Knowledge of the performance of a dielectrophoretic propellant collection system is limited, and there is no proof yet that such a system is practicable. But it is still appropriate to conjecture as to the collecting forces, power requirements, weight, and possible designs of such a system under ideal conditions. Since the system under ideal conditions offers much improvement over existing systems, there is reason to continue studies of its application. Plausible designs are discussed here for a 250,000-lb LH_2/LO_2 space vehicle. This type of vehicle is chosen for comparison purposes because of future use of such vehicles for space missions and the availability of design information.

A dielectrophoretic collection system is composed of a set of electrodes with a nonuniform a.c. electric field established between them which may be used for controlling propellant orientation prior to engine restart or during ullage gas venting. The electrodes are located near the propellant tank outlet to insure liquid collection in this area and flow of liquid to the pumps and engine without entrapped vapor. The system may be designed either to retain the liquid within the electrode system at all times during a zero-g coast or to collect the liquid just prior to engine restart or ullage gas venting. In either case, the electric field attracts the propellant with a force that by design is greater than the expected disruptive forces of terminal maneuvers, engine shutdown, induced propellant sloshing, etc. Since the vehicle ullage rocket system is assumed to provide 0.01-g linear acceleration for 30 sec prior to the engine restart, the dielectrophoretic system will be designed for average collection forces of this magnitude. Because of the nonuniformity of the electric field, the maximum collecting force will be much higher than the average, and the minimum force will be much lower than the average.

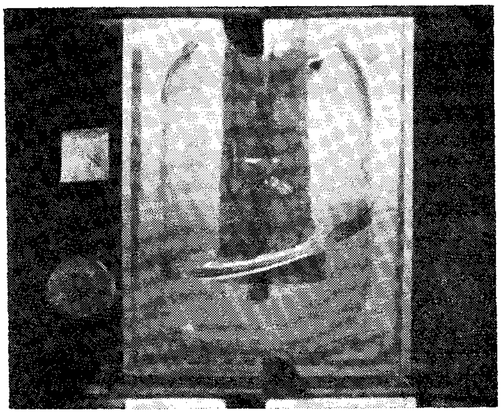

Fig. 4 Direct current collection; V $\simeq$ 25,000 v.

Two specific electrode systems will be used as examples to obtain the dielectrophoretic forces, power requirements, and system weights. A comparison can then be made between these dielectrophoretic systems and an ullage rocket system. Approximate solutions of the dielectrophoretic forces will be used because analytic solutions for the complicated electrode configurations are not available.

The first system (Fig. 5) is designed to collect 1000 lb of LH_2 and 5000 lb of LO_2 over the tank outlets prior to engine restart. In the LH_2 tank, five electrodes are positioned around the tank circumference with the middle electrode over the tank outlet. The electrodes are supported on electrical insulators at the junction of the cylindrical LH_2 tank wall and the common hemispherical dome. The electric field is between the electrodes, charged to a high a.c. voltage, and the tank wall and dome, which are grounded. In the LO_2 tank, seven electrodes are clustered on the bottom dome in a hexagonal configuration with the center electrode above the LO_2 tank outlet (Fig. 5). The electric field is between alternately charged electrodes and the grounded LO_2 dome. The field intensity and dielectrophoretic force cannot be solved analytically for the LH_2 electrode configuration (a numerical solution is possible using the relaxation technique), but the force will increase both radially toward the electrodes and tangentially toward the bottom of the electrodes. Order-of-magnitude estimates of the dielectrophoretic forces in the LH_2 tank will be obtained by assuming a cylindrical geometry, which is approximately equivalent to the actual geometry. The electrode configuration in the LO_2 tank closely approximates a cylindrical geometry (Fig. 6), and the equations for dielectrophoretic force between two concentric cylinders should be fairly accurate.

The equivalent cylindrical geometry for the LH_2 tank electrodes has an imaginary cylindrical wall surrounding each electrode, with a radius equal to $\frac{1}{2}$ the separation distance between electrodes and equal to the average separation distances between the electrodes and the walls. The imaginary wall approximates the equipotential surface, which lies midway between any two electrodes and on the tank walls. The radius of each of the electrodes is $r_1 = 0.05$ m, and the radius of each of the imaginary walls is $r_2 = 0.45$ m. The length of the electrodes is 2 m in order to collect 1000 lb of LH_2. Similarly, the LO_2 tank electrodes are of radius $r_1 = 0.05$ m, and the radius of the imaginary wall around each is $r_2 = 0.317$ m. The height of the electrodes is 1 m in order to collect 5000 lb of LO_2.

The LH_2 and LO_2 electrodes will be charged to 0.5 and 1.0 Mv, a.c., respectively. From Eq. (14), the radial collecting force for LH_2 is 1.45 g at the surface of each of the five inner electrodes. At the imaginary wall, $r_2 = 0.45$ m, and the force is 1.96×10^{-3} g. The average collecting force throughout the entire LH_2 collection system is 0.03 g [Eq. (15)]. Equation (8) gives the average height to which liquid will rise against a given g value or the corresponding adverse g value for liquid to be maintained at the level of the collecting electrode. For the 2 m height of the LH_2 system, the average longitudinal force acting on the LH_2 is 2×10^{-3} g. For the LO_2 collection system, the maximum radial collection force is 1.33 g, the minimum radial force is 5.2×10^{-3} g, and the average radial force is 0.065 g. The average longitudinal force acting on the liquid is 2.56×10^{-3} g. The ratio of average longitudinal field force to the average capillary force is approximately 300 for the LH_2 tank and 800 for the LO_2 tank.

The second dielectrophoretic system, shown in Fig. 7, is designed to force propellant to the bottom of the tank when the tanks are half full. Seven cylindrical electrodes of radius $r_1 = 0.05$ m are positioned in each tank in a hexagonal pattern (see Fig. 7). The electrode lengths are approximately $\frac{1}{2}$ the respective tank lengths or 4 m for the LH_2 electrodes and 2 m for the LO_2 electrodes. In the LH_2 tank, the separation distance between the electrodes is approximately 2 m, and thus, the imaginary wall radius is $r_2 = 1$ m. Assuming that 1 Mv is applied to the electrodes, the maximum radial force of attraction on the LH_2 will be 3 g's; the minimum radial force will be 3.75×10^{-4} g, and the integrated average radial force will be 1.3×10^{-2} g. For the tank half filled with LH_2, the average longitudinal force attracting the liquid to the bottom of the tank will be 2.8×10^{-4} g.

In the LO_2 tank, the separation distance between electrodes is 1.4 m, and the imaginary wall radius is 0.7 m. For 1 Mv applied to the electrodes, the maximum, minimum, and average radial forces will be 0.55 g, 1.9×10^{-4} g, and 0.5×10^{-2} g, respectively. For the tank half filled with LO_2, the average longitudinal force of attraction will be 1.6×10^{-4} g.

Venting

The second electrode system described previously automatically provides longitudinal forces of approximately 2.8×10^{-4} and 1.6×10^{-4} g in the LH_2 and LO_2 tanks, respectively, to collect all of the liquid to the bottom of the tank and thus provide for venting of the vapor without entrapped liquid. However, the first electrode system, designed to collect 1000 lb of LH_2 and 5000 lb of LO_2, would require a separate electrode system for venting. Settling of the propellant for venting can be achieved by a single electrode. For example, a 0.05-m-radius, 4-m-long electrode projecting up from the LH_2 tank bottom with 1 Mv applied between the electrode and tank wall would provide an average of 10^{-4} g along the tank axis to settle the propellant.

High-Voltage Supply

The high-voltage supply for a dielectrophoretic system of the size we have considered should provide from 0.3 to 1.0 Mv with a resistive current of 10^{-7}–10^{-9} amp. The low current requirement results from the excellent insulating properties of LH_2 and LO_2 (10^{18} ohm-cm and 10^{17} ohm-cm, respectively). An a.c. output is necessary in order to minimize the liquid free charges, which cause instability and repulsion of collected propellant. The a.c. output can be provided by transformers or electrostatic generators. Since d.c. voltage might be used to advantage in some cases, various d.c. supplies will be described in addition to the a.c. supplies.

Four types of high-voltage supplies are currently available which can meet these requirements: 1) nuclear battery, 2) piezoelectric generator, 3) high-voltage transformer, and 4) electrostatic generator operated in an a.c. or d.c. mode. Nuclear batteries composed of a β- or α-emitting radioisotope inside a collecting electrode could maintain ~1 Mv. Linder[13] obtained 365 kv with a β source of 0.25 curies of Sr^{90}, which has a half-life of 30 yr and an emitted energy of 2.2 Mev, decaying to stable Zr^{90}. Many types of nuclear batteries are commercially available, such as a 10-kv Kr^{85} battery (half-life of 10 yr).[14] If a d.c. supply were to be used, the radioisotope source could be contained inside and along the axis of the electrodes. The interior of the electrode would be coated with a dielectric material. High-energy electrons emitted by the source would pass through the dielectric and charge the outer surface but low-energy particles produced by gas ionization would not pass through the dielectric and discharge the device. Therefore, the voltage would increase to a maximum value, which can be calculated from the circuit characteristics.[15–17] Usually, the maximum voltage is less than, but of the same order of magnitude as, the electron energy of the emitted β particle. The high-field region is formed between the collector electrode and outer electrode, which is connected to and neutralizes the source. If a.c. voltages were required, pairs of collecting electrodes could be alternately charged and dis-

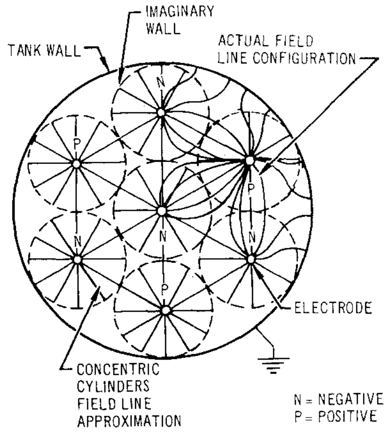

Fig. 6 Typical hexagonal electrode configuration (top view).

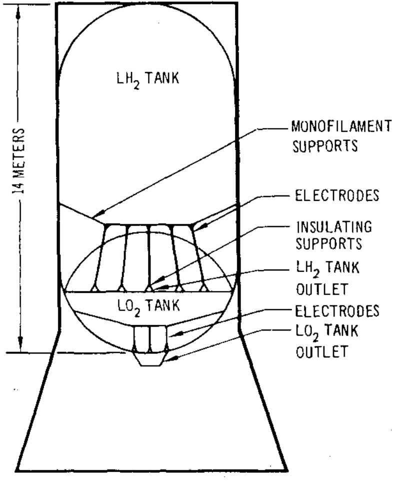

Fig. 5 Electrode configuration I.

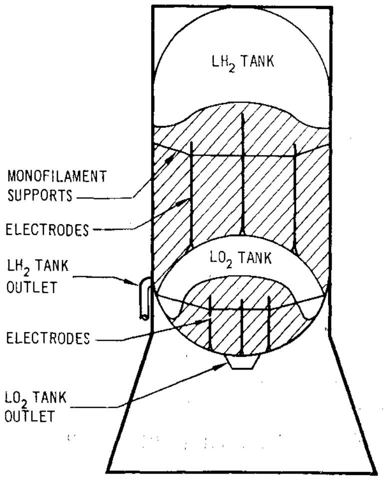

Fig. 7 Electrode configuration II.

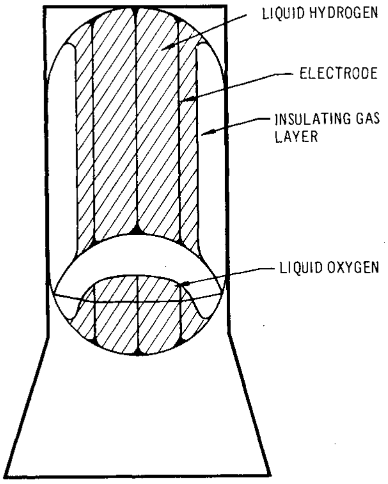

Fig. 8 Propellant positioning for decreasing boil off loss.

charged. The frequency of the effective a.c. voltage obtained by switching would be limited by the time required to charge and discharge each electrode which would depend upon the amount of radioisotope present. Voltage switching in this manner may not be practical, but should be considered because of the low weight of such a system.

Piezoelectric generators consist of anisotropic crystals such as quartz which provide high voltages when under tension or compression. The polarity of the output voltage reverses with tension or compression of the crystals. A piezoelectric generator§ developed by the Clevite Corporation has been operated[18] at 500 kv. Such devices might be of use in our case, but the weight is likely to be high.

A 350-kv supply consisting of a d.c. to a.c. inverter and a series resonant circuit transformer has been considered, and is estimated to weigh ~15 lb.[11] High-voltage transformers of this type would have to be developed for application to a dielectrophoretic system.

Several types of electrostatic generators are described in Refs. 19–23. Disk-type generators capable of 500 kv (a.c. or d.c.) are described which provide 10 kw of power.[20] Such generators operated at higher voltages and much lower outputs (~1 w) could be used for dielectrophoretic systems. Ion Physics Corporation has suggested a small, lightweight Van de Graaff generator[24] for our application that would provide 1 Mv a.c. with currents of the order of 10^{-6} amp. The generator would be operated in the a.c. mode by switching the polarity of the belt charger; the a.c. frequency would be on the order of 0.1 cps or greater. The unit would have approximately a 3-in. diam by 20-in. length and would weigh ~15 lb; it appears to be the lightest high-voltage power supply available. It could be pressurized to 200 psi with CO_2 and N_2 or SF_6, or operated with the space vacuum as insulation.

Systems Comparison

The total system weight of both dielectrophoretic systems is composed primarily of the electrodes, insulating supports, high-voltage generators, and batteries or solar cells to power the generators. The electrodes would be made of highly polished aluminum or stainless steel in order to minimize corona discharge from asperities on the electrode surfaces. Aluminum electrodes of 0.02-in. wall thickness are assumed. Included in the electrode weight for each configuration is the weight of high-voltage cable, which connects the positive electrodes to each other and the negative electrodes to each other. Because a.c. voltage is assumed, the polarity of the electrodes reverses, but the relative polarity is maintained; i.e., successive electrodes in the hexagonal configuration are always oppositely charged as shown in Fig. 6. The insulating supports in the LH_2 tank are assumed to be of polypropylene, which has a relatively low density (0.905 g/cm^3) and a high dielectric strength (650 v/mil). The weight of each support is approximately 3 lb for the 500-kv LH_2 electrodes, and 6 lb for the 1-Mv LH_2 electrodes. Teflon insulating supports are used in the LO_2 tank, and each support for the 1-Mv electrodes weighs approximately 10 lb. The high-voltage generator weight is assumed to be 15 lb, and two generators are required for each tank, except for the LH_2 tank of the first design in which all of the five electrodes are at the same polarity. The battery weight and type of primary power source cannot be determined without specifying the number of restarts and vent cycles, the collection time required, and the over-all vehicle mission. However, the dielectrophoretic systems will bring about collection in less than 1 min, and thus, for the assumed mission requiring 15 vent cycles and one restart, a 1-hr total usage time is sufficient. On this basis, and assuming the small Van de Graaff generators will require a total of 0.2 kw for operation, a total of 0.2 kw-hr will be required which can be obtained from the vehicle power supply. Assuming that the vehicle power supply consists of space batteries, which typically have power-to-weight ratios of 0.05 kw-hr/lb, the battery weight required for the dielectrophoretic systems is only 4 lb. Weights are summarized in Table 1. The total weight for the first system is 180 lb, and for the second, 265 lb.

In comparison, a typical auxiliary propulsion system designed to settle the propellant would accelerate the vehicle at $10^{-2}\,g$ for 30 sec for each restart and at $10^{-3}\,g$ for each venting cycle. By assuming that one restart and 15 vent cycles are required, the auxiliary propulsion system weight for a 250,000-lb space vehicle would be approximately 2200 lb, based on Douglas Aircraft Company experience with large space vehicles. The average longitudinal collecting forces for the auxiliary propulsion system are 10^{-3}–$10^{-2}\,g$, or 5 times as great as those for the dielectrophoretic systems. However, because of its low power requirement, the dielectrophoretic system can be used for longer periods of time, and thus settle the propellants with lower forces. Also, the average radial forces of $1\text{–}5 \times 10^{-2}\,g$ are relatively high and would bring about rapid collection of propellant around the electrodes, which are centered on the tank outlets. A dielectrophoretic system, because of its low power requirements, becomes more attractive as compared with an auxiliary propulsion system as the number of restarts or vent cycles increases or as the total time for liquid-gas separation and propellant collection increases. For relatively long usage times, solar cells would be used in place of batteries; the total solar cell weight required for continuous operation of the dielectrophoretic system would be 40 lb.

Additional Considerations

Electric field effects can be used to decrease boiloff of propellant during long-term storage. We have considered

Table 1 Dielectrophoretic propellant collection system weights

Weight	System I (1000-lb LH_2/5000-lb LO_2), lb LH_2	LO_2	System II (half-tank), lb	
Electrode	21	11	51	24
Insulation	15	70	42	70
Generator	15	30	30	30
Monofilament support	5	5	5	5
Battery	4	4	4	4
Total	60	120	132	133
Total system (for LH_2 and LO_2 tanks)	180		265	

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§ Material used is "PZT-4," a lead zirconate-lead titanate ceramic.

the possibility of collecting all of the LH_2 from the tank walls into the center of the tank; LH_2 collected in this manner would have an insulating gas layer between it and the tank wall which would greatly decrease the heat transfer to it. For the 250,000-lb space vehicle during a postlaunch coast phase, the rate of boiloff of LH_2 collected in the center of the tank would be $\sim\frac{1}{5}$ that for LH_2 collected on the walls (the normal case in zero g). This would correspond to a weight savings of 1000–2500 lb for a 5-hr coast for an internally insulated tank. A set of cylindrical electrodes similar to those in the second dielectrophoretic system, but extending over the full tank length, would collect LH_2 off the tank walls, as shown in Fig. 8. The LH_2 could be held in this configuration against longitudinal forces of the order of 10^{-3} g or greater. These estimates are made by equating the change in electrostatic field energy for the liquid located at the bottom of the tank and for the liquid collected around the electrodes with the change in potential energy for the liquid in the two positions.

A decrease in propellant loss by boiloff can also be achieved by stirring the propellant to maintain a more uniform temperature in the liquid. The tank pressure would build up more slowly, and fewer vent cycles would be required. Stirring can be achieved in two ways with a dielectrophoretic system. First, dielectrophoretic forces are temperature-dependent and induce free convection currents similar to those in a gravitational field.[7] Under some conditions, this free convection effect would be useful in decreasing temperature stratification. A more effective method, however, is the use of a d.c. field in which charges moving through the liquid would induce stirring. The problems of the amount of stirring required, the decrease in boiloff, and the power requirements of such a system have not been studied. However, for the 250,000-lb space vehicle in a coast phase, the estimated boiloff rate for thoroughly mixed LH_2 is approximately $\frac{1}{5}$ that for a no-mixing case. During long-term storage, d.c. fields could be applied intermittently to mix the propellant rather than venting the ullage gas. After mixing, the propellant could again be collected around the electrodes. The boiloff loss of LO_2 could also be decreased by the preceding methods, but it may not be necessary because the LO_2 boiloff rate is less than 0.1 of the LH_2 boiloff rate.

The dielectrophoretic system requires extremely high voltages in application to large tanks in order to minimize the number and size of electrodes, and hence, system weight. However, the corresponding electric field intensities are well below those at which corona discharge or arcing would occur under the conditions of temperature and pressure in the tanks. The dielectric strengths of the propellants are very high ($\sim$1 Mv/cm) and are thus 15 times the maximum electric field intensity of the system. Breakdown field strengths of the pressurizing gases are lower than those of the liquids, and thus, as a conservative estimate, the system is designed for voltages well below those at which breakdown will occur in the gases. Data on gas breakdown at very high voltages and high density are not available, and any specific dielectrophoretic system will require extensive full-scale testing to insure that breakdown will not occur. However, since the electric field is highly nonuniform, breakdown in the form of corona discharge will occur at voltages significantly below arcing voltages. This corona discharge voltage is obtained by setting the electric field intensity at the electrode surface equal to the dielectric strength of the gas.

Then the maximum voltage that can be applied between two concentric cylinders in a gas before corona discharge takes place is[12]

For GH_2

$$V_{\max} = 1.8 \times 10^6\, r_1(3.92b/T)\, \ln(r_2/r_1)$$

For GO_2

$$V_{\max} = 3.2 \times 10^6\, r_1(3.92b/T)\, \ln(r_2/r_1)$$

The term in the first parenthesis shows the dependence of $V_{\max}$ on the gas density. In calculating $V_{\max}$ for the electrodes, both tank pressures are assumed to be 45 psia, and the hydrogen and oxygen vapor temperatures are assumed to be 30° and 120°K, respectively. In the first dielectrophoretic design the value of $V_{\max}$ in the LH_2 tank is approximately 0.5 Mv, and in the LO_2 tank it is 2.1 Mv. For these applied voltages, the voltage safety factors are 10 and 2 for LH_2 and LO_2, respectively; in the second dielectrophoretic design, the voltage safety factors are 6 and 3.1, respectively.

Electric arcing in the LO_2 tank could lead to ignition of the electrodes, tank walls, or contaminants in the LO_2, and a catastrophic explosion might occur. The arcing problem was investigated in connection with the LO_2 converter of Ref. 25 with arc energies of a few mjoules at 20 kv. It was concluded that the device was safe even if arcs were to occur. This problem has not been studied for large LO_2 tanks with high voltages and arc energies of the order of 1–10 joules, but precautions could be taken to insure that arcing would not occur. The applied voltage would be 0.2 to 0.5 of that at which corona discharge would occur in the gas (the corona discharge voltages would be obtained for a particular electrode assembly in the LO_2 tank with mixtures of O_2 and the inert pressurizing gas, e.g., He, at the minimum operating pressure and maximum operating gas temperature of the tank); the current could be monitored, and the voltage could be decreased whenever current surges characteristic of corona discharge were detected. It is highly unlikely that an arc will occur in the *liquid* oxygen, which has a higher dielectric strength than the gas. Since the electric field intensity is highest at the electrode surfaces, a layer of liquid would be collected on the surfaces and retained with forces on the order of 0.5–3 g's; this liquid layer would provide additional electrical insulation. If an arc were to occur, much of its energy would be dissipated in the liquid itself rather than at the electrode surface. In addition, a sheath of Teflon on the electrodes would further dissipate the arc energy and prevent oxygen from reaching the metal surfaces. The combination of a high-voltage safety factor, detection of corona discharge, and dissipation of arc energy, should render a dielectrophoretic system safe for use with LO_2. No danger of an arc-induced explosion exists in the LH_2 tank.

Conclusions

The brief analysis of the dielectrophoretic forces indicates that collection and retention of dielectric liquids in zero g can be guaranteed. The experiments demonstrate collection and aid in evaluating electrode configuration. The two collection systems illustrate that dielectrophoretic systems have a very low weight as compared to auxiliary propulsion systems; furthermore, the system weight is relatively insensitive to the usage time required. The system can also be used to greatly decrease propellant boiloff loss; even on short-term missions, the propellant weight savings would more than offset the dielectrophoretic system weight. Several voltage supplies capable of meeting the high-voltage, low-current requirements of the system are commercially available or could be developed for space application. The problem of determining high-voltage breakdown values in dense, low-temperature gases has not been solved, and it has been necessary to assume a local corona discharge mechanism. However, adequate collecting forces are achieved at voltages ≤ 0.3 of the corona discharge voltages. The arcing problem requires further study, especially in the LO_2 tank where arcs could cause explosions, but precautionary measures exist to insure safe operation of the system.

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