RESEARCH ON COLLOID THRUSTERS

by
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Abstract

We present first results of our joint work aimed at reviving colloid thruster technology for micropropulsion applications. A review of the science and technology of these thrusters as it was developed in the 1960's and '70's is followed by descriptions of the further advances made in the last decade by electrospray science, many of them at the Yale Laboratory of one of the authors. We conclude with recent laboratory results which confirm the feasibility of the approaches we envision for these applications.

1. Introduction

Colloidal thrusters are electrostatic accelerators of charged liquid droplets. They were first proposed and intensively studied from around 1960 to 1975 as an alternative to conventional ion engines. Their appeal at that time rested with the large "molecular mass" of the droplets, which was known to increase the thrust density and the efficiency of an ion engine. The price to pay for this large mass-to-charge ratio is higher accelerating voltage for a given specific impulse, and the technology developed at that time led to voltages in the 12-100 kV range, which created packaging problems.

After lying dormant for over 20 years, there is now a resurgence of interest in colloid engine technology. This is motivated by:

(a) The new emphasis on miniaturization of spacecraft. The very small thrust per emitter now becomes a positive feature, allowing designs with both, fine controllability and high performance.
(b) The advances made by electrospray science in the intervening years. These have been driven by other applications of charged colloids, especially in recent years, for the extraction of charged biological macromolecules from liquid samples, for mass spectroscopy. These advances now offer the potential for overcoming previous limitations on the specific charge q/m of droplets, and therefore may allow operation at more comfortable voltages (1-5kV).

Miniaturization of plasma thrusters is known to lead to high plasma densities and reduced lifetime. Colloids do not suffer from this effect, because charges are directly extracted from a liquid.

We have initiated collaborative work on colloid thrusters at MIT, Busek Co. and Yale Univ. Sponsored in part by AFOSR and by a Phase I SBIR contract to Busek from NASA Glenn. This paper attempts to place our work in perspective, by reviewing the current state of the relevant science, as well as the established technology of the earlier development period. In addition, we discuss some preliminary laboratory studies already accomplished.

2. Literature Review

2.1 Early Work on Electrospray Phsyics

That the surface of a liquid (conducting or polar) can become unstable when subjected to a strong enough normal electric field has been known for a long time [1]. The linear instability condition

$$E = \sqrt{\gamma k / \varepsilon_o} \qquad (1)$$

which gives the required destabilizing field strength for a surface wave number k, when the surface tension is γ was derived by Hendricks and Pfeifer [2] using the classical surface stability analysis of Lamb [3]. Beyond the linear stage, the result is usually a multiplicity of wandering sharp liquid tips, each issuing a thin jet of highly charged droplets[4]. When the liquid is confined to the exit of a thin tube, a single liquid tip can be obtained, which facilitates the study of the associated phenomena. This was exploited extensively in the pioneering experimental work of Zeleny, ca. 1915 [5], [6], who documented the formation, under certain conditions of voltage and flow rate, of nearly perfect conical tips. The theoretical explanation for this shape was provided by G.I. Taylor in a 1964 paper [7]. Taylor found that a liquid cone of included semi-angle $\alpha = 49.3^\circ$ (independent of fluid properties) satisfies the following boundary conditions: (a) Being equipotential, and (b) Having the proper distribution of normal electric field to exactly balance the surface tension pull. His

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own measurements, confirmed this angle, at least near the tip of their liquid points.

Despite these considerable advances, these classical studies were unable to explain satisfactorily the physics of the thin jet formation at the cone's tip. Lacking a firm theoretical basis, the limited data available were correlated through various conflicting semi-empirical models; this stage is well summarized, as of 1966, in Ref. 2.

2.2 Literature related to the first generation of Colloid Thrusters

Starting around 1960, application studies began to appear in which a suitable combination of liquids and electrode configurations was being sought for propulsion purposes, Krohn [8],[9] studied first liquid metals, and then doped organic solvents, with an early focus on glycerol.

The realization that simultaneous acceleration of ions and droplets (themselves with as spectrum of specific charge) would imply inefficient use of power for thrust generation, also dates from this period, the first analysis being due to Hunter [10].

Cohen et al [11] describe early research on colloidal thrusters at TRW, where glycerol was the selected fluid. Glycerol is an excellent solvent, but the highest conductivities possible in glycerol solutions of various salts are below 0.1 Si/m (with the exception of those involving H_2SO_4)[12]. The use of Time-of-Flight (TOF) mass spectrometry as a standard diagnostic tool in this field appears to have been initiated by H. Shelton, of this group. Using glycerol solutions and single Pt tubes of 0.2 mm ID, the authors report three operating modes, from low to high voltage (with no clear specification of the flow rates involved). At $V \leq 3000V$ only intermittent emission occurs; at higher voltages, the emission current has a ±10% modulation on a DC background; within this regime, if flow and voltage are adjusted "just right", completely steady DC operation occurs. This desirable regime appeared to be quite elusive and could be lost upon voltage changes of a few percent. Another important, and possible related observation, was that "a dozen or more jets were emitted from a single capillary tube needle". Cohen et al went on to operate needle arrays (at 5-10 kV), and eventually added a 120 kV accelerator to such arrays. The need for this extreme voltage arose from the limited charge/mass (q/m) available from their working fluid (≈200-400 Coul/Kg at most). As can be easily appreciated, handling these voltages implied a major technical challenge, requiring extensive use of spark arrestors, multi-element ceramic insulators, etc. Substantial x-ray generation occurred at times.

Similar studies, with additional data sets generated about several potential fluids, were being carried at Electro-Optical Systems (EOS) [12]. Liquid Cesium and 98% H_2SO_4 generated pure ion streams (negative in the case of H_2SO_4). In this latter case, q/m reached values of 370,000-450,000 Coul/Kg: this was not pursued further, however, due to the very corrosive nature of sulfuric acid. Most of the other fluids studied were glycerol-based. Perel et al reported a number of interesting performance trends from their tests: (a) The specific charge of droplets decreased as the flow rate increased (this will be later seen more clearly in the context of modern electrospray data and models). (b) For glycerol-based solutions, a mixed ion-droplet regime was generally present. In anticipation of our later discussion of more recent data, this behavior of glycerol appears anomalous, since only much more conductive solutions can reach ion emission within a stable Taylor cone regime. The key difference appears to be the multi-cone structures reported in Ref. [11]. (c) It was found that high efficiency was obtained for very low and very high mean specific charges (corresponding to only droplets and only ions), and were substantially lower in between. Finally, the authors also reported some successful test of bipolar arrays, with alternatively positive and negative charge emitters. This might be one approach to charge neutralization, avoiding the need for cathodes.

The EOS/Xerox team continued their developments, culminating a few years later with a full thruster with an annular-shaped emitter [13],[14], rather than the more traditional assembly of individual needles. This increased thrust density and assembly ruggedness, without changing the basic scaling laws previously established for needles, except maybe for their space charge limit. Performance tests lasting over 100 hrs. indicated $Isp \cong 1485s.$, $F \cong 0.4mN$ and $\eta \cong 0.73$; although an impactor-type thrust balance had been described in Ref. [12], these data appear to have been derived from detailed analysis of TOF traces instead. Several interesting observations can be made about the results in Ref. [14]. First, the lack of tight temperature control on the emitter, caused erratic mass flow rate variations by up to a factor of two. The current and thrust also fluctuated, but when correlated vs. the instantaneous flow rate, the dispersion was much smaller; this indicates that either strong heat sinking or a feedback thermal control will be necessary for precise thrust delivery. The

problem will be alleviated for fluids with less temperature-dependent viscosity, such as formamide. The data reported in [14] indicate the scalings $thrust \dot{m}^{-3/4} (Isp \approx \dot{m}^{-1/4})$, and $I \approx \dot{m}^{1/2}$. These scalings will be shown later to be consistent with single Taylor cone operation, or perhaps, in this case, with a fixed number of Taylor cones. It is to be noted that these tests were conducted at a fixed voltage of 13 kV, and with a fixed geometry. A subsequent series of "high performance tests" is also reported in Ref. [14], in which voltage was also increased. The thrust data now deviated from the $\dot{m}^{3/4}$ line, increasing as voltage was increased. As will be seen, no such deviation is expected in single-cone operation, and the implication, as shown by our own results (Sec. 3), could be that additional cones were being started as voltage was raised (although this was not commented upon by the authors). This so-called "highly stressed regime" is still poorly understood, and is one of the areas to be addressed in future research.

One other important observation was reported in Ref. [13]: even at a constant flow rate, reducing the emitter temperature had the effect of increasing the average q/m emitted by reducing the number of emitted droplets, while retaining that of ions. Once again, this is not consistent with recent understanding of the single-cone regime, for which viscosity is known to be an insignificant parameter. In addition, as noted, the very fact that a low conductivity glycerol solution does reach ion emission remains unexplained.

At about the same time, two groups at TRW and AF also presented performance and life test results for essentially complete colloid thrusters. Kidd and Shelton [15] built a cluster of 12 needle arrays of 36 needles each, for a nominal thrust of 4.4 mN, and tested one of the arrays for 4350 hrs. The fluid was glycerol/NaI, with 3gm NaI per 100 ml solution. The accelerating voltage was 12.3 kV, and the extractor was 2kV below the collector potential, to avoid electron back-flow. A cylindrical shield was added around each Pt needle, which was credited with significantly reducing erosion. The needles had 0.13 mm ID, 0.35 mm OD, with the outer edge sharpened. The module temperature was closed-loop controlled to $\pm 1^{\circ} C$, and a proportional valve was also included, with feedback control from the measured current. This kept short-term fluctuations of flow rate within ±3%, although there were larger long-term drifts. The authors discussed end-of-test damage and the damage mechanisms. Needle erosion was limited, apparently restricted to some negative ion sputtering of dry areas. There was a conductive film of less than 5μm thickness on the needles, producing some current leakage, and there was on some needles a char residue which was identified as due to electron bombardment of glycerol. Measures were discussed to reduce these effects, but none of them were limiting after over 4000 hrs.

The other thruster development was reported by Huberman and Rosen [16]. They used an annular slit configuration (as in Ref. [13,14]), and a concentric shield, as in Ref. [15]. In addition, this shield was segmented into three independent 120° segments, which could be differentially powered to obtain some ±10° thrust vector control. Each individual annular source delivered 110μN of thrust, (for about 100 hrs.), and a four-source array was also tested satisfactorily, including neutralization by a single tungsten wire cathode. Performance stability to ±3% was reported.

Independent of these US developments, colloid propulsion appears to have been pursued at about the same time in the Soviet Union. This work has not been surveyed in detail, and only the recent paper by Shtyrlin [17] will be quoted. This paper reports on the development, at the Moscow Aviation Institute, of a "monoblock" thruster with up to 1 mN thrust, Isp=1000s, acceleration voltage of 15kV, and an overall mass of 5 Kg. A life of 2800 hrs. is quoted. The fluid used is not mentioned.

Interest in colloid propulsion appears to have vanished after 1974, as no relevant published material was found after this date. Several factors probably conspired to this end:

(a) The general downturn in space technology work in the post-Apollo era (b) The perfecting of classical Kaufmann ion engines, which delivered similar performance with less complexity (c) The high operating voltages (>10KV) required (d) The difficulty in scaling up to thrusts of many mN, or powers in the >1 kW range.

2.3 Recent Developments in Electrospray Science

Mass Spectometry is a very large area of scientific and industrial research. Until slightly over a decade ago it was essentially limited to materials which could be introduced as vapors in a gas without decomposition. This excluded many large species of biological, pharmaceutical, and biomedical interest, which tend to be damaged by

traditional processes of volatilization and ionization. This situation was dramatically altered by the discovery in 1989 by Fenn and colleagues [18] that individual large molecular ions could be extracted intact from a liquid solution by electrostatic atomization from a Taylor cone. The field of electrospray ionization began then an explosive growth accounting at present for over 1000 journal articles/year. More important from our point of view is the new impulse that this new application has given to basic studies in electrospray science. A brief outline of these development will be given here.

There is experimental evidence [19] of the formation of liquid tips with angles smaller than Taylor's value of 49.3°, which, as shown experimentally by de la Mora [20], is encountered only as a limiting case when the flow of liquid approaches its minimum value. Considerably smaller angles form at higher flow rates due to space charge associated to the spray of drops ejected from the cone apex. The theory developed in [20] showed that, for sprays in air, where collisionality dominates over inertia, an extension of Taylors result is possible, where the cone has a angle $\alpha < \alpha_T$, and the spray is also conical, with a conical angle β uniquely related to α, and sharing the same apex. The $\beta(\alpha)$ relationship was experimentally confirmed.

Extensive data on liquids of low conductivity and dielectric constant were published by Cloupeau and Prunet-Foch [21,22], who also pointed out the existence of several spray regimes, as well as by Gomez and Tang [23]. But our main interest centers on the high conductivity liquids studied by Fernandez de la Mora and co-workers [24,25]. These are based mainly on formamide (CH_3NO, m.w.=45 g/mol, $\varepsilon \cong 111 - 13N$ $(moles/\ell\ solvent)$, $\gamma = 0.058N/m$). Solutions of $LiCl$ in formamide yield a conductivity which can be represented between $N = 0.015 mol/\ell$ and $N = 3 mol/\ell$ as $K(Si/m) \cong 1.03N^{0.694}$, which reaches 2.2 Si/m at N=3 mol/ℓ. This represents a substantial increase over the range of conductivities possible with other solvents, and opens up the possibility of high charge/mass droplets, as well as that of significant ion emission.

The experiments in Ref. [24] also used, for generality, a variety of other solvents and solutes, covering the range of K up to about 0.3, and ranging in dielectric constant from about 10 to 110. In all cases, stable single Taylor cones were obtained (at voltages above a threshold required for starting) as long as the non-dimensional volumetric flow rate

$$\eta = \left(\frac{\rho K Q}{\gamma \varepsilon \varepsilon_o}\right)^{1/2} \qquad (2)$$

exceeded some value of order 1. An upper limit on η (≈3-10) was also noted, but it appeared to be related mainly to electrode configuration. As long as the Taylor cone existed, the current was found to obey in all cases the law

$$I = f(\varepsilon)\left(\frac{\gamma K Q}{\varepsilon}\right)^{1/2} \qquad (3)$$

where f(ε) was about 18-25 whenever ε>40, and dropped more or less linearly with ε below that value. Eq. (3) was found to be insensitive to voltage and electrode configuration. Viscosity did not figure at all in these findings. Finally, the radius of the jet formed at the cone's tip was found to be

$$R \cong 0.2\, r^* \ ; \ r^* = \left(\frac{\varepsilon \varepsilon_o Q}{K}\right)^{1/3} \qquad (4)$$

These values for the jet radius, however were neither accurate, nor have they been extended to substances other than ethylene glycerol or to the size range below 5 μm. The most comprehensive measurements of $f(\varepsilon)$ for a wide range of ε were reported by Chen and Pui [26,27].

Fernandez de la Mora and Loscertales explained these very simple and general results by a semi-quantiative model based on the fact that the liquid tip cannot remain equipotential, as assumed in Taylor's model, at distance $\leq r^*$ from the tip. Inertia is shown to play no role when $\eta \leq 1$, although it should at η>>1 (and this is the case in liquid metals, as discussed in Ref. [25]). More surprising is the lack of any visible influence of viscosity, despite the creeping-flow nature of the liquid motion; apparently, the flow pattern is that of a simple irrotational sink flow, in which viscous effects would indeed disappear.

Additional detail on the nature and properties of the droplets produced by electrospraying from highly conductive solutions is reported in Refs. [28] and [29]. In [28], it is observed experimentally that the droplets are nearly monodisperse (except for the presence of "satellite" droplets) when Q is near the minimum for Taylor cone operation, but that bifurication into additional modes appears in the size distribution as Q is increased. This is of interest for colloid thrusters, which will normally be made to operate near Q_{MIN}, since this maximizes q/m. In [29], charge and mass are measured separately, and it is found that, even though charge may spread in a range $q_{MAX}/q_{MIN} \approx 4$ the

charge per unit volume is nearly uniform, which is interpreted as indicating that charge remains locked to the liquid during jet breakup. Again, a uniform q/m is of some importance for the proper focussing and control of colloid beams in a colloid thruster.

Although no comprehensive theory has yet appeared covering all of the phenomena discussed above, the recent analytical work of Cherney [30] has laid out many of the fundamental concepts, including bulk and surface transient of change and viscous-driven recirculation inside the liquid tips. His work provides approximate expressions for the evolution of the cone into a thin jet, which eventually breaks into the individual droplets.

The comments so far have concentrated on the emission of droplets . But, as evidenced by the glycerol work in the 1960's and 70's, and by the recent macromolecule analysis advances, ions can also be extracted from electrolytes under some conditions, and this is also of direct technological importance for high-performance colloid thrusters. The literature on "ion evaporation", as the field tends to be called, is by now vast, and no attempt will be made to cover it in any detail. Rather, we will select a few recent articles which are relevant to the kind of high-conductivity solutions envisioned for our application, and also which provide some of the basic scientific underpinnings for understanding the phenomena.

From a variety of observations [31,32], it is known that ions evaporate from solution under fields in excess of 1-3 V/nm, an order of magnitude smaller than required for solid metals. The precise mechanism by which ions appear in an electrospray has been a matter of debate between proponents of field emission and those of some form of droplet evaporation, combined with Coulomb explosions. However, the detailed experiments of Ref [33] have established the first of these routes as the only one of importance in the case of small solutions ions.

The recent work of Gamero-Castaño [34] has further clarified the field emission mechanisms. Using a combination of stopping potential analysis and preferential scattering in a background gas, Gamero has been able to establish that, at high enough ratios K/Q of conductivity to flow rate, the ions originate directly form the neck region of the cone-jet, where the normal field reaches a maximum. This maximum field increases as the jet becomes narrower (by reducing Q or increasing K), until, if the Taylor cone is still stable, the critical field for emission is reached. Further reductions of flow then produce an increase in current, breaking the normal electrospray $I \approx Q^{1/2}$ trend. Solutions with $K \geq 1\ Si/m$ are required in order for this ion-emitting regime to be attained before the cone becomes unstable, and the work in [34] is based on concentrated formamide solutions of NaI (up to 3 Molar). For K/Q values below critical, some ion production was also detected, coming instead from the main droplets or from the small satellite drops, but their contribution saturated at high K/Q, and was eventually dominated by that from the meniscus itself. This latter emission rises very rapidly at the lowest stable flows, and becomes comparable or greater than the droplet-carried current. The detailed mechanics of this mixed regime is as yet unknown, and so is the limit of the ion current component.

3. Experimental Work

A single needle experimental set-up was constructed at Busek to investigate its operation and geometry while electrospraying three potential propellants. The apparatus (Fig. 1) includes the housing of the single needle experiment attached to a large vacuum chamber, an 80x optical microscope to observe the Taylor cone formation, and a color video camera to display the image on a nearby TV monitor.

Most experiments focussed on time-of-flight (TOF) measurements to determine the charge over mass ratio (q/m) of the electrosprayed droplets. A special TOF apparatus was constructed for this purpose and is shown schematically in Fig. 2. Although not nearly as sophisticated as commercially available mass spectrometers, the TOF can distinguish between ions and droplets. The highest droplet q/m was measured to exceed 3000 C/kg and the highest measured ion q/m was 7,900 C/kg. The droplet q/m was independently confirmed by direct beam current (I) and volumetric flow rate (Q) measurements using the relation $q/m = I/\rho Q$ where ρ is the propellant density. This gives us a high degree of confidence that colloid thrusters with $I_{sp} \approx 1000$ sec can be developed while keeping the applied voltage below 5 kV.

We commented in an earlier section that the colloid thrusters developed during the 60's and 70's were based on a multicone electrospraying regime, rather than on a single cone-jet. This assertion is supported by the data in Fig. 3 and photos of the emitting needle tip in Fig. 4. In Fig. 3 we plot the electric

current emitted by a glycerol fed electrospray needle as a function of the voltage difference between needle and a facing grounded electrode. The distance between both electrodes was 4 mm. The needle ID was 50 μm. The flow rate was kept fixed and equal to Q_0=12.5 nl/s. The curve I versus V has a staircase structure at voltages below 4200 V. Thus, we see a first step in the voltage range 2400 V to 3230 V. Here, the current increases slightly with V. The shape of the liquid meniscus held at the tip of the needle is shown in Figs. 4a and 4b. Clearly the liquid meniscus shrinks as the electric stress set on the needle is augmented. However, note that the geometry of both menisci corresponds to that of a well defined cone-jet. In Fig. 3 we observe a sudden increase of electric current when the needle voltage goes beyond 3230 V, reaching a second plateau between 3350V and 3770 V. A picture of the new meniscus geometry, taken at 3600 V, is offered in Fig. 4c: two off-axis emission points are observed. Hence, the total current will be that emitted by two cone-jets, each one approximately fed by one half of the overall liquid flow rate Q_0. If the needle voltage is further increased, a third step appears beyond 3770 V. A third emission place is also barely observed in Fig. 4d, taken at 3960 V. Finally, the staircase structure is lost beyond 4160 V, and the needle current increases continuously with applied voltage (see Fig. 4e, taken at 5200 V). This seems to indicate that the emission of charged particles beyond ~ 4160 V does not occur from individual jets, but the liquid fed through the needle is sprayed from the whole needle rim, probably in a non steady fashion. Although we have not done TOF measurements of this highly stressed regime, the average specific charge of these sprays can be estimated by means of mass-charge conservation arguments. Furthermore, note that there is no reason to expect a production of a steady, monodisperse electrospray in this highly stressed regime and any thruster operating in this mode will inherently have significant thrust "noise" may be intolerable for many missions.

4. *Discussion and Conclusions*

Colloid propulsion has been identified as directly applicable to at least two kinds of

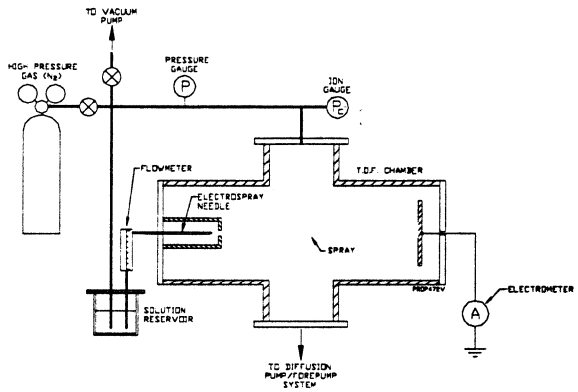

Fig. 1 Basic arrangement required to set a cone-jet in vacuum and measure the stopping potential of the beam particles.

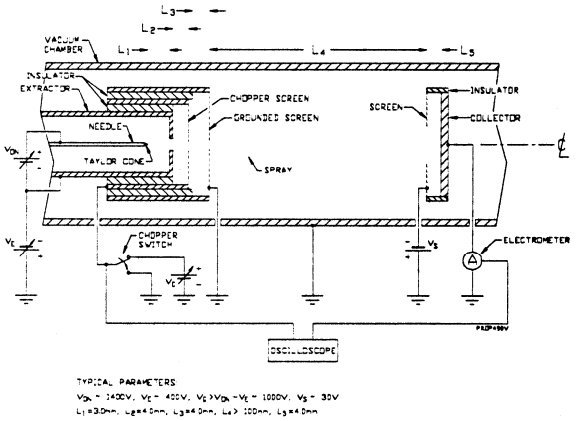

Fig. 2 Needle schematic with chopper (TOF apparatus)

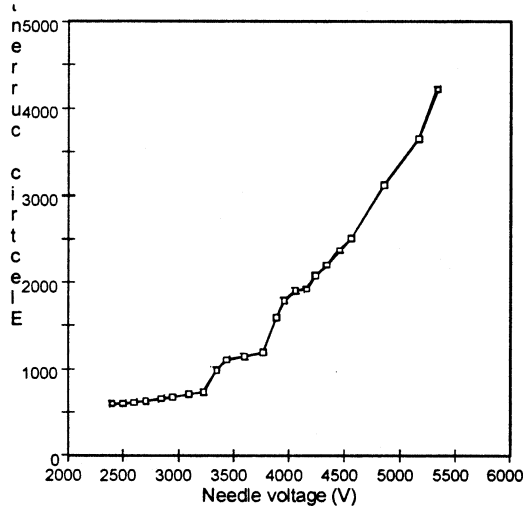

Fig. 3 Electric current versus needle voltage for a glycerol solution. Additional cone-jets are generated in the needle as the voltage is increased. The generation of new jets is observed in the form of current steps

Fig. 4a Cone-jet of glycerol. The needle voltage is set at 2600 V. The liquid meniscus ends in one on-axis jet

Fig. 4b: Cone-jet of glycerol. The needle voltage is 3230 V

Fig. 4c Glycerol in a multi-cone spraying mode. The needle voltage is set at 3600 V. Two off-axis emission points are observed

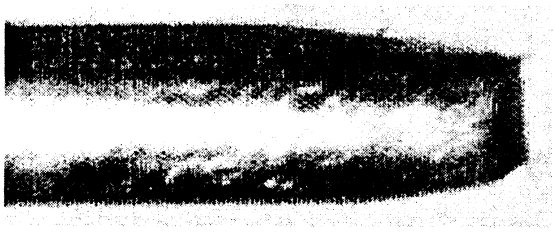

Fig. 4d Glycerol in a multi-cone spraying mode. V_{on} = 3960 V. Three emission points are barely spotted

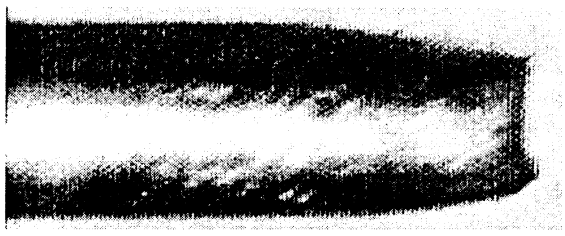

Fig. 4e Highly stressed electrospray of glycerol. V_{on} = 5200 V. Distinct emission points are not observed any longer

space missions: (a) Missions requiring ultra-precise attitude or position control, where the DC operation and fine thrust controllability (though a combination of flow and voltage control) of these thrusters, down to the μN level, will be advantageous. An example could be the LISA gravity were experiments, for which the similar Field Emission Electrostatic Propulsion technology is currently baselined. (b) Missions requiring the high Isp and efficiency of Electric Propulsion, but with severe constraints on power due to spacecraft miniaturization. The flexibility in the choice of working solvent/solute combinations, voltage, cluster configuration, etc., means that colloid thruster designs can be tailored to the specific mission needs. Thus, missions of type (a) may be accommodated with low voltages, leading to moderate Isp≈500 s., while emphasizing the controllability aspects; on the other hand, type (b) missions could use higher voltages and more conductive solutions, in order to obtain better specific impulses. Microfabrication studies now underway at MIT appear promising, and offer further opportunities for miniaturization, resulting in both, lower starting voltages, and reduced evaporation losses.

REFERENCES

1. Zeleny, J., "Instability of Electrified Liquid Surfaces", Phys. Rev. 10, 1-6 (1917).
2. Hendricks, C.D. and Pfeifer, R.J., "Parametric Studies of Electrohydrodynamic Spraying", AIAA 5th Electric Propulsion Conf., S. Diego, 1966.
3. H. Lamb, Hydrodynamics (Dover, NY, 1945).
4. Melcher, J. Continuum Electromechanics, MIT Press, 1981.
5. Zeleny, J., "The Electrical Discharge from Liquid Points and a Hydrostatic Method to Measure the Electric Intensity at their Surface". Phys. Rev., 3, 69-91 (1914).
6. Zeleny, J., "On the Conditions of Instability of Liquid Drops, with applications to the electrical discharge from liquid points". Proc. Comb. Phil. Soc., 18, 71-93 (1915).
7. Taylor, G.I., "Disintegration of water drops in an electric field", Proc. R. Soc., London A 280, 383-397.
8. Krohn Jr., V.E., "Liquid metal droplets for heavy particle propulsion", in Progr. in Astronautics and Rocketry, A.C. Press, N.Y.-London, Vol. 5 (1961).
9. Krohn Jr., V.E., "Gylcerol droplets for electrostatic propulsion" ARS Electric

Propulsion Conference, Berkeley, CA, 1962.
10. Hunter, R.E., "Theoretical Considerations on non-uniformly charged expellant beams", ARL TN-60 136 (Aug. 1960).
11. Cohen, E., Somol, C.J. and Gordon, D.A., "A100-kV, 10-w heavy particle thruster". Paper AIAA 65-377, AIAA 2nd annual meeting, S. Francisco, CA, 1965.
12. Perel, J., et al "Research on a charged particle bipolar thruster". Paper AIAA 67-728, AIAA Electric Propulsion and Plasmadynamics Conf., Colorado Springs, CO, 1967.
13. Mahoney, J. et al, "Performance of Colloid Annular Emitters", Paper AIAA 73-1076, AIAA 10th Electric Propulsion Conf., Lake Tahoe, NV, 1973.
14. Daley, H. et al, "Colloid Annular Array Thruster Development", Paper AIAA 73-1077, AIAA 10th Electric Propulsion Conf., Lake Tahoe, NV.
15. Kidd, P.W. and Shelton, H., "Life Test (4350 hrs.) of an advanced colloid thruster module". Paper AIAA 73-1078, AIAA 10th Electric Propulsion Conf., Lake Tahoe, NV, 1973.
16. Huberman, M.N. and Rosen, S.G., "Advanced high-thrust colloid sources". J. of Spacecraft, Wol. 11, no. 7, July 1974, pp. 475-480.
17. Shtyrlin, A.F., "State of the art and future prospects of colloidal electric thrusters". Paper IEPC-95-103, 24th International Electric Propulsion Conference, Moscow, 1995.
18. Fenn, J.B., Mann, M., Meng, C.K., Wang, S.K and Whitehouse, C., "Electrospray ionization for mass spectrometry of large biomolecules". Science, 246, 64-71, 1989.
19. Hayati, I. Bailey, A.I. and Tadros, T.F., "Investigation into the mechanics of electrohydrodynamic atomization", J. of Colloid Interface Sc., 117; part I, pp. 205-221. Part II, pp. 222-230.
20. Fernandez de la Mora, J., "The effect of charge emission from electrified liquid cones". J. Fluid Mech., Vol. 243, pp. 561-574 (1992).
21. Cloupeau M. and Prunet-Foch, B., "Electrostatic spraying of liquids in cone-jet mode". J. of Electrostatics, 22 135-189, 1989).
22. Cloupeau, M. and Prunet-Foch, B., "Electrostatic spraying of liquids: main functioning mode". J. Electrost., 25 (165-184) (1990).
23. Gomez, A. and Tang, K., "Characterization of low flow rate, high charge density electrosprays". In Proc. 5th Intl. Conf. on Liquid Atomization and Spray Systems, NTIS Special Publication 813, pp. 771-778.
24. Fernandez de la Mora, J. and Loscertales, J.G., "The current emitted by highly conducting Taylor Cones". J. Fluid Mech., vol. 260, pp. 155-184 (1994).
25. Gamero-Castaño, M., Aguirre de Carcer, I. and Fernandez de la Mora, J., "On the current emitted by Taylor cone-jets of electrolytes in vacuo: Implications for liquid metal sources:. J. of Applied Physics, Vol. 83, No. 6, March 1998.
26. Chen, D.R., Pui, D.Y.H. and Kaufma, S.L. (1995) Electrosprays of conducting liquids for monodisperse aerosol generation in the 4mm to 1.8mm diameter range. J. Aerosol Sci., 26, 963-9-77.
27. Chen, D.R. and Pui, D.Y.H. (1997) Experimental investigation of scaling laws for electrospraying: Dielectric constant effect. Aerosol Sci. Tech, 27, 367-380.
28. Rossell-Llompart, J. and Fernandez de la Mora, J, "Generation of monodisperse droplets 0.3 to 4μm in diameter from electrified cone-jets of highly conducting and viscous liquids". J. Aerosol Sc., Vol. 25, No. 6, pp. 1093-1119 (1994).
29. DeJuan, L. and Fernandez de la Mora, J, "Charge and size distribution of electrosprays drops". J. Colloid Interf. Sc. 186, 280-293 (1997).
30. Cherney, L.T., "Structure of Taylor cone jets: limit of low flow rates", J. of Fluid Mechanics, 1999, Vo. 378, pp. 167-196.
31. Iribarne, J.V. and Thompson, B.A., J. Chem. Phys. 64, 2287 (1976).
32. Fenn, J.B., J. Am. Soc. Mass Spectrom, 524, 524 (1993).
33. Loscertales, I.G. and Fernandez de la Mora, J., "Experiments on the kinetics of field evaporation of small ions from droplets", J. Chem. Phys. 103 (12), pp. 5041-5060 (1995).
34. Gamero-Castaño, M. and Fernandez de la Mora, J, "Direct measurement of ion evaporation kinetics from electrified liquid surfaces", J. Chem. Physics., 1999 (to appear).