Temperature Effects and Capillarity in an Electrostatic Liquid Thruster

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The performance of a 3-cm-long capillary-fed colloid thruster is measured as a function of temperature and capillary channel width. The data are complementary to the large body of data available on the performance of pressure-fed thrusters. Propellant mass flow rate and thrust change considerably as temperature is increased over the range 19-40°C, but efficiency does not show any significant change. To obtain high-exhaust velocity and high-mean specific charge the propellant temperature should be as low as possible. At constant temperature, propellant mass flow rate is proportional to the square of capillary channel width. If the thruster is operated at high-current levels, sudden drops in thruster efficiency may occur because of a hydrodynamic effect.

Introduction

COLLOID thrusters, propelled by glycerol doped with soldium iodide, have been developed in the USA and Europe during the last decade. Space tests of this type of thruster have not yet been conducted but ground tests suggest that it will be a reliable, easily controlled unit which may eventually supersede the hydrazine thruster for certain satellite attitude-control and station-keeping functions.

Propellant feed to the working zone of a colloid thruster may be by a positive-drive pressure or by capillary action. Virtually all work in the USA has been on positive-drive systems. In Europe some attention has been given to capillary systems[1] in the belief that they would be sufficiently reliable and possibly simpler than pressure-fed systems. However, regardless of feed-system type, an alternative to the standard glycerol doped with sodium iodide propellant has yet to be found. This propellant is temperature sensitive because of changes in both viscosity and electrical conductivity, and temperature control of pressure-fed thruster units is now accepted and is also envisaged for capillary-fed units.

This paper reports upon measurements carried out on a capillary-fed linear-slit thruster unit which was tested with glycerol doped with sodium iodide (20% weight NaI) over a temperature range of about 20-40°C. Measurements were also made over a range of capillary channel dimensions and these results are to be fully reported elsewhere.[2]

Theory

The body of a linear-slit colloid thruster may be represented schematically by Fig. 1 (acceleration electrodes not shown). The width and length of the capillary channel are w and l respectively. The working edge length is n. If $n \gg w$, end effects are negligible and the propellant flow from the reservoir to the working zone may be treated as a two dimensional problem. During thruster operation the meniscus of the liquid in the working zone recedes into the capillary slit and there is a net pressure drop ΔP along the length of the capillary. ΔP depends on the propellant mass-flow rate $\dot{m}$ as follows[2]

$$\Delta P = -12\mu \dot{m} l / n \rho w^3 \tag{1}$$

This pressure drop corresponds to a meniscus mean radius of curvature R_d where $w/2 < R_d < R$. R is the radius of curvature of the meniscus in the propellant reservoir. ($R \to \infty$ for a large reservoir.) μ and ρ are propellant dynamic viscosity and density, respectively.

In a capillary-fed thruster the pressure drop ΔP is caused by the action of an electric field E acting on the propellant surface at the thruster edges. E may be considered as an independent variable during thruster operation while ΔP and, hence $\dot{m}$ are dependent variables. To quantify ΔP, it is necessary to know precisely how E depends upon edge geometry in the presence of the electrically conducting propellant. In addition, the physical processes which occur during spraying must be understood. These processes are not fully understood at present. The following observations indicate how thruster performance may depend upon propellant temperature.

Consider the effects of changing propellant temperature. The changes in propellant viscosity, ν, and electrical conductivity σ brought about by temperature change have been considered elsewhere.[3] Kidd[4] measured viscosity of glycerol doped with sodium iodide over the range 20-80°C and his results interpreted over the more restricted temperature range considered here show that $\nu \propto T^{-2.85}$. Electrical conductivity measurements by Bailey[3] using a standard conductivity cell at 1 kHz showed that as $\sigma \propto T^{-2.37}$. These later measurements apply for low values of electric field. The field values applicable in the thruster working zone are so high that the conductivity of the propellant is field dependent.[5]

If the propellant viscosity alone were to change with temperature, the liquid meniscus in the spraying zone, which is primarily dependent upon liquid conductivity and electric field, would not change. The pressure drop equation requires that any change in ν must cause an inverse change in $\dot{m}$ to maintain ΔP constant. Increases in temperature would thus induce an increase in $\dot{m}$, and if thruster voltage V and current I remained constant, the mean specific charge $\langle q/m \rangle$ of the expellent would drop as

$$\langle q/m \rangle = I/\dot{m} \tag{2}$$

If propellant conductivity increases, the rate at which surface charge builds up also increases. If the electric field in the working zone remains constant then the higher value of surface charge will result in greater surface forces and accelerations which result in a reduction in droplet formation times. The foregoing effects tend to increase the mean specific charge of the expellant.

In summary, the conductivity and viscosity changes brought about simultaneously by a change in propellant temperature in a capillary-fed thruster may therefore be expected to have oppositing effects, but without further understanding

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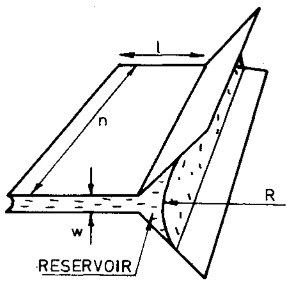

Fig. 1 Schematic diagram of linear-slit colloid thruster.

of the physical processes of electrostatic atomization it is not possible to quantify these effects.

Experimental

All tests were done using a 3-cm-long linear-slit thruster having platinum-iridium working edges. It was possible to vary the capillary channel width w by using shims between the two halves of the thruster body. Channel length l was also changed from 5-1mm in 1mm steps by grinding away the bottom of the propellant reservoir. Results reported here are for channel lengths of 5 mm (thruster performance as a function of current) and 1mm (thruster performance as a function of temperature).

Before the thruster was filled with propellant it was thoroughly degreased in xylene in an ultrasonic bath. This was followed by washing in a detergent solution before rinsing with alcohol. Propellant which was stored under vacuum was then transferred to the thruster reservoir immediately prior to mounting the unit within the vacuum chamber. System pump down then commenced with the minimum delay so that the propellant was exposed to atmospheric conditions for a total time of about a minute. Scrupulous cleanliness was observed during the preparation of the propellant itself and the sodium iodide was disolved in the glycerol under vacuum. The propellant was not filtered and no problems of capillary channel blocking were experienced.

Thruster performance may be assessed in terms of such independent or primary parameters as voltage V, current I, thrust T, and propellant mass-flow rate $\dot{m}$. Other dependent parameters such as mean exhaust velocity $\langle v \rangle$, average charge-to-mass ratio $\langle q/m \rangle$, and thruster efficiency η are usually derived from the primary parameters. In our studies the primary parameters were measured directly.

The voltage of the thruster main power supply was controlled by a helical potentiometer which was driven by a low-speed motor so that voltage could be changed at a slow, constant (but adjustable) rate. This facility was useful for plotting thruster V-I characteristics on an X-Y plotter.

Direct measurements of thrust T and propellant mass-flow rate $\dot{m}$ were done on a microbalance which is fully described elsewhere.[6] The thruster was enclosed in a screened box and mounted on the balance beam to thrust downwards. A stainless-steel wire mesh, with a geometrical transparency of 0.92, was mounted 1 cm in front of a honeycomb collector which itself was about 50 cm below the thruster. The screen was normally maintained at a potential of $+100$ V to collect secondary electrons. The whole thruster assembly could be heated by the radiation from a lamp. Propellant temperature was measured by a small specially made thermometer which was inserted into the propellant reservoir. The thermometer was a simple sealed glass unit containing alcohol. Such a simple system was used so as to avoid problems of high-voltage insulation and feed wires to the balance that could have arisen if a more sophisticated electronic thermometer had been used. It was calibrated in a separate experiment and it was estimated that it was accurate to about 0.5°C. During thruster testing the thermometer was read by using a cathetometer.

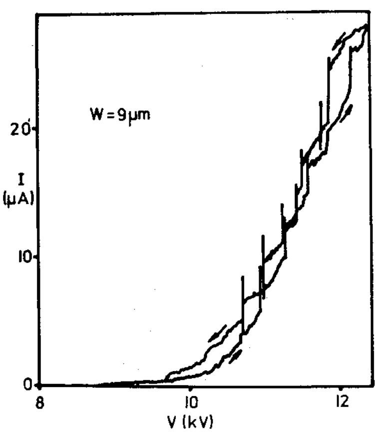

Fig. 2 Quantum-like current jumping.

Results

The thruster was protected against voltage breakdown by inserting a 14 MΩ resistor in the current supply line. The V-I characteristics were recorded directly on an X-Y plotter by increasing the voltage continuously at a rate of 1 kV-min up to a maximum value and then decreasing it back to the starting point at the same rate. The recorded characteristics need to be corrected for the current drop across the 14 $M\Omega$ series resistor as the recorded voltage is the power-supply voltage rather than the thruster voltage. Characteristics are presented in uncorrected form so that the fine structure of the curves is preserved.

Figure 2 shows in detail quantum-like current jumps that occur when the thruster is operated over a low range of current and voltage. This characteristic was recorded for a propellant temperature of 20°C. Hysteresis effects which are evident on this and all other V-I characteristics are anticlockwise in direction, i.e., currents observed during thruster voltage decrease tend always to be higher than currents noted during voltage increase.

By heating the thruster body with a lamp, the effects of propellant temperature on thruster performance were measured. The family of curves shown in Fig. 3 shows the effects of propellant temperature in the range 19-30°C. Hysteresis is observed to decrease significantly with temperature increase, whilst the slope of the V-I curve remains unchanged.

With capillary channel dimensions of $w = 0$ μm and $l = 1$ mm, the thruster was heated from about 20-40°C and thruster currents of 80, 120, and 160 μA. Thrust and mass-flow data are given in Figs. 4 and 5 and the dependencies of the derived parameters on temperature are shown in Fig. 6. The derived parameters were calculated from the following well-known relationships: mean exhaust velocity, $\langle v \rangle = T/\dot{m}$; mean specific charge, $\langle q/m \rangle = I/\dot{m}$; overall efficiency, $\eta = T^2/2\dot{m}VI$.

To illustrate the performance of the thruster at constant temperature the thruster was characterized over a range of capillary channel dimensions. The dependence of $\dot{m}$ on w is considered in detail elsewhere[2] and it is shown that $\dot{m} \propto w^2$. The dependencies of T, $\langle v \rangle$, $\langle q/m \rangle$, and η on thruster current, for a capillary channel length of 5 mm are shown in Figs. 7-10.

Discussion of Results

The current transitions shown in Fig. 2, which are both upwards and downwards, are similar to those observed during measurements on a single spraying site,[3] although the presently observed transitions are approximately ten times greater than those previously observed. Possibly, a whole group of sites undergoes a transition when stimulated by the transition of a single site. The hysteresis observed in Fig. 2, and on other V-I characteristics, is not caused by localized temperature changes in the thruster working zone, as was proved by the high-speed with which the transitions occurred.

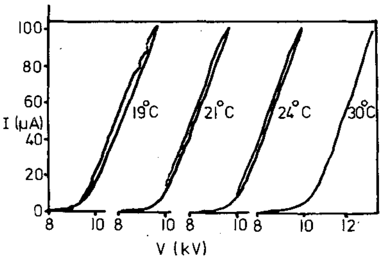

Fig. 3 Effects of propellant temperature on *V-I* characteristics.

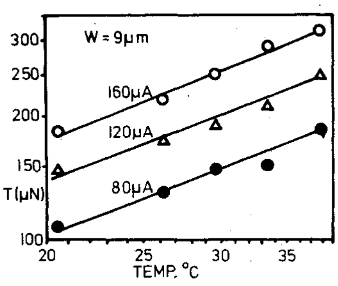

Fig. 4 Thrust dependence on propellant temperature.

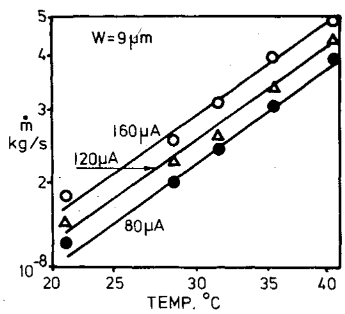

Fig. 5 Propellant mass-flow rate dependence on propellant temperature.

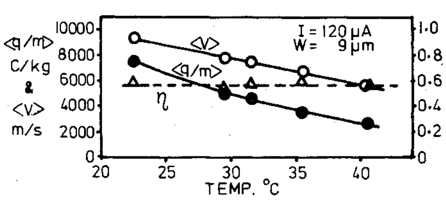

Fig. 6 Dependence of derived parameters on propellant temperature.

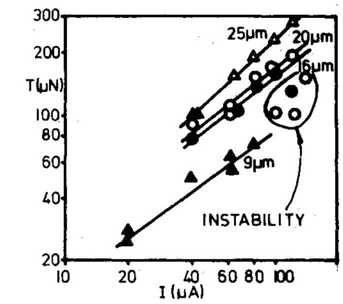

Fig. 7 Thrust as a function of current.

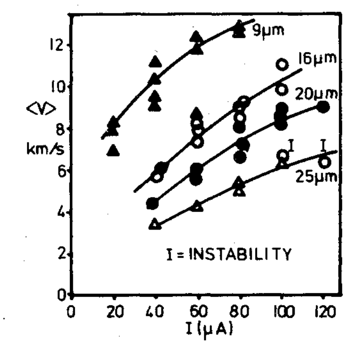

Fig. 8 Exhaust velocity as a function of current.

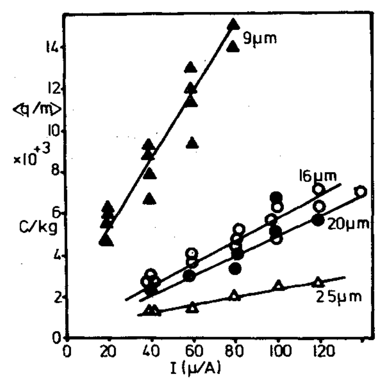

Fig. 9 Exhaust mean specific charge as a function of current.

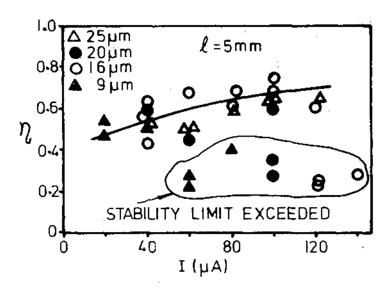

Fig. 10 Thruster efficiency as a function of current.

Transitions from a position on the return part of a characteristic to the lower curve could be deliberately provoked by rapidly switching the thruster power supply off and on again.

The temperature-dependent hysteresis of the *V-I* characteristics shown in Fig. 3 is probably hydrodynamic in origin, the temperature sensitivity possibly being caused by changes in the viscosity of the propellant or possibly due to changes in wetting angle. It seems likely that the shape of the whole meniscus in the working region changes with field and may take up one of two stable configurations. Some bulk movement of this sort seems to be required to account for the large magnitude of the hysteresis effect. It can be shown that the formation of a small perturbation on the meniscus surface corresponds to an additional energy store in the spraying system, but for the size of sites envisaged (sub-micron sized) about 10^6 sites would be required to account for the observed effects. Although it seems almost obvious that changes in viscosity with temperature are responsible somehow for the hysteresis effect is is difficult to see how viscosity can affect the magnitude of the hysteresis. Transition rate would seem to be a much more susceptible parameter to changes in viscosity.

The *V-I* characteristics do not display any significant change in slope over the temperature range considered. It would therefore seem that the changes in ν and σ which bring about changes in $\dot{m}$ and $\langle q/m \rangle$ balance out so that the thruster operating current remains relatively constant, at constant applied voltage, as temperature is changed. This performance is quite different from the temperature dependent performance of a pressure fed thruster where thruster current increases significantly as propellant temperature is increased.[4]

The effects of propellant temperature changes on thruster performance are shown in Figs. 4-6. Although $\dot{m}$ and T change quite considerably as temperature rises, the thruster efficiency remains constant. The drop-off of $\langle v \rangle$ and $\langle q/m \rangle$ suggests that the propellant temperature should be as low as the thrust requirements permit. Both $\langle v \rangle$ and $\langle q/m \rangle$ are derived from separate primary parameters (T, $\dot{m}$, I) but as $\langle v \rangle$ comes about by the acceleration of charged droplets in the thruster working region these parameters should be related by $\langle v \rangle^2 \propto \langle I/m \rangle$. It is clear from Fig. 6 that this relationship is followed experimentally. The observed changes with temperature of T, $\dot{m}$, $\langle v \rangle$, and $\langle q/m \rangle$ are similar to those seen in pressure fed units when temperature is changed with feed pressure maintained constant.[4]

The reason for the observed dropping off of $\langle q/m \rangle$ with temperature cannot be completely explained without detailed knowledge of the spraying-site mechanism. In particular it is necessary to know how the $\langle q/m \rangle$ of droplets from a single spraying site changes as the propellant mass-flow rate to that site is changed, either by drive pressure changes or by temperature changes.

Figures 7 and 8 should be considered together, as for any real thruster application both T and $\langle v \rangle$ would be dictated by mission requirements. For many applications, $\langle v \rangle$ should be at least 10^4 m/sec. This requirement necessitates careful control of $\dot{m}$ and for the capillary unit that was investigated, shim thicknesses greater than 16μm would not be desirable. At $\langle v \rangle = 10^4$ m/sec, a thrust level of about 150 μN was obtained at 100 μA for the 16 μm shim. This corresponds to 50 μN/cm length of slit and an $\dot{m}$ of about 5×10^{-9} kg/s/cm. (Note $\dot{m} = T/\langle v \rangle$). A 1 mN unit would therefore require a total length of 20 cm and would use 10^{-7}kg of propellant/sec. It would thus be able to operate continuously for 115 days on 1 kg of propellant. The thruster efficiency would be greater than 60%.

Figure 10 shows that a severe drop in efficiency occurs above a certain level and this level increases as w increases. For $l = 5$ mm, this limit was reached at currents as low as 50 μA when a 9 μm shim was used. When the 25 μm shim was used no such drops in efficiency were observed. The drops in efficiency occurred quite suddenly and at the same time the thruster expellant spray was observed to become slightly visible and striated across the width of the beam. The thruster no longer operated stably. It seems likely that the stability limit is hydrodynamic in nature as it was found in other tests to depend upon capillary-channel length. At the stability limit, parts of the thruster-edge region may become starved of propellant which may cause ion emission to occur with an attendant drop in efficiency.

Conclusions

Further understanding of the basic physical process of electrostatic spraying of liquid is necessary before the characteristics of a colloid thruster are properly understood. Measurements reported here on temperature effects on a capillary-fed thruster are complementary to the large body of data available on the performance of pressure-fed thrusters. The present data show that the efficiency of a capillary-fed unit exhibits little, if any, change with temperature, but that to obtain high exhaust velocity and high mean specific charge, propellant temperature should be as low as possible.

When the thruster was operated at high current levels, sudden drops in efficiency were observed and the onset of these drops depended upon capillary channel length. There is evidence to suggest that these drops have a hydrodynamic origin and further work should be done to fully understand this effect. It is probable that the surface condition of the inner walls of the capillary channel strongly influence the stability limit of a capillary-fed colloid thruster.

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