Applications to Space Operations of Free-Flying, Controlled Streams of Liquids

E.P. Muntz* and Melissa Dixon†
University of Southern California, Los Angeles, California

Potential uses for free-flying, recoverable streams of liquids in space are identified. One application, where droplets are the radiating component of a lightweight thermal heat rejection system, has been studied previously by Mattick and Hertzberg. Other applications (i.e., systems for the disposal of surplus liquids) have already been used in space. New possibilities are also considered: a droplet aerobrake system, an orbital planetary gas accumulation system, a space material transport system, a method for remotely accomplishing space construction tasks using droplet streams, and a low-contamination attitude control or stationkeeping thruster. The proposed applications require that the streams have varied but generally high directional and speed stability. Charts summarizing liquid stream performance are presented. New experimental results extending the performance characteristics by an order of magnitude compared to previous observations are reported.

Nomenclature

D_0	= stream diameter away from the nozzle
k^*	= nondimensional wavenumber
k_0^*	= effective nondimensional wavenumber
L_e	= entrance length for fully developed Poiseuille flow
p_v	= vapor pressure
Re_{0D}	= Reynolds number based on stream diameter
R_0	= stream radius away from the nozzle
V	= average stream speed at the nozzle exit
$\bar{V}_d$	= average droplet speed
V_0	= average stream speed away from the nozzle
We_{0D}	= Weber number based on stream diameter
β	= amplification growth factor
μ	= viscosity
ρ	= density
σ	= surface tension
$\sigma(V_d)/\bar{V}_d$	= velocity dispersion of the droplet stream
$\sigma(\theta)$	= angular stream dispersion
τ_0	= stream breakup time
τ_∞	= undisturbed breakup time
τ_R	= velocity relaxation time

Introduction

THE exposure of liquids to the high vacuum of space has been associated with the disposal of surplus water or other fluids[1-3] and fuel venting.[4] In these situations, the liquid's exposure to space is considered a necessary evil, leading to serious concerns about contamination of the vehicle by atomized liquid or vapor. Recently, the proposal for a liquid droplet radiator[5] has suggested a more positive application of free-flying liquids in space. There also has been specialized work on metal powder production using liquid metal streams, saturated with a high-pressure gas, suddenly exposed to a low ambient pressure.[6] However, until the recent work of Muntz and co-workers[7,8] and the earlier pioneering study by Fuchs and Legge,[1] surprisingly little attention has been given to either predicting or systematically studying the behavior of liquid streams in high vacuums.

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*Professor, Department of Aerospace Engineering. Fellow AIAA.
†Research Assistant, Department of Aerospace Engineering. Student Member AIAA.

Commonly, a fluid is ejected to vacuum through an axisymmetric nozzle, producing streams typically a few millimeters in diameter for water disposal[1] to 100 μm diam in the liquid droplet radiator. Streams will break up into droplets due to surface tension-driven instabilities, except when the liquid properties are such that cavitation destroys the stream or evaporation cooling causes it to become very viscous. The several possibilities are illustrated in Fig. 1. Stream breakup into droplets is a classic problem in fluid mechanics.[9,11] It can be controlled with great precision when it takes place in a high vacuum using low-vapor-pressure liquids. For space applications, it is necessary to understand the relationships and interactions of the many fluid mechanic and thermodynamic issues that arise when liquid streams are ejected into a vacuum. Evaporation, flashing or cavitation, diffusion of dissolved gases, and cooling by radiation and evaporation can all interact with the fluid mechanical breakup and droplet formation, causing a loss of control over the stream. The interactions have been discussed in detail in Refs. 1, 7, and 8.

There are several potential uses of liquid streams in space. Beyond the liquid droplet radiator,[5] one can propose the transport of material between spacecraft in the form of liquids or slurries. The transport of material from asteroids or moons (with masses less than about 10^{-4} Earth masses) without landing on the object also seems feasible. An extension of this idea to the ballistic transport of material from remote sites to a central processing station on any larger moon that has no atmosphere may be attractive. Another possibility is the use of separate, well-directed streams of polymers and ultraviolet sensitive hardeners to form in situ epoxy structures or to apply coatings in space. A sheet of droplets may be used as an easily deployable (but also rugged) passive drag producer for orbital transfer vehicles. A liquid stream can be used as a very low contamination attitude control thruster with a specific impulse about the same as a cold gas. Finally, a zero net mass use momentum transfer between spacecraft can be accomplished by projecting liquid from one vehicle to another, either one-way or in both directions simultaneously.

Some Potential Uses of Liquid Streams in Space

Several potential uses for liquid streams in space are outlined in this section. Assumptions are made about important characteristics of liquid streams that will be justified or at least made respectable in subsequent sections of the paper. For our immediate purposes, it is assumed that streams of low-vapor-pressure fluids ($p_v \leq 10^{-5}$ Torr), with diameters from a few tens of micrometers to a few tens of millimeters, will form droplet streams that can be directed with drop-to-drop angular dispersions no greater than a few microradians and drop-to-drop speed dispersions no greater than a few parts in a million. It is further assumed that these same stream characteristics apply to liquids with vapor pressures up to several Torr for the smallest diameters and to a few tenths of a Torr for the larger diameters. Finally, it is assumed that streams formed from suspensions or slurries of a crushed solid and low-vapor-pressure liquid also provide microradian angular stability and microfraction speed stability.

Several possible uses of liquid streams are discussed briefly in the subsections that follow. Some if not all are speculative. However, considering the generally low level of prior interest in the behavior of liquids in either a high vaccum or space, it is important to note the number of possibilities that do appear. As more is learned about liquids exposed to the space environment, additional potential applications will almost certainly be recognized.

Liquid Droplet Radiator

The use of 10^6 or so recapturable droplet streams has been proposed as a lightweight thermal radiator for high power space platforms.[5] A sketch of one radiator configuration is shown in Fig. 2.[12] There is currently an active research and development program on this application at both the U.S. Air Force Rocket Propulsion Laboratory and the NASA Lewis Research Center. Studies to date indicate factors of three or more savings in radiator weight for megawatt size thermal radiators. There are a number of technical issues yet to be settled. Among these is the formation and control of a large number of closely spaced droplet streams, as well as their efficient recapture.

Aeroassisted Deceleration

The transition from geosynchronous to low Earth orbit requires a speed change of around -4 km/s, of which -2 km/s can be accomplished close to the Earth, making it possible to consider employing an aerobrake. We examine here the use of a recoverable droplet sheet to transfer momentum from an orbital transfer vehicle (OTV) to the upper atmosphere. One of many possible configurations is illustrated in Fig. 3. For a 10,000 kg OTV, the results of preliminary calculations of the area of the droplet sheet, as well as the droplet temperature required to reject the kinetic energy of the speed change as radiated thermal energy, are shown in the figure. In this application, the liquid would probably be molten tin or some other liquid metal (see Ref. 5 for the properties of candidate radiator materials). The droplet aerobrake would be relatively immune to damage, rapidly deployable (basically, the sheet startup time, which is the few seconds required for a droplet to travel from the generator to the receiver), and could double as a radiator or vice versa. There are many remaining questions of both system and technical natures that have to be examined before the ultimate attractiveness of a droplet aerobrake can be assessed. The concept does appear to be feasible and is worth further attention.

Planetary Gas Scavenging

Some fluids exhibit a rather high potential barrier for the escape of dissolved gases. One of these is DC-705 (also DC-704), which is a low-pressure diffusion pump oil manufactured by Dow Corning. Consider the droplet aerobrake configuration of Fig. 3, but operated at low temperatures with

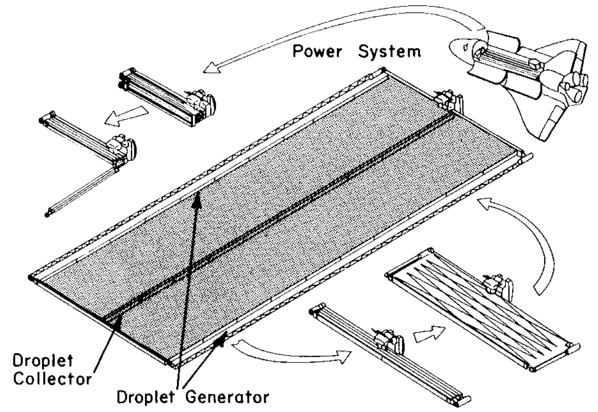


Fig. 2 Liquid droplet radiator unfolding from the Orbiter bay, from Ref. 12.

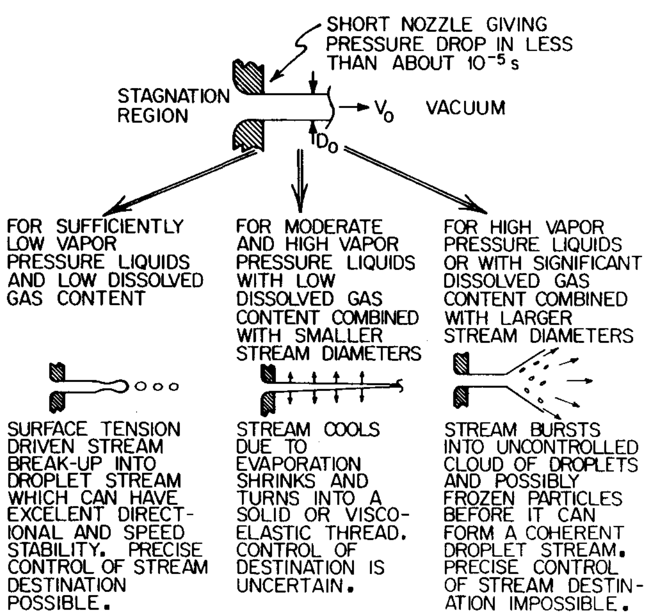
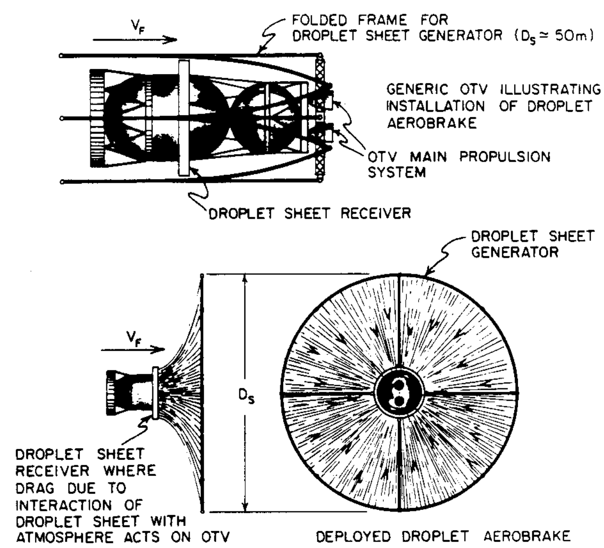


Fig. 1 Summary of possible events when liquid streams are formed in a vacuum.



FOR 10^4 kg OTV BRAKING FROM 10 km/s TO 8 km/s

ALTITUDE (km)	IMPACT MOMENTUM (ρV^2, N/m²)	MEAN FREE PATH (m)	SHEET SIZE, D_s (m)	SHEET MASS ($\rho_\ell = 1$, kg)	LIQUID TEMP (K)
120	4	1.5	50	1×10^2	730
140	6×10^{-1}	10.0	150	1×10^3	450

Fig. 3 Deceleration of an orbital transfer vehicle using a droplet sheet aerobrake.

DC-705. At an altitude of 250 km, the oxygen atom flux to a 50 m diameter area is equivalent to about 2×10^2 atm·cm³/s of O_2. We assume that the high-speed oxygen atoms, which have relative kinetic energies several times the surface potential barrier (essentially the energy required to make a "hole" in the fluid), embed themselves in the liquid and subsequently recombine. The potential barrier for escape from the liquids, which is about 20 times the thermal energy at 295 K for DC-705, would permit a practical O atom concentration in the liquid of around 3×10^{17}/cm³. We assume a fluid that is not susceptible to attack by O atoms. To gather 1 atm liter of O_2 would require processing about 10^2 liters of liquid. The energy required to do this (liquid stream speeds are a few meters per second) is very small. There are a number of remaining technical issues, including the effects of O atom recombination or chemical reactions with the fluid and the actual O atom capture coefficient, which was assumed to be one in this preliminary estimate. There are also system issues; for instance, lifting O_2 into orbit may require no more energy than that needed to make up the drag generated by absorbing the oxygen atoms. However, these are technical and systems questions that can only be answered by further study. The proposed gas absorber does offer the possibility of retrieving significant quantities (700 atm liters of O_2 per hour in the example used here) of planetary gases.

Material Transport

It appears attractive to examine the prospect of transporting material in space by liquid or slurry streams. It is relatively straightforward to accelerate unit density liquid or slurries to speeds as high as 10^3 m/s; a more common value might be 3×10^2 m/s. Solids, ground to an average size of a few tens of micrometers, can be transported as a slutter formed using a low-vapor-pressure liquid in a several millimeters diameter stream.

The idea for material transport is to generate a stream of the liquid or slurry to be transported and direct it to a remote receiver. The transport might be between spacecraft, between a small object and a spacecraft, or on the surface of larger moons. The only requirement is that there be little or no atmosphere and relatively small gravity. As an illustration, the ballistic transport of material on a moon is illustrated by the flow chart in Fig. 4. Here it is assumed that a remote mining operation is transporting material to a central processing plant. The remote site's power for stream generation is provided by power recovered from the stream of carrier fluid returning to the remote site. The area that could be covered by such an operation is illustrated in Fig. 5, where the exploitable area is plotted vs stream velocity for several assumed gravities. A 2.6×10^2 m/s stream on Earth's moon will permit exploitation of 2×10^3km². At maximum range, 10^3 hp is required to transport 100 m³/h of slurry. Assuming no losses and a slurry that is 50% carrier fluid, this power could be provided by returning the carrier fluid to the site at 3.6×10^2 m/s. Because of the small angular dispersion of the stream, the receivers need only be a few meters in size.

The transport of certain types of materials by liquid streams offers the potential for significant volume flow over intermediate distances without a transportation infrastructure. Thus, roads, pipelines, or temporary connections between spacecraft could be avoided. Certainly, high-vapor-pressure fluids such as liquid gases would be difficult to deal with in this manner. However, there are other materials that will fit into such a stream transportation scheme with little difficulty.

Space Construction

Chemical reactions have been observed between intersecting droplet streams of two chemicals.[14] An interesting possiblity is to extend this idea to applications in space construction or space repair. Consider two droplet streams, one a polymer and the other an ultraviolet sensitive hardener. The stream sizes or speeds are adjusted so that the hardener and polymer are in the correct proportions when they are delivered. If the fluids have a speed of around 10 m/s and a viscosity like DC-704, there will be very little material loss due to splattering.[13] An illustration of such a scheme for stabilizing a joint in a space structure is shown in Fig. 6. The directional stability of droplet streams permits one to propose having the two streams merge at, say, a range of 1 km within a few square millimeters area. Refurbishment or initial application of surface coatings is another possibility.

Fluid Disposal

Some of the first applications of fluid streams in space were for water disposal and fuel venting. This has been discussed in

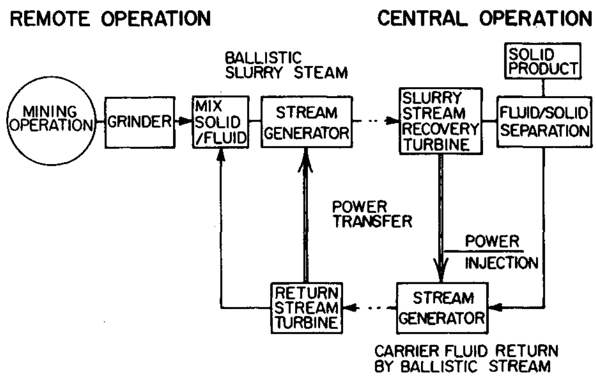


Fig. 4 Flow diagram for ballistic material transport on the moon.

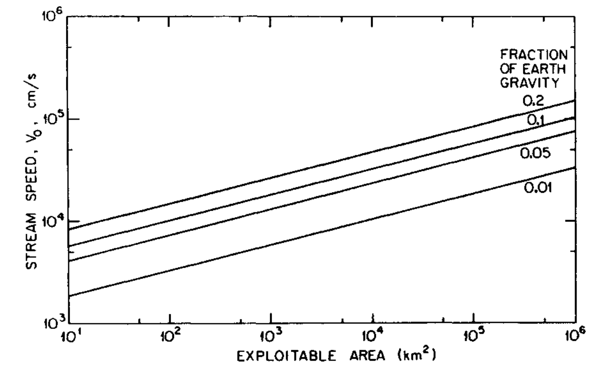


Fig. 5 Exploitable area for a ballistic material transport system as a function of stream speed.

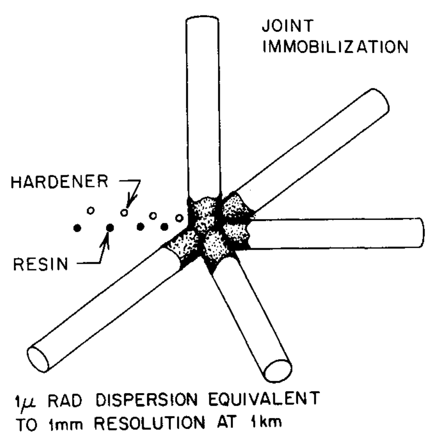


Fig. 6 Space construction task using droplet streams: joint stabilization.

Refs. 1 and 4. Since these applications are relatively familiar they will not be mentioned further.

Liquid Thrusters

The specific impulse of liquid streams as a function of stagnation pressure are illustrated in Fig. 7 for two candidate fluids. With practical limits on stagnation pressure, the streams exhibit specific impulses about the same as cold nitrogen (70 s); an upper limit might be as high as hydrazine, used as a monopropellant (170 s), if hydraulic pressure amplification is employed. With a stagnation pressure of 10^3 atm and a 200 μm diam stream, a thrust of 6.3 N can be produced at a volume flow rate of 20 cm^3/s. The reason for using liquids as a propellant would be to take advantage of their potential for being an extremely small source of contamination. As an example, consider a lithium stream slightly above its melting point. Assume a surface element 10 cm from the stream and in the same plane as the exit plane of the liquid stream's nozzle. The number flux of lithium atoms reaching the surface is about 10^6 $(cm^2 \cdot s)^{-1}$, which gives about 10^{-2} monolayers every 3×10^3 h of continuous operation.

An application similar to the attitude control thruster might occur during close-in maneuvering of transfer vehicles near a space station. Here, departing or arriving vehicles could maneuver by projecting liquid streams that are collected by the station; also the station could project streams that are collected by the transfer vehicles. There would be no net usage of propellant, as the two would merely be exchanging momentum while using a recirculating mass of fluid.

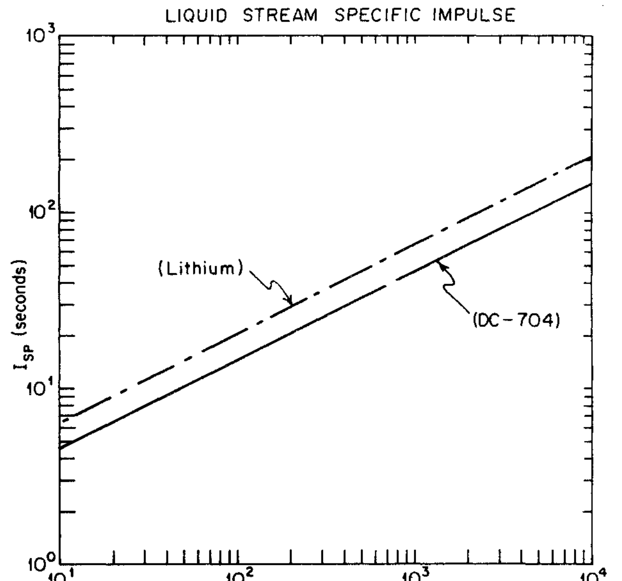


Fig. 7 Specific impulse of liquid thrusters as a function of stagnation pressure.

Discussion of Fluid Mechanics and Performance Maps for Droplet Streams in a Vacuum

The success of many of the proposed applications mentioned in the previous section depends on the actual performance that can be achieved by droplet streams in terms of directional stability and drop-to-drop speed dispersion. In this paper, we indicate the directional properties of a droplet stream by the standard deviation in angle $\sigma(\theta)$ of the stream's drops, where θ is measured from the nominal stream centerline and the nozzle exit is assumed to be a point source. The droplet speed variation is described by the standard deviation of droplet speed ratioed to the mean droplet speed $\sigma(V_d)/\bar{V}_d$.

Droplet Stream Fluid Mechanics

The breakup of liquid streams into droplets has been studied for well over 100 years.[9-11,15,16] Most of the experimental work has been done in air at atmospheric pressure, although there have been exceptions.[16] For the purposes of this section, consider a cylindrical stream of low-vapor-pressure fluid, such as Dow Corning DC-704 at 300 K, entering a high-vacuum chamber. It is assumed that the fluid is viscous and that the injection nozzle so shaped that the flow is parallel at the injection nozzle's exit surface. For the moment, we neglect any effects of the flow's radial velocity profile or the meniscus formed by wetting of the exit surface by the stream fluid. The stream has a speed V_0 and a diam D_0 (in general V_0 and D_0 can be different from the stream speed at the nozzle exit V and from the nozzle diameter D). Stream Reynolds and Weber numbers are

$$Re_{0D} = \rho V_0 D_0 / \mu$$

and

$$We_{0D} = \rho V_0^2 D_0 / \sigma \tag{1}$$

where μ, σ, and ρ are the liquid's viscosity, surface tension, and density, respectively. The response of the stream to imposed sinusoidal oscillations of the radius has been studied by Plateau,[11] Rayleigh,[9] Weber,[17] and many subsequent authors. In the linear theory, disturbances whose wavelengths are greater than the stream circumference are found to be unstable and grow exponentially in time (and thus space for a moving jet). The growth factor β, where the disturbance amplitude is $\epsilon_0 e^{\beta t}$, is given approximately for a viscous fluid by Weber[17] and Sterling and Sleicher[18] as

$$\beta^2 + \left(\frac{3\mu k_0^{*2}}{\rho R_0^2}\right)\beta = \left(\frac{\sigma}{2\rho R_0^3}\right)(1 - k_0^{*2})k_0^{*2} \tag{2}$$

Here, k_0^* is the nondimensional wavenumber $2\pi R_0/\lambda$ and R_0 the radius of the stream. Plots of β vs k_0^* are shown in Fig. 8 for lithium just above its melting point, DC-704, Hg, and H_2O.

Nonlinear amplification factors are similar, although there are differences in detail.[19] When strongly driven (several percent radial perturbation amplitude), a capillary stream with water-like viscosity will break up into droplets in a time

$$\tau_0 = \left(\frac{k_2 D_0}{2V_0}\right)\left(\frac{\rho V_0^2 D_0}{2\sigma}\right)^{1/2} = \left(\frac{k_2}{2\sqrt{2}}\right) We_{0D}^{1/2}\left(\frac{D_0}{V_0}\right) \tag{3}$$

where k_2 is between 10 and 20 for wavenumbers at which β is a maximum.[19] The term $(\rho R_0^3/\sigma)^{1/2}$ is a characteristic time corresponding to the characteristic capillary speed $V_c = (2\sigma/\rho R_0)^{1/2}$. For well-isolated streams with no imposed disturbance, the work of Grant and Middleman[16] provides an empirical breakup time,

$$\tau_\infty = 19.5(D_0/V_0) \cdot (We_{0D}^{1/2} + 3We_{0D}/Re_{0D})^{0.85} \tag{4}$$

This applies to low-speed streams that are presumably unaffected by the ambient atmosphere. Here, we will permit the extension of this correlation to higher velocities because of the very low ambient pressures considered. The validity of the correlation beyond distances of about 10^3 stream diameters, or for speeds beyond a few meters per second, has not been demonstrated.

We have made a few preliminary measurements of the breakup of a DC-704 stream. It had a speed of 34 m/s in a 10^{-5} Torr atmosphere and was formed with a 146 μm diam orifice. The breakup times for this stream from Eqs. (3) and (4) are, $\tau_\infty = 6.24 \times 10^{-3}$ and $\tau_0 = 2.04 \times 10^{-3}$ s. The measured breakup time for the stream when it is strongly driven is 4.1×10^{-3}, which is in reasonable agreement with Eq. (4), par-

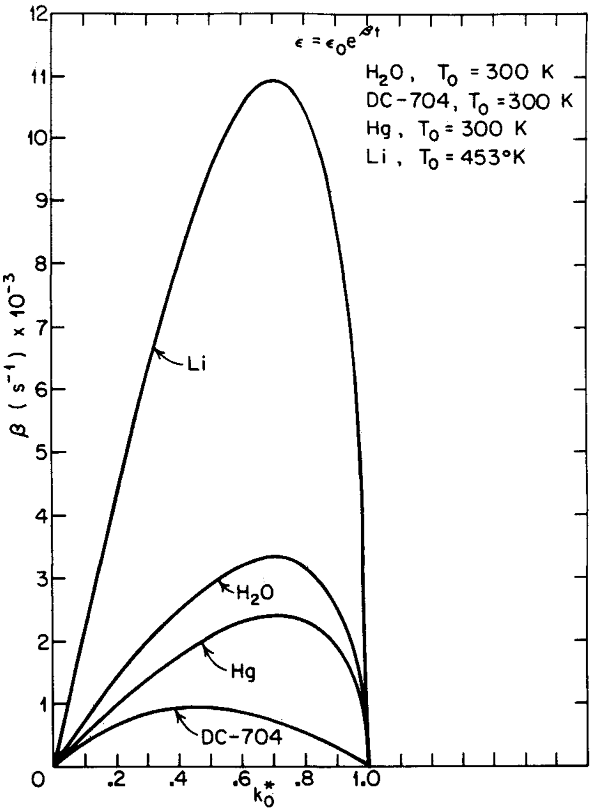


Fig. 8 Amplification factor as a function of nondimensional wavenumber.

ticularly since Eq. (4) results from experiments where the streams were not actively disturbed.

In the theory of Weber and Rayleigh, it has been assumed that there is no difference between applying a disturbance to an infinite cylinder of liquid and applying it at the nozzle in a progressive jet. As demonstrated by Goren and Gottleib,[20] this is indeed a reasonable assumption when the stream speed $V_0 \gg V_c$, a requirement frequently met in applications.

Recently, there has been an interest in the characteristics of the droplet configurations that result from the breakup of liquid streams with imposed periodic disturbances.[21] The interest has been for aerosol research[22] and in such applications as ink-jet printing.[19,23] The necessarily nonlinear theory of such breakup characteristics is incomplete, but quite extensive and has been reviewed by Bogy.[21] It has been found by Chaudhary and colleagues[19,23] that appropriate control of the amplitude of the harmonics of the primary disturbance frequency can be used to adjust the uniformity of the droplet stream formed from a liquid jet. In most practical situations, it is next to impossible to apply a single-frequency disturbance to a liquid jet, particularly in a vacuum. The experimental literature is full of somewhat divergent conclusions about the detailed characteristics of droplet formation. The principal question is the formation of so-called satellites and their subsequent motion. Satellites are small drops that form between the main drops of the stream. Usually, they eventually merge with one or other of the main drops that are on either side of them in the stream. A desirable configuration for the breakup is to have no satellites with one drop corresponding to one disturbance wavelength. The conditions under which satellites are obtained and their direction of eventual merging is unquestionably affected by the form of the disturbance that is in reality applied to the stream.[21,23] Since the disturbance waveform is very sensitive to the response characteristics of each experimental setup, it is not surprising that the results of different investigators do not always agree in every detail. There is, however, one point about which most investigators agree: by adjusting the exciting frequencies ever so slightly and being in a k_0^* range above 0.65 for fluids with water-like viscosities, it is possible to generate satellite-free streams.

A satellite-free droplet stream can be a very coherent phenomenon, composed of a stream of uniform droplets all moving at closely the same speed in the same direction. A major contributor to irregularities in droplet speed and direction is their interaction with an ambient atmosphere. In a vacuum, any drop-to-drop variation in speed or direction can come only from variations in the breakup process or from unsteady forces applied at the exit of the nozzle. The exit surface of the nozzle may be wet by the stream fluid. This permits surface tension forces to act on the stream, possibly in an unsteady manner, but generally at a frequency much lower than that represented by the drop-to-drop separations divided by the droplet speed.

The nozzle itself must, of course, have a sufficiently gradual entrance curvature to prevent the formation of a separation bubble (cf. Ref. 24) that could lead to unsteady stream conditions. Finally, there is a velocity relaxation length downstream of the exit in which viscous forces in the stream accelerate the boundary-layer fluid and bring the flow toward a uniform speed. It has been suggested by both Grant and Middleman[16] and Sterling and Sleicher[18] that the velocity relaxation can cause stream instabilities. The time for a uniform profile to be approached is given approximately by

$$\tau_R = L_e / V_0 \tag{5}$$

where $L_e = 0.025\ Re_{0D} D_0$ is the entrance length in a straight circular duct that is required for fully developed Poiseuille flow to be approached. There is an additional interesting effect if the velocity profile at the nozzle exit is significantly nonuniform.[25] For Poiseuille flow, application of the equations of continuity and momentum to the stream indicate that for $Re_{0D} > 100$ the stream contracts as the velocity profile relaxes. When the stream speed has become uniform radially, the stream diameter is $D_0 = 0.87D$. The final stream speed V_0 is $1.32V$, where V is the initial average stream speed. If a disturbance applied at the nozzle has a nondimensional wavenumber k^*, the final effective wavenumber is

$$k_0^* = 0.66k^* \tag{6}$$

The velocity relaxation will be important only when there is a significant boundary-layer thickness at the nozzle exit.

Performance Maps

The performance of droplet streams, in the context of their potential uses in space, is conveniently indicated by the distance that can be traveled by the stream before it becomes too large to recollect due to its angular dispersion or, due to the droplets' speed dispersion, too agglomerated to be useful. To begin, the simplest situation is the angular dispersion, where distances that can be traversed are shown as a function of required collector area in Fig. 9, with the angular dispersion as a parameter. Measurements reported in Ref. 7 indicate that $\sigma(\theta) \simeq 10^{-6}$ rad is a realistic value. Note that quite large distances are possible for relatively modestly sized collectors.

The question of droplet speed dispersion is more complicated. It is first important to realize that the droplets in a high vacuum follow each other very precisely, with no observable lateral (normal to the direction of stream motion) displacements from one drop to the next. The lateral displacements that do occur take place on a time scale much longer than the time between droplets. Thus, if adjacent droplets have small differences in speeds, they merge or separate along the stream axis. It is straightforward to estimate the merging or agglomeration of a droplet stream if the droplet speed dispersion is known.

In Fig. 10, the results of applying mass continuity and geometric considerations are presented. Relationships are exhibited between droplet size and original stream diameter, as a function of the disturbance's nondimensional wavenumber k_0^*; also shown is the spacing between drops as a function of the nondimensional wavenumber. For the operating range of k_0^* that generally can be achieved, the droplet spacing is quite small and the droplets are slightly greater than twice the stream diameter. For an expanded range down to $k_0^* = 0.01$, the spacing becomes quite large, along with the drop size. The large spacing at small $k_0{}^*$ is important for the long-range projection of streams with little droplet agglomeration. This is illustrated in Fig. 11, where the distances that can be traveled without significant agglomeration by droplets generated from liquid streams are indicated, with k_0^* and $\sigma(V_d)/\bar{V}_d$ as parameters. If small k_0^* and $\sigma(V_d)\bar{V}_d < 10^{-6}$ could be achieved, quite significant distances would be traversed without agglomeration. Preliminary measurements of $\sigma(V_d)/\bar{V}_d$ have shown[8] that 1.5×10^{-5} is a typical result in the k_0^* range of 0.5-0.7. Experiments described later indicate that significant improvements on this value are possible.

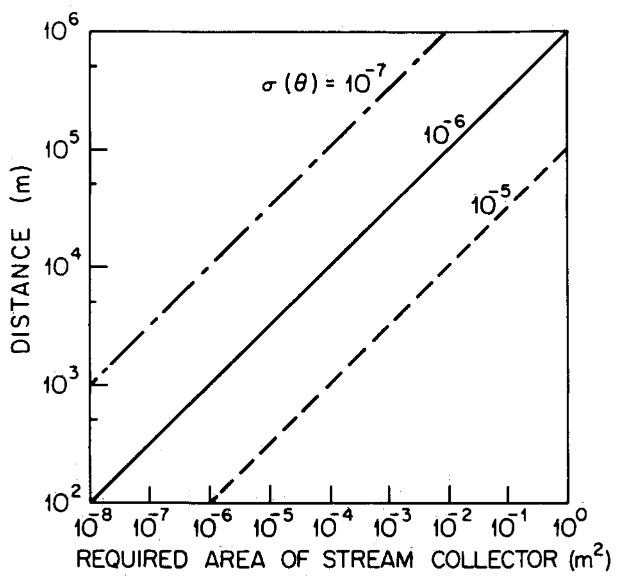


Fig. 9 Required collector area as a function of flight distance for liquid streams with angular dispersion as a parameter.

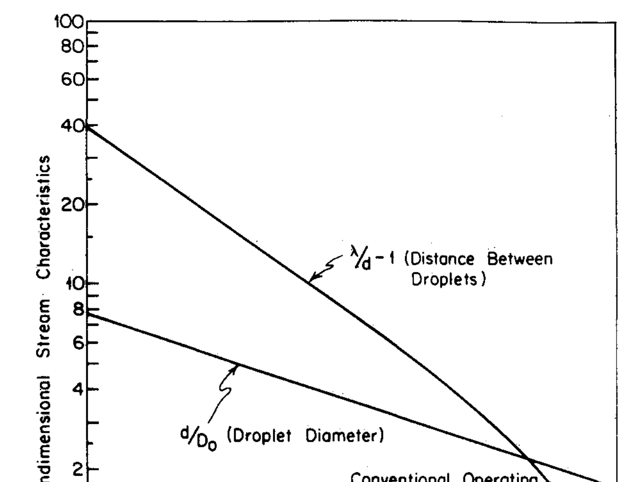


Fig. 10 Separation between droplets in a droplet stream in droplet diameters and droplet diameter in stream diameters, both as a function of nondimensional wavenumber of stream disturbance.

Experimental Results on Stream Angular and Speed Dispersions

Droplet Directional and Speed Stability

As noted above, many of the potential applications of liquid streams in space depend on their having high directional and speed stability. We have undertaken experiments to investigate both the directional and speed stability of low-vapor-pressure fluids in a vacuum. The experiments were conducted in the apparatus illustrated in Fig. 12. It is a vibrationally isolated, 5.5 m long vacuum flight tube. The tube is mounted on a vertical optical bench along with vacuum pumps and instrumentation. This group forms an inertial mass, isolated from ground motion for periods up to about 0.5 s. Besides electrical leads, the only external connections during operation are via flexible tubing to the mechanical backing pump and the water supply for diffusion pump cooling. The droplet stream generator at the top of the apparatus projects a stream of droplets to the bottom, with observation of the stream possible at both the beginning and end of the flight. The generator and nozzle configuration are shown in Fig. 13. The nozzles are formed in sapphire crystals and are obtained from Flow Industries, Inc., Bellevue, WA. In preliminary measurements[7,8,26] using a 10 ns dye laser pulse, triggered at about 20 Hz, shadow images of the droplet stream were obtained with a closed-circuit television system and a video cassette recorder (see Ref. 26). The droplet stream images from observations at the end of the tube can be interpreted in terms of individual droplet speed variations relative to an average droplet speed.[27] Also, by appropriate measurements of the position of the stream over a period of time, its angular dispersion can be found. A more detailed description of the experiments, instrumentation, and data is presented in Ref. 26.

Two low-vapor-pressure fluids were used, DC-704 and butyl phthalate. The important properties of these fluids are presented in Table 1. Results of the early experiments are summarized in Table 2 (and also in Refs. 8, 26). First of all note

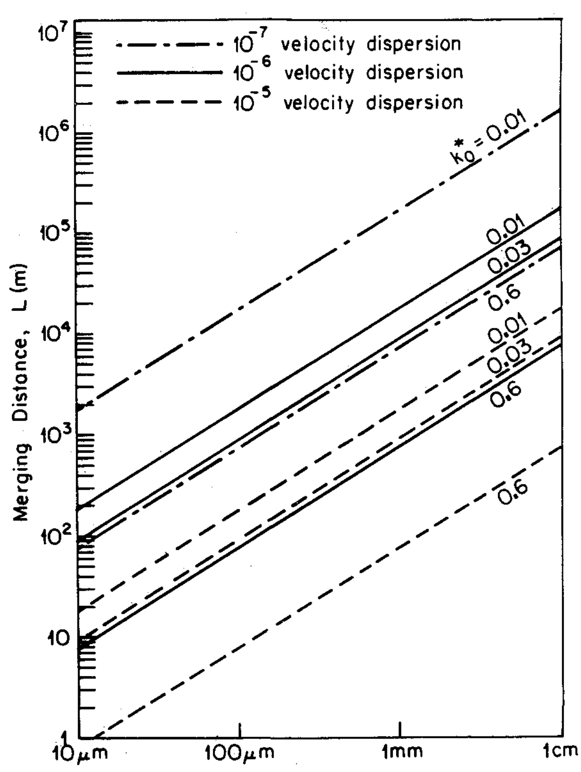


Fig. 11 Distances a droplet stream can travel without significant agglomeration as functions of droplet diameter, with nondimensional wavenumber and speed dispersion as parameters.

Table 1 Properties of liquids used in experiments

Liquid	Kinematic viscosity, cs	Surface tension, dynes/cm	Density, kg/m^3	Vapor pressure, Torr
DC 704	39	37	1000	9×10^{-8}
Butyl phthalate	14.4	50	1040	1×10^{-4}

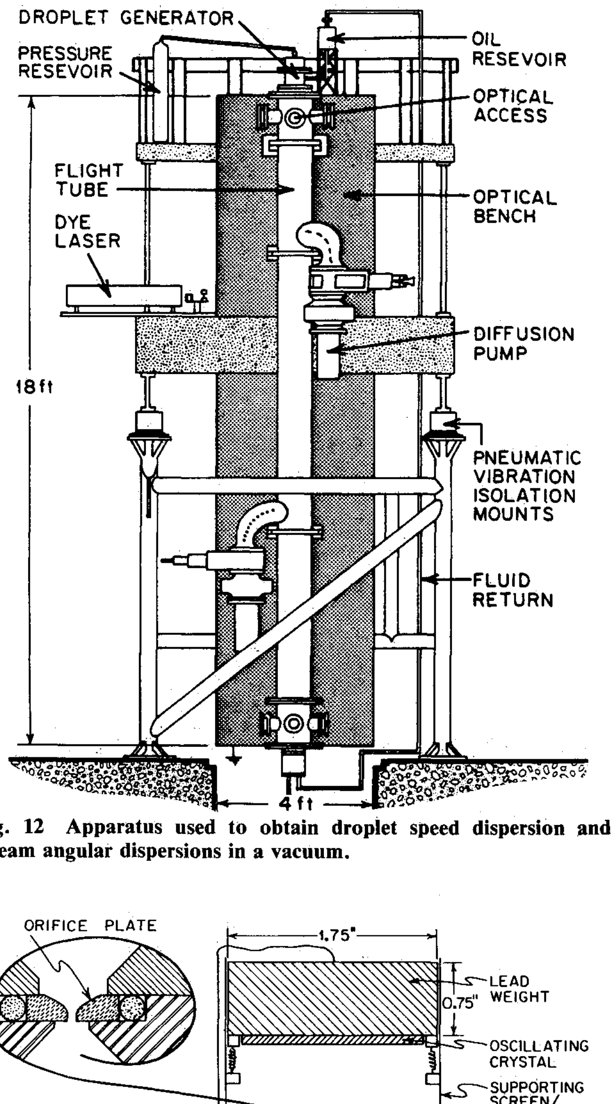


Fig. 12 Apparatus used to obtain droplet speed dispersion and stream angular dispersions in a vacuum.

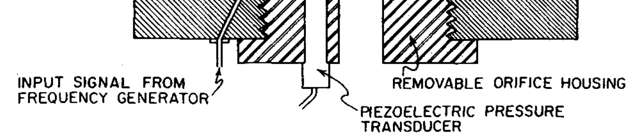


Fig. 13 Schematic diagram of droplet stream generator with details of the nozzle configuration and mounting arrangement.

that the directional stabilities of the streams are excellent, being typified by a standard deviation of ± 2 μrad. The droplet speed dispersion is not quite so good, represented by a standard speed deviation of $\pm 1.5\times10^{-5}$.

The droplet speed variations are important. While microradian angular stability of the stream is acceptable for many potential space applications of liquid streams (Fig. 9), droplet speed dispersions of 10^{-5} are marginal (Fig. 11). Thus, we have engaged in an intensive effort to understand the sources of the droplet speed dispersions. For this work, we employed a detector developed by Dixon[27] and illustrated in Fig. 14. The output signal from the detector is digitized by a Hewlett-Packard 5180A waveform recorder, which can store 16,384 data points at frequencies up to 20 MHz. The data are subsequently transferred to floppy disk storage for future analysis or display. The stream disturbance is created in the stagnation chamber by a piezoelectric crystal that is vibrationally isolated from the rest of the droplet generator structure. The pressure oscillations in the stagnation chamber are monitored by a Kistler pressure transducer. A sketch of the stagnation chamber configuration is shown in Fig. 13. For the experiments report the piezoelectric oscillator was driven by two phase locked Hewlett-Packard function generators (HP 3325A) that were controlled by a high-stability, frequency reference source (HP Option 001). The function generators were used to provide a stable signal with superimposed harmonics or an amplitude modulated carrier signal. The output of the function generators was amplified by an ENI 240L power amplifier before being fed to the piezoelectric oscillator.

Table 2 Direction and speed stability of low-vapor pressure liquid stream break-up products

Liquid	D, μm	V_0, m/s	k_0^*	$\dfrac{\sigma(V_d)\times10^6}{V_d}$	$\sigma(\theta)\times10^6$, rad
704	146	24	0.59	21	<1
704	146	49	0.59	13	3
704	146	100	0.59	11	2
BP	146	38	0.74	12	3
BP	146	67	0.71	25	2
BP	146	121	0.69	12	<1

Only a brief report of the results of this study can be given here. We have discovered a way to operate over a wide range of k_0^*, while at the same time producing extremely small droplet speed dispersions. This is illustrated by the experimental traces reproduced in Fig. 15. The pressure trace at the top of the figure is the fluctuating component of the stagnation pressure. Notice the amplitude modulation of the basic carrier wave. The lower trace is a record of the detector output after the stream has traveled 5.4 m. Notice how uniformly spaced the droplet signals appear with one droplet for every wavelength of the amplitude modulation. The apparent phase relationship between the upper and lower traces is not significant.

Our understanding of this phenomenon has been developed from a series of experiments and analysis described in detail elsewhere.[28] Briefly, Fig. 16 illustrates a capillary stream's response to the amplitude modulated carrier signal. The stream breaks up into droplets with a drop-to-drop separation of the carrier wavelength. Associated with each droplet is a differential speed relative to the neighbor droplets. This differential speed is a result of the amplitude differences imposed by the modulation. All of the carrier droplets within one period of the modulation coalesce into one droplet further downstream due to their differential relative speeds. The final droplet stream is composed of droplets that have a drop-to-drop separation corresponding to the amplitude modulation of the initial stream disturbance. At this point in time, we have operated amplitude modulated streams as low as $k_0^*=0.03$ with $\sigma(V_d)/V_d=1\times10^{-6}$.

For comparison purposes, it is interesting to examine a conventionally excited droplet stream where the excitation is the

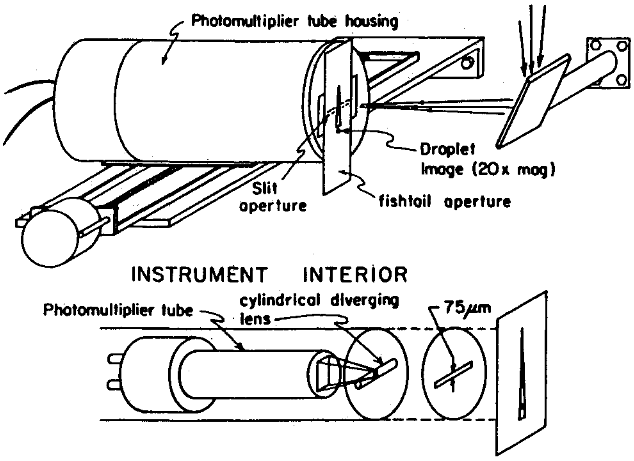


Fig. 14 Detector used to record profile of droplet images.

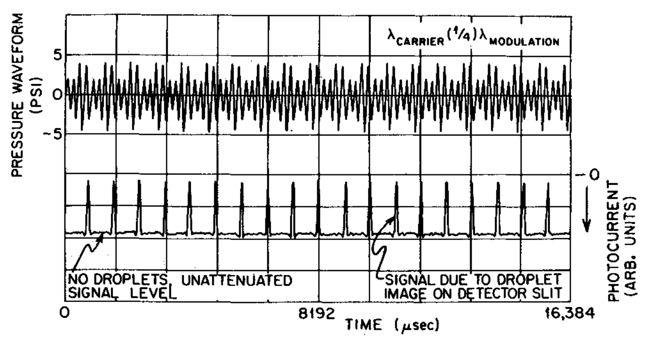


Fig. 15 Example of output from the detector demonstrating results achieved when amplitude modulation of carrier wave used as stream disturbance (distance from nozzle 5.4 m, $V_0 = 24$ m/s, $k^*_{0c} = 0.65$).

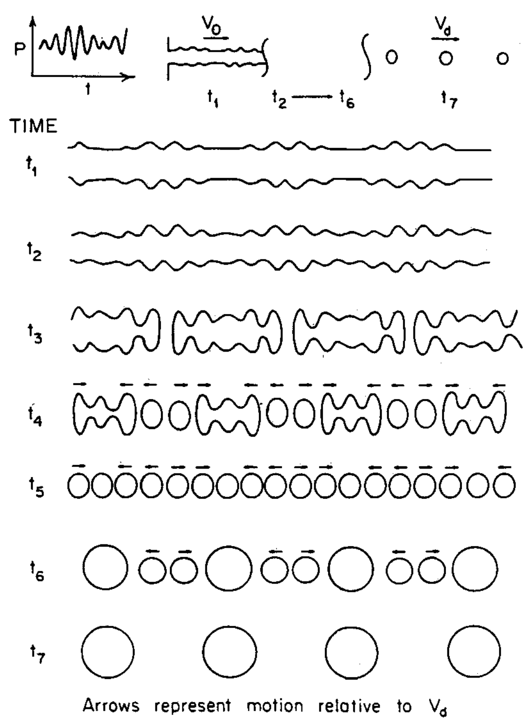


Fig. 16 Formation of composite droplets that takes place when a capillary stream is disturbed with an amplitude modulated perturbation.

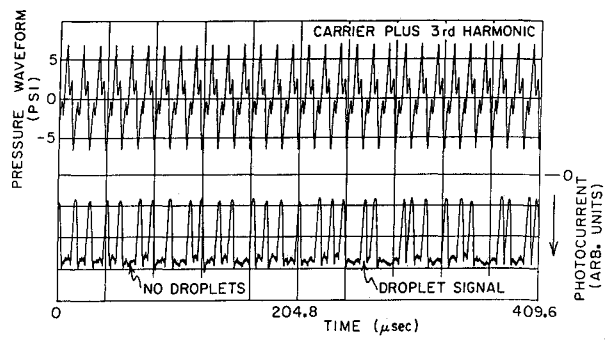


Fig. 17 Example of output from the detector demonstrating results achieved when stream driven by carrier plus added third harmonic (distance from nozzle 5.4 m, $V_0 = 34$ m/s, $k^*_0 = 0.8$).

basic carrier frequency plus a third harmonic (three times the fundamental frequency). A typical result is shown in Fig. 17 where the droplet $k^*_0 = 0.8$ and the $\sigma(V_d)/\bar{V}_d = 2.5 \times 10^{-5}$. A pure carrier excitation produces a significantly higher speed dispersion than the carrier with the added third harmonic.

Summary

A number of potential uses for free-flying, recoverable streams of droplets in space have been identified. The possible applications are such that in most cases close control must be maintained over the direction and speed of the droplet streams. It is concluded from the work reported here that it will be possible to project droplet streams of low-vapor-pressure fluids over large distances, without agglomeration due to speed dispersion or intolerable spreading due to angular dispersion. It appears that serious consideration of the proposed uses for droplet streams in space that were discussed in the paper will not be precluded, either by droplet spreading or agglomeration.

The issue of how finite vapor pressure fluids will affect droplet stream performance has not yet been studied in great detail. However, a serious start into this complicated subject is presented in Ref. 8.

Acknowledgments

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