Characteristics, Control, and Uses of Liquid Streams in Space

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Assessing the possibilities for using liquid streams in space requires a quantitative knowledge of the response of a stream when it is suddenly exposed to a high vacuum. The paper reviews what is known about the vacuum behavior of low and finite vapor pressure liquid streams. Recent vacuum flight tube data, on the directional and speed stability of the droplet streams that form due to surface tension driven instabilities of a capillary jet of low vapor pressure fluid, are related to the physical responses to a vacuum environment of streams of finite vapor pressure liquids. Stream bursting caused by cavitation, surface cooling effects, and the behavior of dissolved gases are considered in the context of the fluid mechanics of stream breakup and droplet formation. Based on our study, it is concluded that small-diameter streams (several hundreds of microns) of fluids with vapor pressures up to several torr can be expected either to freeze and eventually vanish due to evaporation, or to form well-controlled droplet streams with the droplets subsequently freezing and finally disappearing due to evaporation. Larger-diameter streams with vapor pressures in the tens of torr range and above are expected to burst, forming an uncontrolled cloud of stream fragments that will subsequently freeze and eventually evaporate. A method for restricting evaporation from controlled droplet streams is suggested.

Nomenclature

c_p	= specific heat
C_p	= pressure coefficient using vapor pressure of stream
C_{pB}	= pressure coefficient using bubble wall vapor pressure
D,D_0	= nozzle and stream diameters, respectively
$\mathfrak{D}$	= diffusion coefficient
k	= Boltzmann's constant
k^*,k_0^*	= nondimensional wave numbers based on nozzle and stream diameters, respectively
K	= thermal diffusivity $(=\alpha/\rho c_p)$
ℓ_v	= heat of vaporization
L_e	= length of nozzle required to attain fully developed Poiseuille flow
m_g,m_ℓ	= mass of gas and liquid molecules, respectively
n_g	= number density of dissolved gas
n_{gS}	= surface number density of dissolved gas
n_v	= number density of vapor
$n_{vS}(T_S)$	= number density of vapor corresponding to the surface temperature
$\dot{N}(t)$	= dissolved gas flux
p_B	= internal bubble pressure
p_R	= constant in Clausius-Clapeyron equation
p_S	= pressure at stream surface
p_v	= vapor pressure
p_{vB}	= vapor pressure of bubble wall fluid
$\dot{q}(t)$	= heat transfer
Re_D	= nozzle Reynolds number
Re_{0D}	= stream Reynolds number
R_B	= bubble radius
R_{BE}	= equilibrium bubble radius
R_{B0}	= initial bubble radius
R_0	= stream radius
t'	= dummy variable in integration
T,T_0,T_s	= absolute, initial, and surface temperatures, respectively
U_2	= energy to make a "hole" in a fluid
V	= average stream speed at nozzle exit
V_0	= average stream speed away from nozzle
V_c	= characteristic capillary speed
V_d	= droplet speed
We_{0D}	= stream Weber number
x	= co-ordinate normal to stream surface, inward direction is positive
α	= thermal conductivity
β	= amplification growth factor
Γ	= fractional loss of a quantity from the stream
$\delta r_T/R_0$	= thermal layer thickness nondimensionalized by nozzle radius
$\delta r_{T_{p_v}}(\kappa)/R_0$	= nondimensional thermal layer thickness when the vapor pressure has decreased to a fraction κ of its original value
$\delta r_{\mathfrak{D}}/R_0$	= dissolved gas layer depth nondimensionalized by nozzle radius
$\delta r_{T,\epsilon}/R_0$	= nondimensional thermal layer thickness due to thermal emission from surface
$\Delta\hat{E}_\epsilon$	= fraction of stream energy radiated
$\Delta\hat{M}_{\mathfrak{D}}$	= accumulated fractional dissolved gas mass loss
$\Delta\hat{M}_v$	= accumulated fractional mass loss due to vaporization
ϵ	= emissivity
ϵ_0	= nondimensional initial amplitude of stream disturbance, in stream radii
κ	= arbitrary fraction of a quantity remaining in the stream
λ	= wavelength of stream disturbance
μ	= viscosity
ρ	= density of liquid
σ	= surface tension
σ_{SB}	= Stefan-Boltzmann constant
$\tau_{\mathfrak{D}}(\kappa)$	= time to reduce the total quantity of dissolved gas in the stream to a fraction κ of its initial value; $\kappa=0.9$ in Figs. 9 and 10

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$\tau_{\mathfrak{D}S}(\kappa)$ = time for the surface concentration of dissolved gas to be reduced to a fraction κ of its original value
$\tau_\epsilon(\kappa)$ = characteristic time for stream's energy content to be reduced by thermal radiation to a fraction κ of its original value; $\kappa=0.9$ in Figs. 9 and 10.
$\tau_{\epsilon S}(\kappa)$ = time for surface temperature to decrease due to thermal radiation to a fraction κ of its initial value
τ_{0L} = stream breakup time in linear theory
τ_{0NL} = stream breakup time for low viscosity fluids from nonlinear theory
τ_∞ = undisturbed breakup time
$\tau_{p_v'S}(\kappa)$ = time for the vapor pressure of the stream's surface to decrease to a fraction κ of its original value, κ is e^{-1} in Fig. 10
τ_R = velocity relaxation time
τ_{TS} = time for stream surface temperature to reach T_S due to evaporation cooling
$\tau_v(\kappa)$ = time for evaporation to reduce stream's cross-sectional area or mass to a fraction κ of its initial value; κ is 0.9 in Fig. 10
$(\ )_S$ = refers to conditions at the stream surface

Introduction

THE purpose of this paper is to explore the behavior of liquid streams in a vacuum. Characteristic responses that relate to such fluid properties as vapor pressure, viscosity, dissolved gas content, surface tension, and density, when a liquid stream is suddenly exposed to a high vacuum, are surveyed. An understanding is developed of the major interactions between the fluid mechanics of the stream and the liquid's thermodynamic and physical properties. A visual review of some of the possibilities is presented in Fig. 1. Surprisingly little attention has been given either to predicting or systematically studying the behavior of liquid streams in high vacuums. The work that has been reported is associated mostly with practical space requirements, such as the disposal of surplus water or other fluids[1-3] and fuel venting.[4] There has also been some specialized work on metal powder production using liquid metal streams, saturated with a high-pressure gas, suddenly exposed to a low ambient pressure.[5]

Several novel potential uses of liquid streams in space have recently been identified. The most prominent is the liquid droplet radiator.[6] Other suggestions include transportation of material between spacecraft in the form of liquids or slurries.[7] 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.[7] 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.[7] Another possibility is the use of separate, well-directed streams of polymers and ultraviolet sensitive hardeners to form in situ epoxy structures in space.[7] A sheet of droplets might be used as an easily deployable but rugged passive drag producer for orbital transfer vehicles[7] or as a means for recovering quantities of upper atmospheric gases.[7] These and other potential uses of liquids in space are listed in Table 1. Also identified in the table are areas of basic information about liquid

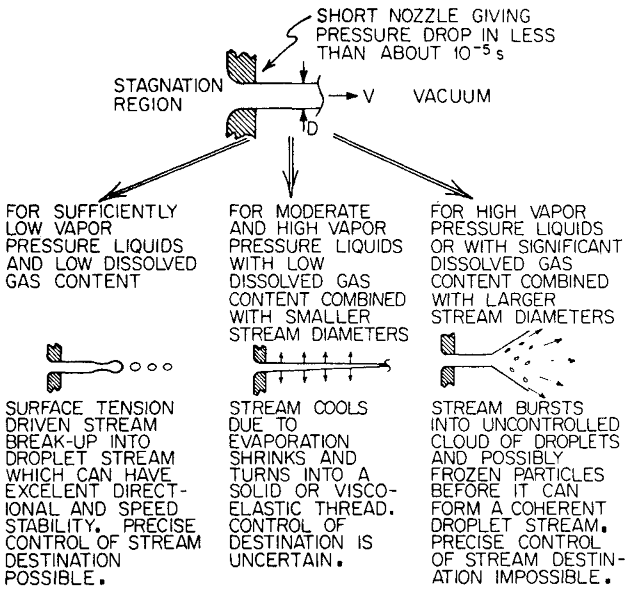

Fig. 1 Summary of possible events when liquid streams are formed in a vacuum.

Table 1 Liquid streams in space: Potential applications and related areas of critically limiting information

Applications	Liquid droplet radiator	Planetary gas scavenging	Aeroassist brake/control	Material transport	Space construction	Fluid disposal	Liquid thruster
Areas							
Droplet speed dispersions	X			X	X		
Stream directional control	X	X	X	X	X		X
Evaporation effects			X	X	X	X	X
Bursting or cavitation effects				X	X	X	X
Liquid solid slurries	X			X	X		
Dissolved gas effects, atmosphere/surface interactions		X	X			X	
Droplet collision dynamics	X	X	X	X	X		X
Charging effects				X	X		X
Droplet cloud with aerodynamic shadowing		X	X				
High and low intensity radiation interaction with droplets and particles	X		X				
Liquid stream recapture	X	X	X	X	X		

streams in a high vacuum that are relevant to the applications. The indicated boxes in the matrix presentation show where sufficient information, particularly critical to an application, is at present unavailable. The topics discussed in this paper are an initial response to some of the requirements for basic information exhibited in Table 1. Each of the applications in Table 1 is discussed in greater detail in Ref. 7. Many of the applications are speculative; however, considering the limited interest that has been taken in the behavior of low and finite vapor pressure liquids in either terrestrial high vacuums 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 applications will almost certainly be recognized.

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. These 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 or to freeze. Stream breakup into droplets is a classic problem in fluid mechanics.[8-10] It can be controlled with great precision when it takes place in a high vacuum using low vapor pressure liquids.[7] The usefulness of liquid streams in space depends on their controllability. For material transport and space construction, it is a basic requirement that a stream must be directed with a precision approaching a few microradians angular dispersion.[7] Additionally, in many cases the standard deviation of individual droplet speeds relative to their average speed must be less than 10^{-6}.[7]

For serious analyses of the suggested space applications, it is necessary to understand the relationships and interactions of the many fluid mechanic and thermodynamic issues that arise when finite vapor pressure liquid streams are ejected into a vacuum. Evaporation, flashing or cavitation, diffusion of dissolved gases, and cooling by radiation and evaporation, all can interact with the fluid mechanical breakup and droplet formation, causing a loss of control over the stream.

Analysis of Liquid Stream Response to a Vacuum

The purpose of the present discussion is to develop a feeling for the conditions under which liquid streams with finite vapor pressures can be made to retain their fluid mechanic coherence when injected into a vacuum. Previous studies have frequently concentrated on the properties of the fragmentation products that appear after explosive cavitation (bursting).[2,3] We have chosen herein to examine more carefully the possibilities for controlling finite vapor pressure streams that have been injected into a high vacuum. A number of fluid mechanical phenomena important to the behavior of liquid streams in a vacuum have been reviewed in Refs. 7 and 11. Physical phenomena associated with liquid streams in a vacuum are explored in Refs. 1 and 11. This paper presents an expanded treatment of the influence of a fluid's physical properties on a liquid stream's thermophysical behavior in a vacuum, as it relates to stream fluid mechanics and breakup phenomena.

Fluid Mechanics Background

Liquid stream breakup due to surface tension driven instabilities has been the subject of a long history of theoretical and experimental investigations,[8-10,12-20] with the majority of experiments at atmospheric pressure. The extensive literature has recently been summarized from the point of view of space applications by Muntz and Dixon.[7] The reader is referred to this previous publication for more detailed comments. Briefly, a cylindrical liquid stream can be forced to break up into droplets if a radial disturbance is applied to the stream such that it has a wavelength in the direction of the stream's axis somewhat greater than the stream's circumference. Recent measurements of the characteristics of a low vapor pressure fluid stream's breakup in a vacuum have shown that a typical angular dispersion of the droplet stream is around ± 2 μrad.[7,11] Also, the droplets can have a very small speed dispersion about their average speed, with $\pm 1 \times 10^{-6}$ the minimum standard deviation of the fractional droplet speed dispersion that has been observed to date.[7,23] As discussed in detail in Ref. 7, owing to the remarkable droplet speed coherence and stream directional stability, droplet streams of low vapor pressure fluids in a vacuum can be made to travel large distances (tens to hundreds of kilometers) without significant droplet spreading or droplet agglomeration. Finite vapor pressure fluid streams may also have these characteristics, but only if they can be formed into droplets prior to cavitation or freezing. The time required for a fluid stream to break up into droplets, which is discussed in this section, will be useful for comparison to a variety of characteristic times developed in the following sections that describe stream cooling, bursting, evaporative and diffusive mass loss, etc. The results for droplet speed and angular dispersions that have been mentioned previously are for laminar flows. The information considered for stream breakup in this paper is likewise restricted to laminar flow.

Consider a cylindrical liquid stream that has a speed V_0 and a diameter D_0 (in general, V_0 and D_0 can be different from the average stream speed at the nozzle exit V and from the nozzle diameter D).[7] Stream and nozzle Reynolds numbers and the stream Weber number are

$$Re_{0D} = \rho V_0 D_0/\mu, \qquad Re_D = \rho VD/\mu$$
$$We_{0D} = \rho V_0^2 D_0/\sigma \tag{1}$$

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,[10] Rayleigh,[8] Weber,[14] 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—thus space for a moving jet as long as the propagation or capillary speed $V_c = (\sigma/\rho R_0)^{1/2}$ is much less than V_0. The growth factor β, where the disturbance amplitude is $R_0\epsilon_0 e^{\beta t}$ (ϵ_0 is the initial size of the disturbance in stream radii and R_0 the stream radius) is given approximately for a viscous fluid by Weber[14] and Sterling and Sleicher[15] as

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

Here, k_0^* is the nondimensional wave number $2\pi R_0/\lambda$, with λ the disturbance wavelength in the stream direction. Plots of β vs k_0^* are shown in Fig. 2 for 100-μm-radius streams of lithium just above its melting point, DC-704, Hg, and H_2O.

Within the framework of linear theory, stream breakup can be defined as the time when $R_0\epsilon_0 e^{\beta t}$ has grown to be equal to the stream radius. Thus, a characteristic time for breakup ac-

Table 2 Properties of water and DC-704 used for the calculations of characteristic times

	α J/msK	C_p J/kgK	$\mathfrak{D}$ m^2/s	ϵ	ℓ_v J/kg	m_v kg	μ_v kg/ms	p_R N/m^2	$\rho\ell$ kg/m^3	σ N/m	U_2/k K
DC-704	1.67E-1	1.88E3	5.28E-11	1	5.86E5	8.10E-25	4.16E-2	—	1.07E3	3.73E-2	3.15E3
H_2O	5.98E-1	4.17E3	2.62E-9	1	2.42E6	3.00E-26	8.36E-4	4.78E10	1.00E3	7.20E-2	1.54E3

cording to linear theory, which of course cannot be strictly correct, is

$$\tau_{0L} \simeq \ln(\epsilon_0^{-1})\{(\rho/\sigma)^{1/2} D_0^{3/2}\} \tag{3b}$$

For an inviscid fluid, using β obtained from Eq. (2) with $\mu = 0$ and for the k_0^* corresponding to maximum β

$$\tau_{0NL} = [K_2(\epsilon_0)/2\sqrt{2}]\,(\rho/\sigma)^{1/2}\{D_0^{3/2}\} \tag{3c}$$

Nonlinear stream breakup is similar although there are differences in detail.[16] According to the nonlinear analysis of Ref. 16, a capillary stream of inviscid fluid will break up into droplets in a time

$$\tau_{0NL} = [K_2(\epsilon_0)/2\sqrt{2}]\,(\rho/\sigma)^{1/2}\{D_0^{3/2}\} \tag{3c}$$

where $K_2(\epsilon_0)$ is a function of the initial disturbance amplitude ϵ_0 and is about 20 for $\epsilon_0 = 0.002$, decreasing to 8 at $\epsilon = 0.1$. The τ_{0L} is a reasonable approximation to τ_{0NL}, giving times 10% shorter than τ_{0NL} at small ϵ_0 to 20% less at $\epsilon_0 = 0.1$. For well-isolated streams of finite viscosity fluids with no imposed disturbance, the work of Grant and Middleman[13] provides an empirical breakup time,

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

This applies to low-speed streams that are presumably unaffected by an ambient atmosphere.[13] Here we permit the extension of the correlation to higher velocities because of the very low ambient pressures we consider. The validity of the correlation beyond distances of about 10^3 stream diameters, for diameters <0.031 cm or >0.137 cm, or for speeds beyond a few m/s has not been demonstrated. The fluid mechanic breakup times τ_{0L} and τ_∞ will be used for comparison with the characteristic physical response times for liquid streams in a vacuum, which are developed in the following section.

As mentioned, a droplet stream formed from a capillary jet can be a very coherent phenomenon composed of a stream of uniform droplets, all moving at nearly 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 comes only from variations in the breakup process or from unsteady forces applied at the exit of the nozzle. Another possibility would be motion induced by interactions between the vapor flowfields of individual droplets; we have not gone into this area in the present paper. The exit surface of the nozzle may be wetted by the stream's liquid. 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. Thus, the droplets of a stream in a vacuum follow each other quite precisely, but the entire stream may wander sinuously with a wavelength equivalent to many droplet spacings.[33]

The nozzle itself must of course have a sufficiently gradual entrance curvature to prevent the formation of a separation bubble, which could lead to unsteady stream conditions. If fully developed Poiseuille flow is achieved in the nozzle, there is a velocity relaxation length downstream of the exit in which viscous forces in the stream bring the flow to a uniform speed. It has been suggested by Grant and Middleman[13] and Sterling and Sleicher[15] that the velocity relaxation can cause stream instabilities. The time for a uniform profile to be achieved is given approximately by

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

where $L_e = 0.02875 Re_D D$ is the entrance length in a parallel circular duct that is required to attain fully developed Poiseuille flow[21]. There is an additional interesting effect if the velocity profile at the nozzle exit is significantly nonuniform.[22] For Poiseuille flow, application of the equations of continuity and momentum to the stream indicate that for $Re_D > 100$ the stream contracts as the velocity profile relaxes. When the stream speed has become uniform radially, the stream diameter is $D_0 = 0.87D$. Thus, the final stream speed V_0 is 1.32 V. If a disturbance applied at the nozzle has a nondimensional wave number k^*, the final effective wave number is $k_0^* = 0.66k^*$. The velocity relaxation will only be important when there is a significant boundary-layer thickness at the nozzle exit. For situations where L_e is greater than the nozzle length L, the major speed adjustments of the boundary-layer fluid will take place in a time

$$\tau_R = \tau_N = L/V \tag{6}$$

Physical Effects

The discussions in this section of the paper center on effects that are consequences of the properties of the stream's liquid after it is suddenly exposed to a high vacuum. These effects include: diffusion of dissolved gas, evaporation, radiation, and cavitation or flashing. Several have been mentioned in the excellent paper by Fuchs and Legge.[1] A sketch of an evaporating, cavitating fluid is shown in Fig. 3. The flow created by a relatively massive evaporation from a surface has been a problem of interest in rarefied gasdynamics for many years.[24,25] In the case of water injection into vacuum, it is discussed in some detail by Koppenwallner and Hefer[26] and by Fuchs and Legge.[1] For our purposes here, we will assume that the pressure imposed at the surface by the departing vapor is the collisionless value of one-half the vapor pressure or $p_s = p_v(T_S)/2$. Associated with evaporation is of course a heat flux, which causes a surface cooling. A related phenomenon is the diffusion of dissolved gas from the liquid, where unsteady "radiation" solutions[27] to the diffusion equation apply. For finite evaporation rates and loss rates of dissolved gas, typical temperature and gas concentration profiles are indicated in Fig. 3.

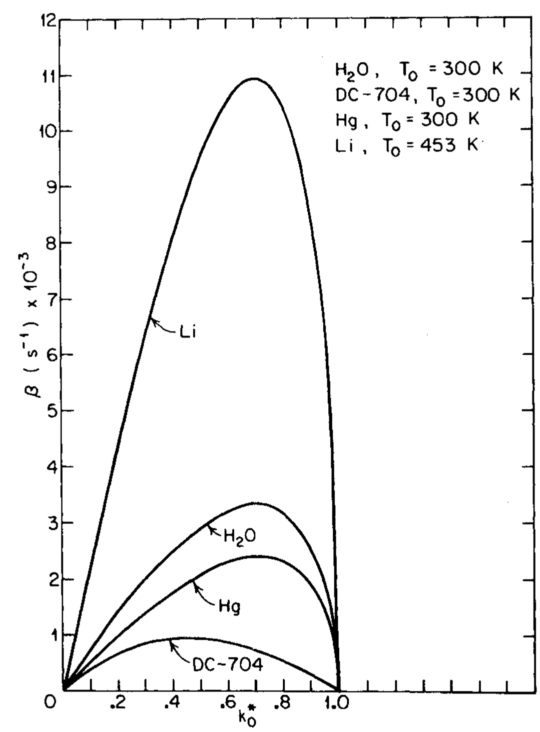

Fig. 2 Amplification factor as a function of nondimensional wave number for a 200-μm-diam stream.

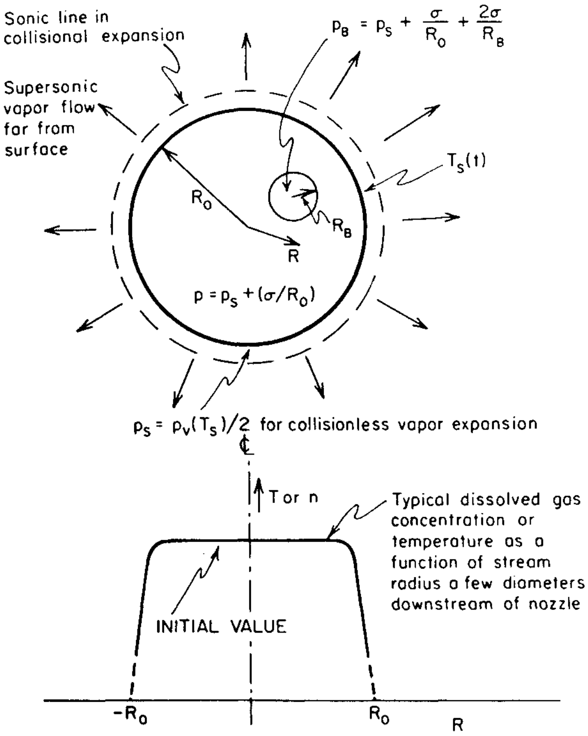

Fig. 3 Cross-section sketch of a liquid stream in a vacuum.

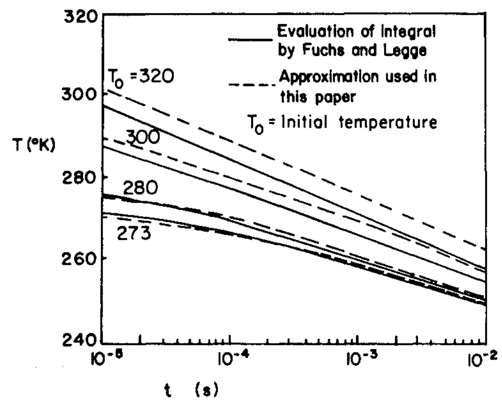

Fig. 4 Surface temperature as a function of time for water streams in a vacuum.

It is useful for the quantitative consideration of liquids injected into a vacuum to have fairly simple measures of a number of physical events. Such measures are important for developing an understanding of the time sequencing of the physical changes that occur. In the remainder of this section, explicit expressions for the characteristic times for changes to take place in a stream's condition are derived, in terms of the liquid's properties and the stream's diameter and speed. The several responses are assumed not to interact with each other except for the effect of temperature on vapor pressure.

Analytical Tools

The response of a cylindrical liquid stream to a high vacuum, where the stream may be either losing dissolved gas or experiencing surface heat transfer due to evaporation or radiation, is governed by some form of the diffusion equation. For our purpose here, which is to develop convenient measures of a liquid's response to a sudden exposure to a high vacuum, it is useful to assume that the major changes in the liquid's temperature or dissolved gas content occur in a relatively thin layer near the stream's surface. In this paper

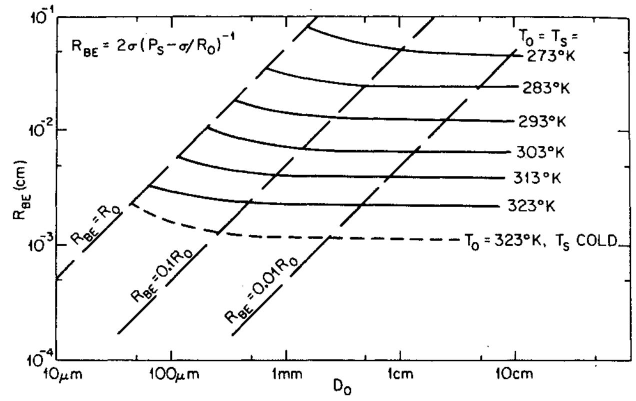

Fig. 5 Equilibrium bubble size for water streams as a function of diameter with temperature as a parameter.

we also assume that the surface is stationary although, as a result of evaporation, there can in some circumstances be a small surface motion. The one-dimensional diffusion equation is considered with the stream modeled by a semi-infinite slab in the positive direction and bounded at $x=0$; for thermal diffusion,

$$\partial T/\partial t = K\partial^2 T/\partial x^2 \tag{7}$$

where K is the thermal diffusivity and

$$\partial n_g/\partial t = \mathfrak{D}\partial^2 n_g/\partial x^2 \tag{8}$$

for mass diffusion, where $\mathfrak{D}$ is the diffusion coefficient and n_g the number density of dissolved gas in the liquid. The boundary conditions appropriate to the physical possibilities are: for mass diffusion,

$$(\partial n_g/\partial x)_S = n_{gS}(8kT_0/\pi m_g)^{1/2}\{\exp(-U_2/kT_0)\}/4\mathfrak{D} \tag{9}$$

where n_{gS} is the surface dissolved gas number density and U_2 a potential energy barrier to the escape of dissolved gas from the liquid's surface; for surface heat load due to evaporation,

$$(\partial T/\partial x)_S = mn_{vS}(8kT_S/\pi m_\ell)\ell_v/4\alpha \tag{10}$$

where n_{vS} is the number density of the equilibrium vapor corresponding to the surface temperature T_S and α the thermal conductivity; for surface heat load due to thermal emission,

$$(\partial T/\partial x)_S = \epsilon\sigma_{SB}T_S^4/\alpha \tag{11}$$

where σ_{SB} is the Stefan-Boltzmann constant and ϵ the emissivity.

Although solutions to the diffusion equation for the boundary conditions of Eq. (9) exist,[27] they are not explicit nor particularly suitable for our purpose, which is to develop straightforward measures of the liquid stream's response. The boundary conditions represented by Eqs. (10) and (11) result in even less useful solutions. There is, however, an approximate way around this difficulty. Schultz and Jones[28] have presented an expression for the surface temperature of a slab subject to transient heat transfer. The expression has been used to calculate the surface temperatures of evaporating water streams by Fuchs and Legge.[1] The Schultz and Jones surface temperature is

$$T_0 - T_S(t) = (\pi\alpha\rho c_p)^{-1/2}\int_0^t \frac{q(t')}{(t-t')^{1/2}}\,dt' \tag{12}$$

and its analog for surface dissolved gas number density is

$$n_{g0} - n_{gS}(t) = (\pi \mathfrak{D})^{-\frac{1}{2}} \int_0^t \frac{N(t')}{(t-t')^{\frac{1}{2}}} \, dt' \qquad (13)$$

The time-dependent surface heat transfer $\dot{q}(t')$ for vaporization is

$$\dot{q}(t') = m n_{vS}(T_S)(8kT_S/\pi m_\ell)^{\frac{1}{2}} \ell_v/4 \qquad (14)$$

In Eq. (14), ℓ_v is the heat of vaporization and $n_{vS}(T_S)$ is the vapor number density corresponding to the equilibrium vapor pressure at T_S. For thermal radiation,

$$\dot{q}(t') = \epsilon \sigma_{SB} T_S^4 \qquad (15)$$

The escape of dissolved gas is described by the flux $\dot{N}(t')$,

$$\dot{N}(t') = n_{gS}(t')(8kT_0/\pi m_g)^{\frac{1}{2}} \exp(-U_2/kT)/4 \qquad (16)$$

The definite integrals of Eqs. (12) and (13) have the interesting property that they are dominated by the values of the integrand near $t' = t$. A useful approximation, which permits a number of simple explicit expressions to be derived, is to assume that $\dot{q}(t')$ or $\dot{N}(t')$ are constant at their values at the end of the time interval. It follows that

$$T_0 - T_S(t) = \alpha^{-1}\{4\alpha t/\pi \rho c_p\}^{\frac{1}{2}} \dot{q}(t) \qquad (17a)$$

$$n_{g0} - n_{gS}(t) = \mathfrak{D}^{-1}\{4\mathfrak{D}t/\pi\}^{\frac{1}{2}} \dot{N}(t) \qquad (17b)$$

Comparing these expressions to the boundary condition of Eqs. (9) and (10) indicates thermal layer and dissolved gas charactertistic depths (normalized here by the stream's radius) of

$$\delta r_T/R_0 = R_0^{-1} \{4\alpha t/\pi \rho c_p\}^{\frac{1}{2}} \qquad (18a)$$

$$\delta r\ /R_0 = R_0^{-1} \{4\mathfrak{D}t/\pi\}^{\frac{1}{2}} \qquad (18b)$$

Equations (18) can be used to estimate a time limit for the validity of the slab simplification. For instance, assuming $\delta r/R_0 < 0.25$, water has a time limit for its thermal layer of about 35 R_0^2 s (R_0 in cm) and 1.9×10^3 R_0^2 s for its mass diffusion layer.

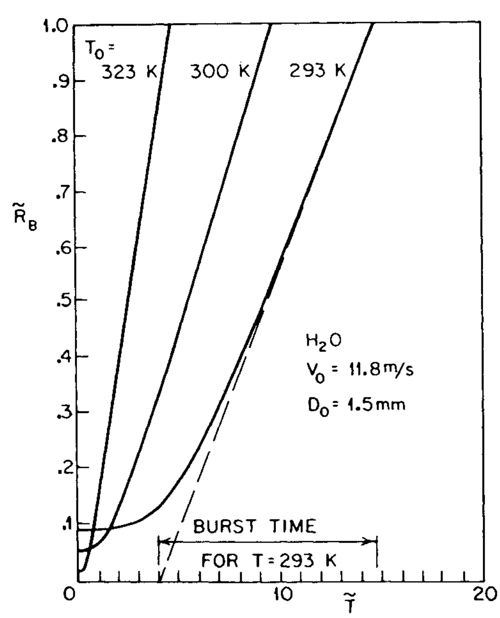

Fig. 6 Calculated bubble growth in a water stream for several stream temperatures.

In terms of surface properties the approximation that leads to Eqs. (17) results in only 10–15% errors in the surface property prediction for an e^{-1} reduction in the surface property. As an example, the surface temperatures for evaporating water streams with different initial temperatures are shown in Fig. 4, for an iterative solution of the approximate equation [Eq. (17a)] and for an iterative numerical solution of the integral equation [Eq. (12)] that is due to Fuchs and Legge.[1] The approximate and exact solutions of Eq. (12) are seen to be in reasonable agreement. In the following we use the simplified expressions for surface properties as a function of time given in Eqs. (17) to define characteristic response times for fluid streams introduced into a vacuum.

Diffusion of Dissolved Gas

Consider a cylindrical stream of fluid injected suddenly into a high vacuum. Dissolved in the fluid is a uniform concentra-

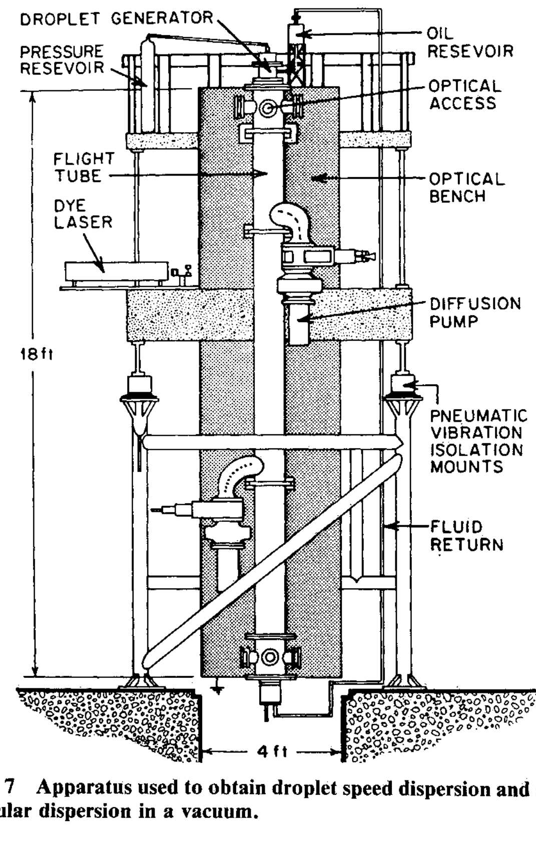

Fig. 7 Apparatus used to obtain droplet speed dispersion and stream angular dispersion in a vacuum.

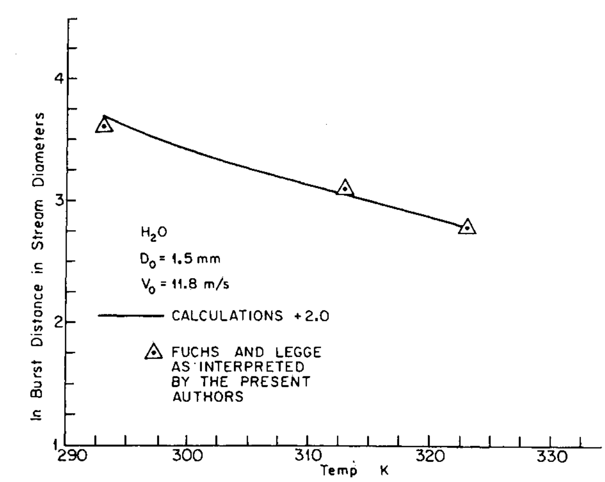

Fig. 8 Comparison of calculated and observed burst distances; demineralized water used in these experiments reported by Fuchs and Legge.

tion of gas, n_{g0}. Escape from the surface of the stream causes the surface concentration of dissolved gas to decrease, with a surface layer formed in which there are significant changes in concentration. From Eqs. (17b) and (16), it is easy to find by substitution the time after exposure for the surface concentration n_{gS} to drop to κn_{g0}, where κ is an arbitrarily specified fraction

$$\tau_{\mathfrak{D}S}(\kappa) = 12.6[(1-\kappa)/\kappa]^2 \mathfrak{D} \exp \times (2U_2/kT_0)/(8kT_0/\pi m_g) \tag{19}$$

It is assumed in this case that the stream remains at its initial temperature T_0. In Eq. (19) U_2 is the energy required to form a "hole" in the liquid[29]; it is usually somewhat larger than the heat of fusion per molecule and can be related to the diffusion coefficient. The expression for $\tau_{\mathfrak{D}S}$ can be conveniently compared to the value for an exact solution of the diffusion equation, since the escape of dissolved gas is similar to the "radiation" boundary condition for which a solution to the diffusion equation exists.[27] For $\kappa = e^{-1}$ the constant on the right-hand side of Eq. (19) is 37.2, whereas the exact solution gives a value of 25. This is the expected difference resulting from our approximation of the integral in Eq. (13), remembering that the 10-15% error is doubled due to the $t^{1/2}$ in Eq. (17b).

Substitution of $\tau_{\mathfrak{D}S}$ from Eq. (19) into Eq. (18b) enables us to write the ratio of the thickness of the diffusion layer, when $n_{gS} = \kappa n_{g0}$, to the stream radius as

$$\delta r_{\mathfrak{D}}/R_0 = 4[(1-\kappa)/\kappa] \exp \times (U_2/kT_0)/(8kT_0/\pi m_g)^{1/2} R_0 \tag{20}$$

Finally, the total fractional mass loss of dissolved gas from the stream, up to a time t, can be found by substituting Eq. (16) into Eq. (17b), solving for the surface concentration $n_{gS}(t)$, and integrating the corresponding mass loss. Normalizing by the original gas content of the stream to provide the accumulated fractional mass loss as a function of time gives

$$\Delta \hat{M}_{\mathfrak{D}} = (\pi \mathfrak{D} t)^{1/2} [1 - \chi^{-1} t^{-1/2} \ln(1 + \chi t^{1/2})]/R_0 = \Gamma \tag{21}$$

where

$$\chi = (8kT_0/\pi m_g)^{1/2} \exp(-U_2/kT_0)/2(\pi \mathfrak{D})^{1/2}$$

In this paper we have used Eq. (21) to calculate, for various streams, the characteristic time $t = \tau_{\mathfrak{D}}(\kappa)$ for an arbitrary fraction Γ of the dissolved gas to have escaped, leaving $\kappa = 1 - \Gamma$ in the stream.

Evaporation and Radiation

The vapor pressure associated with a surface temperature T_S is assumed to be adequately represented by the Clausius-Clapeyron equation

$$p_v = p_R \exp(-m_\ell \ell_v / kT_S) \tag{22}$$

where p_R is a constant obtained empirically. The equilibrium number density of the vapor is $n_v = p_v/kT_S$. With Eqs. (17a), (14), and (22), the time τ_{T_S} for the surface temperature to drop to some specified value T_S due to evaporative heat transfer can be found. We have also chosen to represent the reduced surface temperature by the time required for the surface vapor pressure to have decreased to a fraction κ of its original value. The time required for this to take place is

$$\tau_{p_v,S}(\kappa) = \frac{\pi^2 (k/m_\ell)(\rho c_p \alpha) T_0^3 (kT_0/m_\ell \ell_v)^2}{\kappa^2 [p_v(T_0)]^2 \ell_v^2 [1 + kT_0/m_\ell \ell_v]^3} \tag{23}$$

The corresponding thermal surface layer thickness can be obtained by substitution in Eq. (18a) and

$$\frac{\delta r_{T,p_v}}{R_0} = \frac{2\alpha (kT_0/m_\ell \ell_v)^{3/2} T_0}{\kappa R_0 p_v(T_0) \ell_v^{1/2} [1 + kT_0/m_\ell \ell_v]^{3/2}} \tag{24}$$

Since the surface temperature time history is known from Eq. (17a), the fractional mass loss due to evaporation can be found as in the diffusive escape of dissolved gas. In this case, the integration cannot be done explicitly, and the expression becomes

$$\Delta \hat{M}_v = \left\{ \left[1 - \frac{m_\ell}{4\rho R_0} \int_0^t (p_r/kT_S) \exp(-m_\ell \ell_v/kT_S) \times (8kT_S/\pi m_\ell)^{1/2} \mathrm{d}t' \right]^2 - 1 \right\} \tag{25}$$

where $T_S(t')$ is given by Eq. (17a). The time for a $\Delta \hat{M}_v = \Gamma$ has been used to specify a characteristic time $\tau_v(\kappa)$ for the stream to evaporate to a fraction κ of its original mass $(\kappa = 1 - \Gamma)$.

For thermal radiation, a similar procedure, but using Eq. (15) with Eq. (12), results in a time for the surface temperature to decrease to a fraction κ (i.e., $T_S = \kappa T_0$) or

$$\tau_{\epsilon S}(\kappa) = \pi(1-\kappa)^2 \alpha \rho c_p / 4\kappa^8 \epsilon^2 \sigma_{SB}{}^2 T_0^6 \tag{26}$$

A more useful quantity is the fraction of the total stream energy that is radiated during time t which is given by

$$\Delta \hat{E}_\epsilon = \frac{2\epsilon \sigma_{SB}}{\rho c_p T_0 R_0} \int_0^t T_S(t')^4 \mathrm{d}t' \tag{27}$$

where $T_S(t')$ comes from an iterative solution of Eq. (17a), using Eq. (15). Equation (27) can be solved iteratively for $\Delta \hat{E}_\epsilon = \Gamma = 1 - \kappa$ to find the time required $[\tau_\epsilon(\kappa)]$ to reduce the stream's energy to a fraction κ of its initial energy. The thermal layer thickness due to thermal radiation relative to the stream radius is, from Eqs. (18) and (26),

$$\delta r_{T,\epsilon}/R_0 = (1-\kappa)\alpha/\kappa^4 R_0 \epsilon \sigma_{SB} T_0^3 \tag{28}$$

For situations where $T_0 \approx 300$ K, Eq. (28) indicates that $\delta r_{T,\epsilon}/R_0 > 1$ except for κ's very close to unity. Thus, due to the relatively slow rate of radiative energy loss, the slab approximation breaks down and it is more reasonable to assume that the stream has a uniform temperature in the radial direction. In this case, the time dependency of the temperature is

$$T(t) = T_0 \left[1 - (2\epsilon\sigma_{SB}/\rho c_p T_0 R_0) \int_0^t T(t')^4 \mathrm{d}t' \right] \tag{29a}$$

which reduces to

$$T(t) = T_0/(1 + 6\epsilon\sigma_{SB} T_0^3 t/\rho c_p R_0)^{1/3} \tag{29b}$$

Using a constant specific heat, the characteristic time for the energy content to be reduced to a fraction κ of its original value for the uniform temperature approximation is

$$\tau_\epsilon(\kappa) = [(1-\kappa^3)/\kappa^3] \rho c_p R_0 / 6\epsilon\sigma_{SB} T_0^3 \tag{30}$$

Cavitation or Flashing

There is some literature (e.g., Refs. 30 and 31) on the results of suddenly reducing the pressure on relatively large, plane liquid surfaces. There is less information on the behavior of small-diameter liquid jets of moderate vapor pressure liquids in a vacuum. One informative work is that of Fuchs and Legge.[1] Consider Fig. 3; in order for a vapor bubble to exist or grow, its internal pressure must be at least

$$p_B = p_S + \sigma/R_0 + 2\sigma/R_B \tag{31}$$

If we assume that there are no temperature gradients in the liquid, the internal bubble pressure must be the vapor pressure $p_v(T_0)$ and $p_S = p_v/2$, or $p_S = 0$ for a very cold surface. The bubble has a radius at least that given by solving for R_B in Eq. (31) if the bubble is to begin growing. The equilibrium bubble radius, or minimum radius that will permit growth, is

$$R_{BE} = 2\sigma(p_v/2 - \sigma/R_0)^{-1}$$

or, for a cold stream surface,

$$R_{BE} = 2\sigma(p_v - \sigma/R_0)^{-1} \tag{32}$$

For water, values of R_{BE} as a function of stream diameter D_0, with temperature T_0 as a parameter, are presented in Fig. 5. One curve assuming a cold stream surface is also shown, to give an idea of the magnitude of surface cooling effects.

Note that for small jets the equilibrium bubble size is larger than the jet diameter up to quite high temperatures. Such jets are unlikely to be able to cavitate unless there are large quantities of dissolved gas present Presumably, they simply evaporate. It is difficult to imagine a bubble being formed even at the jet boundary under these conditions. One guesses that something like $R_{BE} = 0.1R_0$ is necessary before there is much chance of cavitation. There is another possibility: small bubbles filled with gas trapped at the stagnation pressure of the stream may be entrained in the flow.

In order to obtain some quantitative feeling for bubble growth, we have used a growth equation described by van Stralen.[32] The equation of motion for the radius R_B of a bubble in a viscous liquid is[32]

$$R_B\ddot{R}_B + \frac{3}{2}\dot{R}_B^2 = \frac{\Delta p}{\rho} - \frac{2\sigma}{\rho R_B} - \frac{4\mu\dot{R}_B}{\rho R_B} \tag{33}$$

where

$$\Delta p = p_{vB} - \frac{\sigma}{R_0} - \frac{p_v(T_S)}{2} \tag{34}$$

is the pressure difference driving the bubble expansion and p_{vB} the vapor pressure of the liquid at the bubble wall temperature. The last two terms on the right-hand side of Eq. (34) are the pressure terms acting on the stream, and the first is the internal pressure of the bubble. The vapor pressure p_v is given by the Clausius-Clapeyron equation [Eq. (22)].

The reductions of the surface temperatures with time due to vaporization for both the external stream and the interior bubble wall were calculated using our previous approximation [Eq. (17a)] and solved simultaneously with a nondimensionalized bubble growth equation

$$\ddot{\hat{R}}_B = -\frac{3}{2}\frac{\dot{\hat{R}}_B^2}{\hat{R}_B} + \frac{C_{pB}}{2\hat{R}_B} - \frac{2}{We_{0D}\hat{R}_B} - \frac{4}{We_{0D}\hat{R}_B^2} - \frac{C_p}{4\hat{R}_B^2} - \frac{8\dot{\hat{R}}_B}{Re_{0D}\hat{R}_B^2} \tag{35}$$

for $\hat{R} = 0$ at $\hat{t} = 0$. Equation (35) is written nondimensionally using R_0 and V, along with the definition of Weber and Reynolds numbers based on stream diameter and the pressure coefficients

$$C_{pB} = p_{vB}/(\rho V_0^2/2)$$

$$C_{p_v}(T_S) = p_{vS}(T_S)/(\rho V_0^2/2) \tag{36}$$

Results for water streams at several different temperatures are shown in Fig. 6. In all cases, the initial bubble radius R_{B0} was chosen to be just slightly greater than that corresponding to the equilibrium bubble radius. For water streams up to 323 K (the highest we studied), the calculated cooling of the bubble wall fluid was very small, so that the surface layer thinning due to bubble expansion that is not included in Eq. (17a) is of no quantitative importance. To remove the effects of the initial bubble size, we define a burst time as shown in Fig. 6, assuming the stream has burst when $\hat{R}_B = 1$. The calculated burst times will be compared to experiments in the next section.

Experimental Result and Comparison to Calculated Stream Responses

Droplet Directional and Speed Stability

As noted before, many of the potential applications of liquid streams in space depend on high directional and speed stability. We have reported elsewhere[11,23,33] experimental results on the directional and speed stability of low vapor pressure fluids in a vacuum. The experiments were conducted in the apparatus illustrated in Fig. 7. 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. The only external connection during operation is via flexible tubing to the mechanical backing pump and the water supply for diffusion pump cooling, as well as several power leads and instrumentation cables. 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. Two droplet velocity dispersion devices (DVD^2)[34] are used to observe the configurations and measure the characteristics of the droplet streams. One observes a stream after it has traveled 22 cm, the other when it is 5.4 m from the exit of plane of the orifice. The droplet stream emerges from the droplet generator and travels the length of the flight tube (typically at ambient pressures of a few times 10^{-5} torr). A laser beam is split and sent through both the optical access ports of the apparatus. As the droplet stream passes through the light, its magnified shadow image is reflected onto the receiving slit of a dispersion device. The slit is positioned perpendicular to the stream and just in front of a photomultiplier tube. Each droplet image that passes over the slit causes a dip in the light flux received by the slit. The output from the photomultiplier tube is digitized and recorded. An analysis of the variations in the separations of successive drops can be interpreted in terms of speed variations. Also, angular dispersions can be obtained by appropriate measurements of the stream's position. A more detailed description of the experiments, instrumentation, and analysis is presented in Refs. 7, 11, 23, 33, and 34.

Two low vapor pressure fluids have been used, DC-704 and butyl phthalate. The first is a diffusion pump oil with about the same density as water, a viscosity close to 40 cP, and a surface tension about half that of water. The second fluid has a density close to that of water, a viscosity of 14 cP, and a surface tension of 50 dynes/cm. Both fluids have low vapor pressures. The results of the studies of stream angular dispersion and droplet speed dispersion are reported in detail in Refs. 7, 11, 23, and 33. Briefly, directional stabilities of the streams are excellent, being typified by a standard deviation of $\pm 2\ \mu$rad. The droplet speed dispersions are not quite so good when conventional stream breakup techniques are employed, typically represented by a standard fractional speed deviation

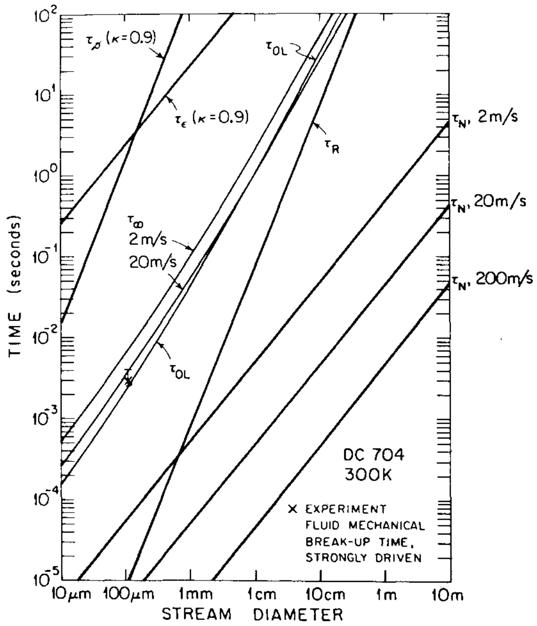

Fig. 9 Characteristic response times of DC-704 streams in a vacuum.

of around $\pm 10^{-5}$. However, a new breakup technique has been developed[7,23] that has produced droplet speed dispersions as low as $\pm 1\times 10^{-6}$. This extremely low-speed dispersion is the result of applying amplitude modulated disturbances to the capillary streams, which positively affects the formation, propagation, and performance of the resulting droplet streams.[7,23]

It is evident from available stream images that the angular dispersion probably originates in a force applied perpendicular to the stream before the stream has broken into droplets.[33] A prime suspect is a surface tension originated force at the exit of the nozzle, since both of the fluids wet the exit surface. The source of the droplet speed dispersion is not as easy to identify. It is due either to small variations in the drop-to-drop breakoff positions from the stream or to slight irregularities in the disturbances applied to the streams to initiate the breakup. Several possibilities are examined in more detail in Ref. 33.

Breakup Time

We have measured the breakup time of a driven DC-704 stream, using the DVD[2] instrument[34] to indicate when droplets are formed. The results agree reasonably well with calculated values from Eqs. (3) and (4) as will be indicated in a following section. Unfortunately, the size of the disturbance actually applied to the stream was not determined reliably in these particular experiments, although from more recent experience it is certain that the induced initial radial disturbance (ϵ_0) was of the order of 0.01.

Stream Bursting

For stream bursting results, we rely on the previous experiments of Fuchs and Legge,[1] as interpreted by us from their published photographs. We have obtained measurements from Fuchs and Legge's photographs to estimate the burst distance of several streams at different temperatures and have plotted the natural log of the burst distance as a function of temperature. For the calculated distances, because of uncertainties in bubble nucleation, we have defined the burst time by the method illustrated in Fig. 6 for 293 K. Comparing the data to a similar plot of calculated burst distances, we found that the slopes of both curves were nearly identical. However, the burst distances from the calculations are much shorter, by a constant multiplier, than the experimental data. The comparison between experiment and prediction, including a constant multiplicative factor, is shown in Fig. 8. The multiplicative factor may be explained by hypothesizing some nucleation distance that depends on the vapor pressure of the liquid in which the bubbles are developing. The bubbles begin significant growth sometime later downstream. The experimental burst distances were observed to be sensitive to the condition of the water with regard to gas content and initial bubble content.

The results of Fuchs and Legge[1] also show that there is a significant increase in the burst length with a decrease in the stream diameter from 3 mm to 0.6 mm at $T_0 = 293$ K. This is not so easy to explain. One possibility can be obtained from Fig. 5. The R_{BE} is about $0.5R_0$ for the 0.6-mm-diam stream, whereas it is less than $0.1R_0$ for the 3-mm stream. The observed effect may also be related to the rate of appearance in the stream of trapped gas bubbles. In this case, the larger stream would have a much higher ($\times$ 25) appearance rate since the mass flow is higher by a factor of 25. A more detailed discussion of water stream bursting is given by Dixon et al.[35]

Calculated Response of DC-704 and Water Streams in a Vacuum Compared to a Few Experiments

Using the expressions developed in earlier sections and the physical properties listed in Table 2, we have calculated the response times for DC-704 and water streams injected into a vacuum. These are presented as a function of stream diameter in Figs. 9 and 10. At the smallest diameters, the thermal layer thickness in the water streams violates the slab approximation used to solve the time-dependent diffusion equation. A line representing the trajectory of the condition $\delta r_T = 0.25R_0$ is shown in Fig. 10, indicating that the violation is limited. The layer thickness is less than $0.25R_0$ for stream diameters and characteristic times to the right and below the $\delta r_T = 0.25R_0$ line. Note that there are differences between some of the curves in Figs. 9 and 10 and their counterparts in Ref. 11. This is a result of using the more accurate expressions for the characteristic times derived in the present paper. Also, there was a plotting error for the τ_R in Ref. 11.

For the DC-704 case (Fig. 9), fluid mechanical breakup, as represented here by τ_∞ [Eq. (4)] and by τ_{0L} [Eq. (3a)] plotted for an ϵ_0 of 0.01, is generally shorter than the other response times. The exceptions are the nominal nozzle transit times τ_N, which are defined here as the times required to travel the length of the nozzle (assumed to be 1 diameter) at the speed V_0 and the velocity relaxation time τ_R. Notice that the driven linear breakup time approaches the undriven empirical times for large diameters. This is physically reasonable because the magnitude of β decreases as $D_0^{-3/2}$ [which is easily demonstrated, at least for inviscid fluids from Eq. (2) with $\mu = 0$]; so that at large R_0, β is small and τ_{0L} should approach τ_∞. The approach can be only approximate, of course, since the empirical τ_∞ has a stream velocity dependency not exhibited by τ_{0L}. It is also well to remember that the larger diameters in the figures are far beyond the range of diameters used in the experiments that supplied the data on which the expression for τ_∞ is based. Also, for the larger stream diameters, any terrestrial results would be suspect because of the influence of gravity. From data presented by Taub[36] or from a comparison of Eqs. (3b) and (3c), it is expected that for small ϵ_0 (say, less than 0.01 or so), the linear theory should provide surprisingly good predictions of stream breakup. The merging of τ_∞ and τ_{0L} at large D_0 in Fig. 9 is connected with this expectation.

Consider the velocity relaxation time τ_R, and remember that it assumes a fully developed parabolic velocity profile at the nozzle exit. Because of the high viscosity of DC-704, the velocity profile relaxation is quite rapid. For 20-m/s streams with diameters of less than, say, 1 cm, it is expected that stream breakup and droplet formation should be unaffected by any effect of radially nonuniform stream speeds, except for radial disturbances introduced by the rapid velocity relaxation

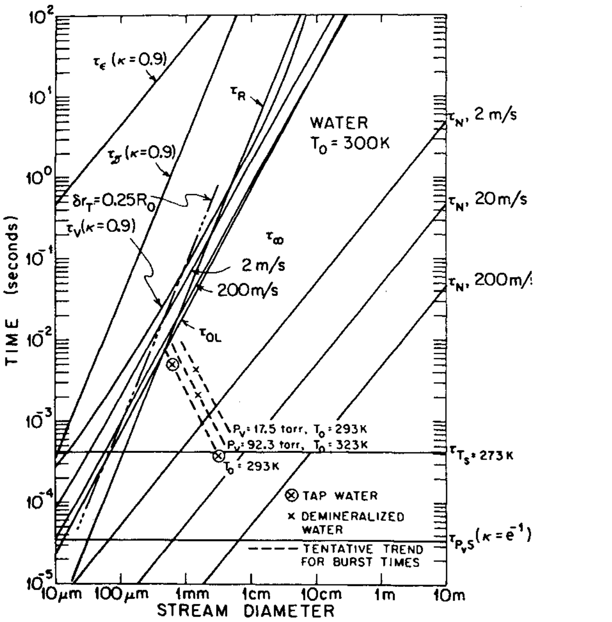

Fig. 10 Characteristic response times of water streams in a vacuum.

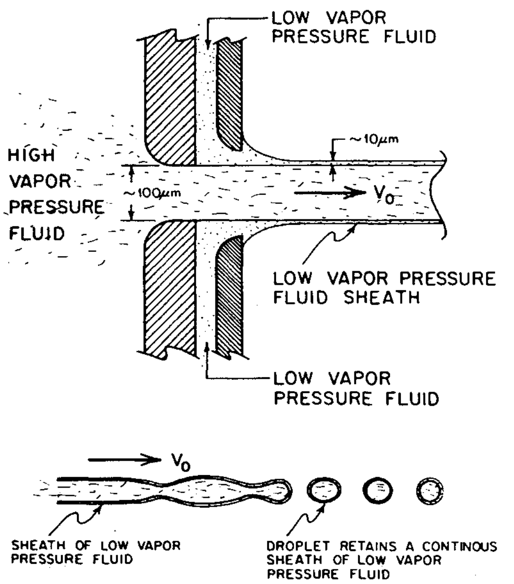

Fig. 11 Proposed method for controlling evaporation from a small-diameter stream of relatively high vapor pressure fluid.

possibly being amplified by the stream. Note that the predicted breakup times, whether driven or undriven, are fairly close together, at least from the perspective of the scale of Fig. 9. It is only for the smaller diameters that the driven stream times depart significantly from the empirical undriven times. An experimental point is shown in Fig. 9 with indicated uncertainty, representing a breakup time observed in our facility. As mentioned before, we are not certain of the size of the applied disturbance but believe it to be of the order of 0.01. There is reasonable agreement between the observation and the predictions. In this connection, note that quite large variations of ϵ_0 do not shift the τ_{OL} curve very much. Both the times for significant stream cooling from radiation and for loss of significant amounts of dissolved gas are very long compared to the breakup times. Injection of a wide diameter range of DC-704 streams into a vacuum should be well behaved, which is consistent with the experimental results that have been reported.[7,23]

The injection of water into a vacuum is more dramatic. Several of the calculated characteristic times are shown in Fig. 10. First of all, the external surface pressure decreases to e^{-1} of its initial value in a very short time ($\tau_{pv,S}$) owing to evaporative cooling. For a 300-K initial temperature, the water surface reaches 273 K ($\tau_{TS=273}$) quite quickly, generally well before the breakup time. Only for streams smaller than about 70-μm diameter is it clear that droplets could be formed using driven stream breakup without questions about the stream surface's freezing. On the other hand, it is likely that significant supercooling will delay the freezing of the surface. Also, the continuous removal of the surface layer resulting from evaporation may delay surface freezing. These effects need to be studied in far greater detail. The times for a 10% loss of mass due to evaporation [$\tau_v(\kappa=0.9)$] occur only a little later than the breakup times. For water initially at 300 K, a line representing $\delta r_T/R_0=0.25$ [see Eq. (18a)] gives an idea of the limits to the validity of the slab approximation for the thermal layer ($\delta r_T<0.25R_0$ to the right of the line).

Superimposed on the predictions for water in Fig. 10 are the results of stream burst times we have interpreted from Ref. 1. Two types of water were used in these experiments—tap water and demineralized water. The points for different temperatures of demineralized water in a 1.5-mm stream are from Fig. 8. Of great interest is the change of burst distance with stream diameter suggested by the tap water data. If this trend is substantiated by further experiments, it appears that even for water, a 100-μm-diam stream would break up into droplets long before it cavitates. The question of whether the surface layer will supercool or begin to freeze and prevent breakup into droplets remains to be studied in detail, although it is clear that despite predicted surface temperatures below 273 K, stream bursting has not been prevented in the 0.6- and 3-mm tap water or the 15-mm demineralized water streams. It can be suggested from the trends presented in Fig. 10 that, apart from freezing issues, a stream of quite high vapor pressure fluid can be prevented from cavitating prior to fluid mechanical breakup by being formed with a sufficiently small diameter. Indeed, based on the results in Fig. 5 and the discussion in a preceding section, there is an expectation that for sufficiently small streams, neither the stream nor the subsequent droplets will cavitate or burst. They will merely evaporate. If a way could be found to prevent the evaporation, fluids with vapor pressures up to perhaps tens of torr could be transported in 100-μm-diam streams.

One way to prevent evaporation is to arrange to coat a high vapor pressure liquid stream with an immiscible low vapor pressure liquid. For instance, a 10-μm-thick layer of low vapor pressure liquid would change the evaporation rate by a factor of about 10^{-6}. Thus, a liquid with $p_v=10$ torr would have an effective vapor pressure of 10^{-5} torr, which is quite tolerable for many applications. A possible means to apply a diffusion barrier to a liquid stream is illustrated in Fig. 11.

For water as for DC-704, the escape of dissolved gas ($\tau_{\mathfrak{D}}$) and cooling due to thermal radiation (τ_ϵ) are much longer than the other times. Because of its low viscosity, water also has long velocity profile relaxation times; however, in most practical cases, a water stream would not have an initial parabolic velocity profile, but rather one with thin boundary layers, thus reducing τ_R substantially, as indicated by Eq. (6). If a water stream does have an initial parabolic profile as the result of flow through a long nozzle, the slow acceleration of the wall fluid may permit freezing to take place at very short distances from the nozzle, leading to ice accumulation and possibly stream disruption. The driven breakup prediction τ_{OL} for water, like DC-704, is relatively close to the empirical τ_∞ for all diameters, lending additional credibility to the predicted times, because the driven curve is not very sensitive to the amplitude of the initial disturbance [Eq. (3a)].

Summary

The potential applications of free-flying droplet streams in space are such that, in most cases, close control must be maintained over the direction and speed of the streams. The events that can occur when a liquid stream is exposed to a vacuum have been discussed in the paper and are summarized in Fig. 1. For low vapor pressure liquids, previous measurements indicate that droplet streams can have directional stabilities of at worst a few μrad.[11,33] The drop-to-drop fractional speed variations can be as low as 1 part in 10^6.[33] For higher vapor pressure fluids, it appears, from the discussion and analysis presented here, that it should be possible to maintain stable, controllable streams, with fluids having vapor pressures up to several torr in streams a few hundred microns in diameter. Fluid streams of one millimeter and greater diameter with vapor pressures in the tens of torr range are expected to burst. A number of questions arise about the influence of stream surface cooling and possible surface freezing on the breakup phenomena. This paper presents only an introductory road map to the complicated, coupled phenomena that take place when finite vapor pressure liquids are ejected into a vacuum. There is much more work required before a satisfactorily complete quantitative description of a fluid stream's response to a vacuum is available.

Acknowledgments

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