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Temperature and Scale Effects Upon Cavitation and Flashing in Free and Submerged Jets

Observations of inception and desinent cavitation numbers in small submerged jets, and observations of the flashing of small, highly superheated, free jets, are presented. The observations, made over a range of jet sizes and water temperatures, reveal a strong influence of geometric scale in both systems. The water temperature has little effect upon the cavitation number for the submerged jet except at high temperatures. Flashing occurs in the free jet after a delay time which is shown to vary as the (−7/2) power of the liquid superheat, and inversely as the jet area.

Introduction

Our present understanding of the mechanisms of cavitation and flashing is far from complete. So, too, is our understanding of the related problem of determining the effects of such system parameters as liquid temperature and geometric scale upon the inception of cavitation. The present inquiry provides new observations of temperature and scale effects upon small, free, and submerged jets. These data provide a basis for making certain inferences about the mechanisms of liquid breakup in each case.

Cavitation in a submerged jet was first studied by Rouse [1][1] who observed cool water in the mixing region of a jet issuing from a $1^1/_2$-in-dia convergent nozzle. He used a hydrophone to determine the point of cavitation inception. Intermittent crepitant sounds marked the beginning of cavitation when the cavitation number, σ, defined as

$$\sigma \equiv \frac{p_{\text{amb}} - p_v}{\rho V^2/2} \tag{1}$$

decreased to about 0.7. The sound had increased to a steady roar when σ reached 0.55.

Jorgensen [2] also measured the sound emission of submerged cavitating jets, but his interest was chiefly acoustical. He presented curves of the power output of sound at various audible frequencies, as a function of σ for $^3/_8$, $^3/_4$, and $1^1/_2$-in-dia convergent nozzles. These curves begin to rise sharply when σ is about 0.4, 0.5, and 0.75, respectively, for the three nozzles.

Numachi, et al. [3] presented an experimental study of the effect of cavitation upon discharge coefficients of orifices in pipelines. However, they did not identify the onset of cavitation, nor the cavitation number, in a way which can be compared with our data. Of greater interest to this study is a detailed discussion of Numachi's work by Ball [4]. For pipeline orifices of $2^3/_8$, $1^3/_4$, and $1^1/_4$ in. dia and a nozzle $1^1/_3$ in. dia, he presented measured inception cavitation numbers, σ_i, of about 1.6, 1.2, 1.0, and 1.2, respectively. Both Numachi and Ball implicitly regarded variations of σ as arising from variations of geometry. The parameter, β—the ratio of the orifice diameter to the pipe diameter (3.07 in., in Ball's apparatus)—changed significantly between apertures, and the variation of σ_i was almost linear in β. We shall subsequently contend that this variation is actually a scale effect and that the geometrical configuration is not particularly important.

None of these preceding investigators has given serious consideration to effects of liquid temperature upon σ_i. In a very rough way, temperature is accounted by the vapor pressure, p_v,

[1] Numbers in brackets designate References at end of paper.

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Nomenclature

A = cross-sectional area of a jet, measured at vena contracta
a = thermal diffusivity
= heat-transfer term in bubble growth equation
ΔG = free energy needed to create an unstable equilibrium bubble
h_{fg} = latent heat of vaporization
m_a = mass of permanent gas in a gas-vapor bubble
p_{amb} = ambient pressure, or reference low pressure in a system
p_a = partial pressure exerted by a permanent gas
p_v = vapor pressure
R = bubble radius
R_0 = radius of an unstable equilibrium gas-vapor bubble
R_s = radius of a stable equilibrium gas-vapor bubble
$\mathcal{R}$ = ideal gas constant on a unit mass basis
r = dimensionless bubble radius, R/R_0
T = temperature (of superheated liquid if unspecified in context)
T_{sat} = saturation temperature at ambient pressure
t_d = delay time between emission and flashing of a free jet
t = time
t_c = characteristic time during which a vapor bubble grows negligibly—a function of ϵ
V = velocity of jet
α = concentration of dissolved permanent gas in a liquid
β = Henry's law constant, or ratio of orifice diameter to pipe diameter
γ = surface tension
ϵ = dimensionless increment of bubble radius
ρ = liquid density
ρ_g = saturated-vapor density
ρ_f = saturated-liquid density
σ = cavitation number defined in equation (1)
σ_d = desinent cavitation number
σ_i = inception cavitation number
τ = dimensionless time specified by equation (9)
τ_c = dimensionless characteristic time during which a bubble grows negligibly—a function of ϵ

in σ. The *rationale* that established σ as a similarity parameter is entirely too simple, however, and an investigation of temperature effects is warranted. Hammitt [5], in a study of venturi sections and a pump impeller, found scale effects but no effect of water temperature in the range 60 to 160 F.

The free jet has been the subject of much less study than the submerged jet. While much attention has been given to free two-phase jets (see for example, [6] and [7]), only Brown and York [8] have observed the flashing of a free jet *after* it has passed into the atmosphere. Their concern was primarily directed toward the spray formations of such jets, while the present investigation will concentrate upon scale and temperature effects.

Related Theory of Bubble Stability and Growth

Cavitation or flashing generally occurs in a liquid flow when certain disturbances are "triggered" into an unstable condition by a local or general lowering of the pressure. The thermodynamic mechanisms of this triggering have recently been discussed by Lienhard [9]. In flows that flash or cavitate at a distance from a boundary,[2] the disturbance is likely to be a bubble composed of permanent gas and vapor.[3] A force balance on such a bubble requires that

$$(p_v + p_a) - p_{\text{amb}} = \frac{2\gamma}{R} \tag{2}$$

where R is, in this case, the equilibrium bubble radius. The pressure, p_a, of the permanent gas is given by Henry's law

$$p_a = \alpha\beta \tag{3}$$

where β is the Henry's law constant and α is the concentration of gas in solution with the liquid.

Plesset and Epstein [13] have shown the gas-diffusion process to be relatively slow. Thus, during a process in which a bubble is disturbed by a turbulent pressure fluctuation or some other rapid environmental change, the mass, m_a, of gas in the bubble is virtually constant and p_a is given by the ideal gas law as

$$p_a = \frac{3m_a\mathcal{R}T}{4\pi R^3} \tag{4}$$

When equation (4) is substituted into equation (2) the resultant equation is satisfied by two real values of the equilibrium radius—one, R_s, is stable and the other, R_0, is unstable. Reference [9] shows that the free energy, ΔG, required to perturb the stable bubble into an unstable condition is

$$\Delta G = \frac{8\pi\gamma}{3}\left\{\left[\frac{3m_a\mathcal{R}T}{8\pi\gamma} - R_0^2\right]\left[1 - \left(\frac{R_s}{R_0}\right)^3\right] + \tfrac{3}{2}(R_0^2 - R_s^2) - \frac{9m_a\mathcal{R}T}{8\pi\gamma}\ln\left(\frac{R_0}{R_s}\right)\right\} \tag{5}$$

When the mass of permanent gas, m_a, approaches zero, equation (5) reduces to Frenkel's [14] expression for the free energy needed to trigger homogeneous nucleation in a pure liquid:

$$\Delta G = \frac{4\pi\gamma}{3}R_0^2 \tag{6}$$

where R_0 is given by equation (2) as

$$R_0 = \frac{2\gamma}{p_v - p_{\text{amb}}} \tag{7}$$

[2] Dailey and Johnson [10] offer strong evidence that even cavitation in a boundary layer is of this character.

[3] Harvey, et al. [11] proposed that such bubbles might sometimes be gas pockets riding on solid particles in the liquid. Holl and Treaster [12] explore this idea further.

A bubble which contains no permanent gas and which has been jarred just beyond the unstable condition will begin to grow in accordance with the requirements of a dynamical equation of the form[4]

$$r\ddot{r} + \tfrac{3}{2}\dot{r}^2 - \frac{r-1}{r} + f(\text{physical properties, time}) = 0 \tag{8}$$

where

$$r \equiv R/R_0 \tag{9}$$

and the independent variable is a dimensionless time, τ:

$$\tau \equiv \left[\frac{(p_v - p_{\text{amb}})^3}{4\rho_f\gamma^2}\right]^{1/2} t \tag{10}$$

The heat-conduction term, f, has been shown [16] to be unimportant in the early stages of growth. Accordingly, equation (8) becomes

$$r\ddot{r} + \tfrac{3}{2}\dot{r}^2 = \frac{r-1}{r} \tag{8a}$$

with initial conditions: $r(0) = 1 + \epsilon;\ \epsilon \ll 1$

$$\dot{r}(0) = 0$$

The numerical solution of equation (8*a*) is shown in Fig. 1. The time scale in this figure can be shifted arbitrarily by choosing different values of ϵ. For any typical value of ϵ, however, there is a single time, τ_c, elapsed before the knee of the bubble-growth curve in Fig. 1. The characteristic lag time in dimensional form, t_c, during which a bubble "idles" before beginning to grow rapidly, is thus

$$t_c = \tau_c(\epsilon)\left[\frac{4\rho_f\gamma^2}{(p_v - p_{\text{amb}})^3}\right]^{1/2} \tag{11}$$

Ma and Wang [18] present a family of curves similar to Fig. 1 for bubbles that initially contain finite amounts of permanent gas.

The bubble-growth curve will inflect at a point just beyond the knee of the curve as heat conduction to the interface assumes control of the growth process. The time elapsed between the knee of the curve and growth to any substantial size (say, $r \geq 10^2$) is well approximated by Forster and Zuber's asymptotic formula

$$R = \left[\frac{\rho_f c_p(\pi a)^{1/2}(T - T_{\text{sat}})}{h_{fg}\rho_g}\right] t^{1/2} \tag{12}$$

[4] Equation (8) is in the form of Dergarabedian's [15] momentum equation. The function, f, represents a retarding effect upon bubble growth which results from the slowness of heat transfer from the superheated-liquid environment to the bubble interface. The function has been dealt with in some detail by Forster and Zuber [16], Plesset and Zwick [17], and others.

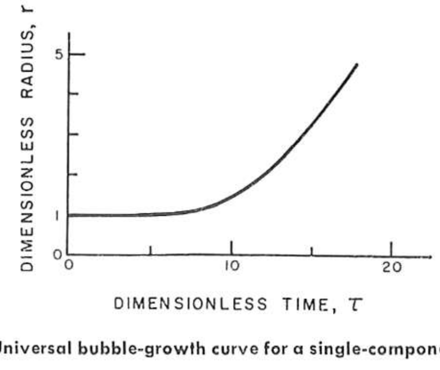

Fig. 1 Universal bubble-growth curve for a single-component system

Cavitation and Flashing as Statistical Phenomena

Every flow will have in it some spectrum of pressure disturbances which in certain instances can trigger bubble growth. Holl and Treaster [12] and Jorgensen [2] have pointed out that when the volume of liquid in a cavitation-prone region is great, there will be a proportionately large number of potential bubble-nucleation sites to be triggered by such disturbances.

It is our conjecture that cavitation inception is, in some measure, a stability phenomenon. When a certain minimum number of nuclei are being triggered they increase the local level of pressure fluctuations to a critical point at which full cavitation becomes self-sustaining. A scale effect enters under these circumstances because this critical level is reached sooner when the cavitation-prone region is scaled up in size.

In the submerged jet the region of maximum intensity of turbulence will increase with the size of the jet. There might be a secondary effect of velocity upon the size of the region of maximum turbulence, insofar as the configuration of the mixing zone depends upon velocity. Accordingly, the cavitation number should increase with size (i.e., cavitation will begin at lower velocities), but the nature of this increase would be difficult to predict. The effect of geometrical configuration will be to alter the shape and relative size of the region of maximum turbulent intensity.

The free jet gives a unique opportunity to witness the statistical character of nucleation. As a free jet leaves an orifice it entrains virtually no vorticity and will be subject only to a very low level spectrum of pressure pulsations. It will therefore flash only when it becomes highly superheated.

Two events must take place before a bubble can begin rapid growth in a superheated liquid:

1 A nucleus must be triggered into an unstable condition by local pressure pulsations. The probability that growth will be started by a given spectrum of pressure pulsations, will be inversely proportional to ΔG; i.e., as less triggering energy is needed, triggering becomes more likely to occur. This probability will also be directly proportional to the jet area since proportionately more potential nuclei will be present.

2 A nucleus, once triggered, must "idle" for a length of time, t_c, before rapid growth begins. During this time it is subject to removal of the low pressure that begot it, and to subsequent collapse. The probability of its survival during this idle time is thus inversely proportional to t_c.

If we call the first event "nucleation" and the second event "survival," and use the symbol $\mathcal{P}$ to designate the probability, then

$$\mathcal{P}(\text{survival}) = \mathcal{P}(\text{survival if nucleation has occurred})\mathcal{P}(\text{nucleation}) + \mathcal{P}(\text{survival if no nucleation has occurred})\mathcal{P}(\text{no nucleation}) \tag{13}$$

but $\mathcal{P}$(survival if no nucleation has occurred) is zero, so

$$\mathcal{P}(\text{survival}) \sim \frac{A}{(\Delta G)(t_c)} \tag{14}$$

The free jet should thus flash after an average delay time, t_d, which is inversely proportional to $\mathcal{P}$(survival). Substitution of equations (6), (7), and (11) in (14) gives

$$t_d \sim \frac{1}{A(p_v - p_{\text{amb}})^{7/2}} \tag{15}$$

Equation (15) embodies three implicit assumptions:

1 There is little cooling of the jet between the time that it leaves the orifice and the time that it flashes.

2 The permanent gas content of the nuclei is low enough to permit the use of equation (6) instead of the more general equation (5).

3 The final stage of bubble growth to large radii is of short enough duration in comparison with t_d that it does not add a significant delay component to t_d.

Experiment

Fig. 2 shows the apparatus in which the present free and submerged-jet observations were made. The open hot-water loop shown in the figure supplies water to a 3-in-dia pipe just upstream of the test section, at temperatures ranging between 65 and over 300 F and pressures ranging between 0 and 100 psig. Details of the system and of experimental procedure are given in reference [19].

Fig. 3(a) shows the submerged-jet test section. This section was bolted directly to the 3-in-dia supply pipe. Fig. 3(b) shows the flow configuration just above the orifice or nozzle, and Figs. 3(c) and (d) show a typical orifice and the converging nozzle. Orifices of $^1/_{16}$, $^1/_8$, and $^1/_4$ in. dia, and a single $^1/_8$-in-dia nozzle, were used.

In the free-jet tests the test section just consisted of one of two flange-plate orifices across the end of the 3-in-dia supply pipe—one of them $^3/_{32}$ in. dia and the other $^5/_{32}$ in. dia.[5]

[5] A brief study of the effect of upstream subcooling upon flashing has already been made with this apparatus, and reported earlier [20].

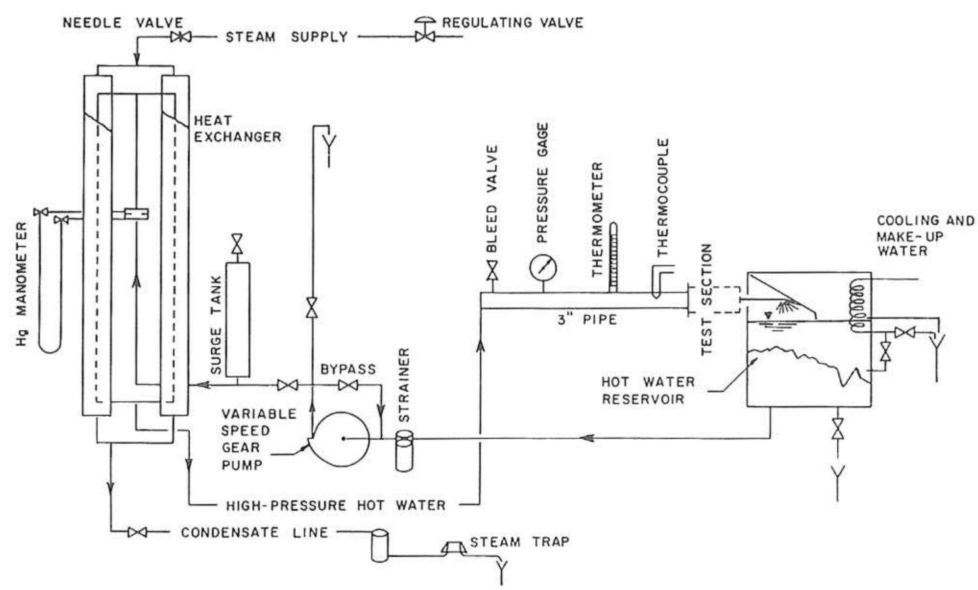

Fig. 2 Free and submerged-jet apparatus

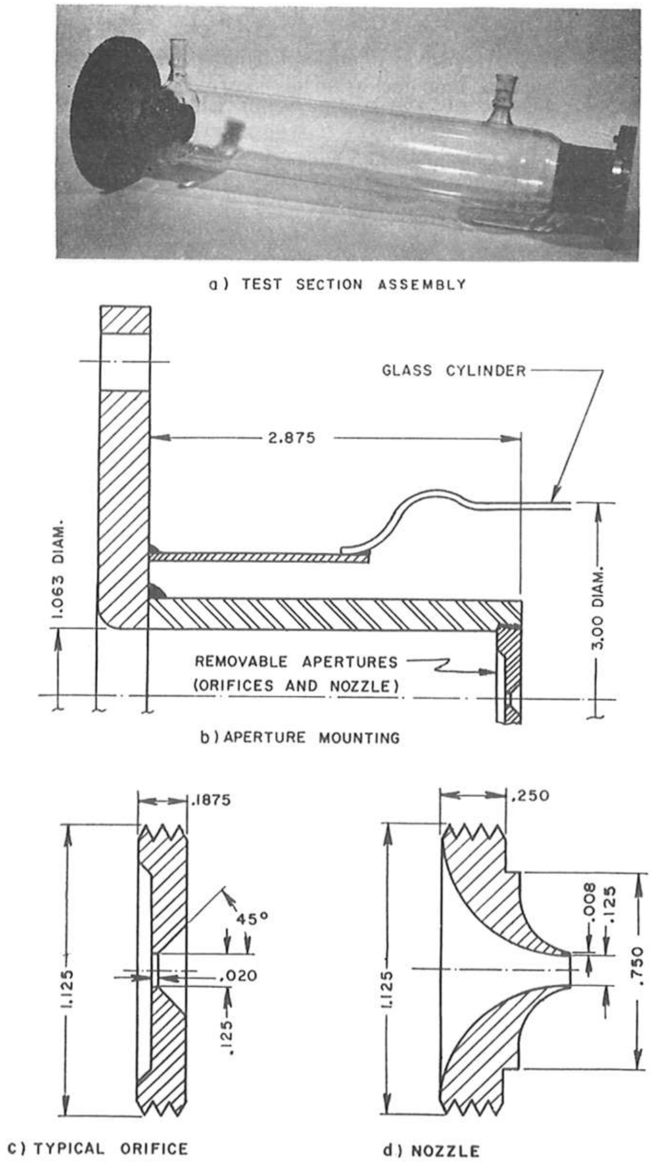

Fig. 3 Submerged-jet test section and details

A uniform procedure of water preparation was employed in each of the experiments. In both cases the system was charged with untreated tap water and the pump set into operation at a moderate speed. The water was allowed to circulate for an hour with the test section in place; at about 200 F for the submerged jet, and at about 225 F for the free jet. This assured comparatively uniform dissolved-gas concentration in the runs.

The submerged-jet runs were made by establishing a relatively high temperature and then increasing the velocity at 4 fps per min until cavitation began. The velocity and temperature were then lowered, equilibrium was reestablished, and the process was repeated. Cavitation desinence was observed, in a like manner, for the $^1/_8$-in-dia orifice.

The incipient and desinent points were observed both by camera and eye, and by ear. The visual technique proved less certain since the first bubbles were blurred to both the eye and to a high-speed (5000 frames/sec) motion-picture camera. The use of a 1-μsec strobe light made satisfactory still photos [19], but these could only bracket the incipient or desinent point.

A short steel bar connecting the test section with an observer's ear gave a more accurate "view" of the cavitation process, and it corroborated the less reproducible visual methods. Some sporadically collapsing bubbles were heard just below the point that we called incipient. The point of incipience was identified when a discontinuous jump to steady cavitation was heard.

Fig. 4 shows the incipient cavitation numbers deduced from the data for the three submerged-orifice jets over the temperature range from 90 to 204 F. Similar results are given for the $^1/_8$-in-dia nozzle in Fig. 5. Fig. 6 shows desinent cavitation coefficients for the $^1/_8$-in-dia orifice. A set of data obtained from still photographs is also included in Fig. 6. The dashed line in Fig. 6 represents the σ_i data for this orifice, from Fig. 4. It shows a typical hysteresis effect; the desinent cavitation numbers are about 20 percent higher than the inception values.

Holl and Treaster define a delay time, in this connection, which differs considerably from the t_d represented by equation (15). This is the "cavitation delay time" defined as the time elapsed before cavitation occurs, when σ is *suddenly* lowered to σ_i. When we abandoned a steady variation of velocity and increased it suddenly to inception values, a similar delay was observed. The delay could be eliminated by providing an appropriate disturbance; tapping the supply pipe with a hammer would immediately trigger cavitation, for example. Furthermore, when the velocity was suddenly increased to a value between the desinent and inception values and left there, cavitation *eventually* set in.

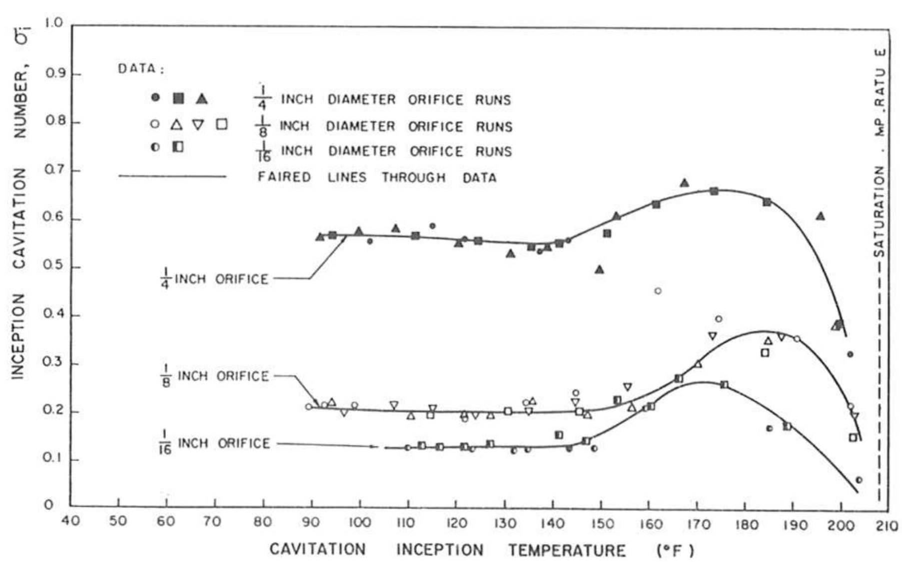

Fig. 4 Effect of size and temperature upon σ_i for submerged-orifice jets

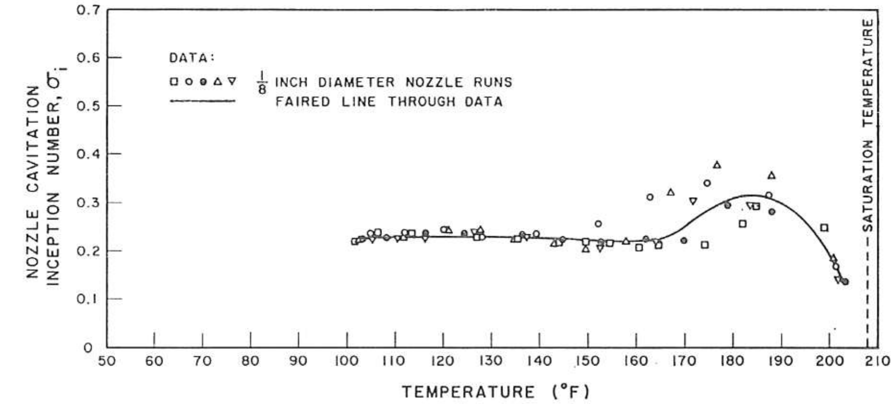

Fig. 5 Effect of temperature upon σ_i for nozzle jets

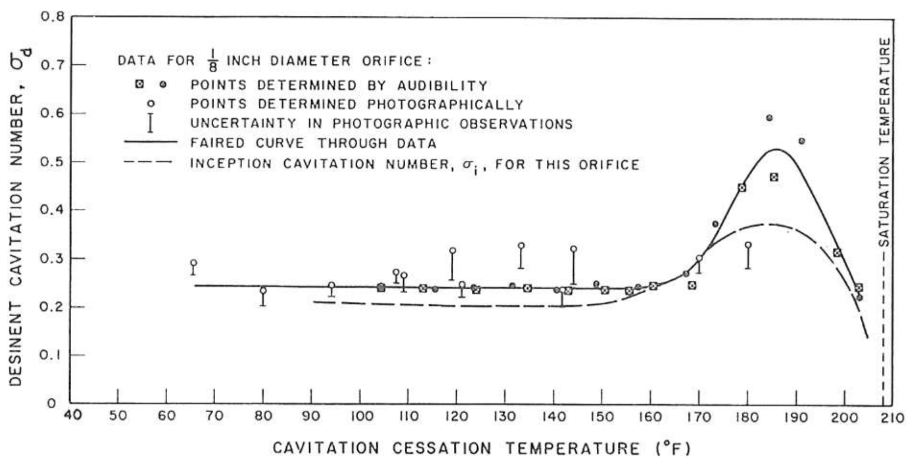

Fig. 6 Effect of temperature upon σ_d for the 1/8-in-dia orifice jet

The free jets were first observed in still photographs made with a 1 μsec strobelight. Fig. 7 includes a set of eight such pictures showing the result of increasing the jet temperature at an almost constant velocity. Such a record tells us much about the way in which the jet shatters, although it reveals little about the stochastic character of breakup.

Three different regimes of flashing were evident as the superheat was increased. The first consisted of bubbles that only partially ruptured the jet. These prevailed between about 260 and 280 F in the $^3/_{32}$-in-dia jet. At higher temperatures more and more bubbles tended to blast holes in the jet. At temperatures near 300 F, the jet broke completely into a fine spray after a point.

Six 100-ft reels of 16-mm movie film were exposed at about 5000 frames per sec with a Fastax camera. Five of these covered the temperature range from 267 to 296.9 F for the $^3/_{32}$-in-dia jet. Since billows of fine mist generated by the $^5/_{32}$-in-dia jet precluded photography at higher temperatures, we only made a motion picture during one fairly cool (269.2 F) run in this case. The movies were observed frame by frame on a microfilm reader. The distance from the orifice to the point of appearance of each bubble was measured and divided by the velocity to give the delay time, t_d. Finally these data were arranged into six histograms shown in Fig. 8.

The histograms reveal a phenomenon that was dramatically evident when the films were viewed in motion. In all cases, but in particular at the higher temperatures, each histogram displays a marked spike. This spike occurs at the position (or delay time) about which repeated *standing breakup* took place—at least in the higher temperature runs. Time and again a sequence of bubbles would fracture the jet continuously at a position near the position corresponding with t_d. This gave the impression of standing points of breakup. Presumably large pressure pulsations emanate from the breakup point and trigger all nuclei arriving from upstream.

Discussion and Conclusions

The section on cavitation and flashing as statistical phenomena suggested that there was a self-perpetuating quality to cavitation and flashing. That this is indeed the case has been borne out qualitatively in at least four ways: (*a*) The inception of steady cavitation was generally sudden and it followed when a low level of isolated random cavitation had been established. (*b*) Steady cavitation could be established at once at points between σ_i and σ_d if the system were artificially disturbed. (*c*) The standing breakup phenomenon observed in the free jet implied that flashing sustained itself by creating its own substantial pressure disturbances.

The fourth evidence of the self-sustaining character of cavitation is to be found in the pronounced scale effect that we anticipated would occur as a result of enlarging the cavitation-prone region. Fig. 9 combines the previous σ_i data for submerged jets, given by Jorgensen, Ball, and Rouse, and adds the present σ_i data for temperatures below 150 F. In this figure, the jet diameter has been multiplied by the square root of the appropriate coefficient of contraction. Both orifice and nozzle data are combined on the single curve. The faired line through the data touches all but one of the orifice points, and one third of the nozzle points. That the other two thirds of the nozzle points yield lower cavitation numbers suggests that the exterior faired geometry of these nozzles somewhat reduces the severity of turbulent mixing.

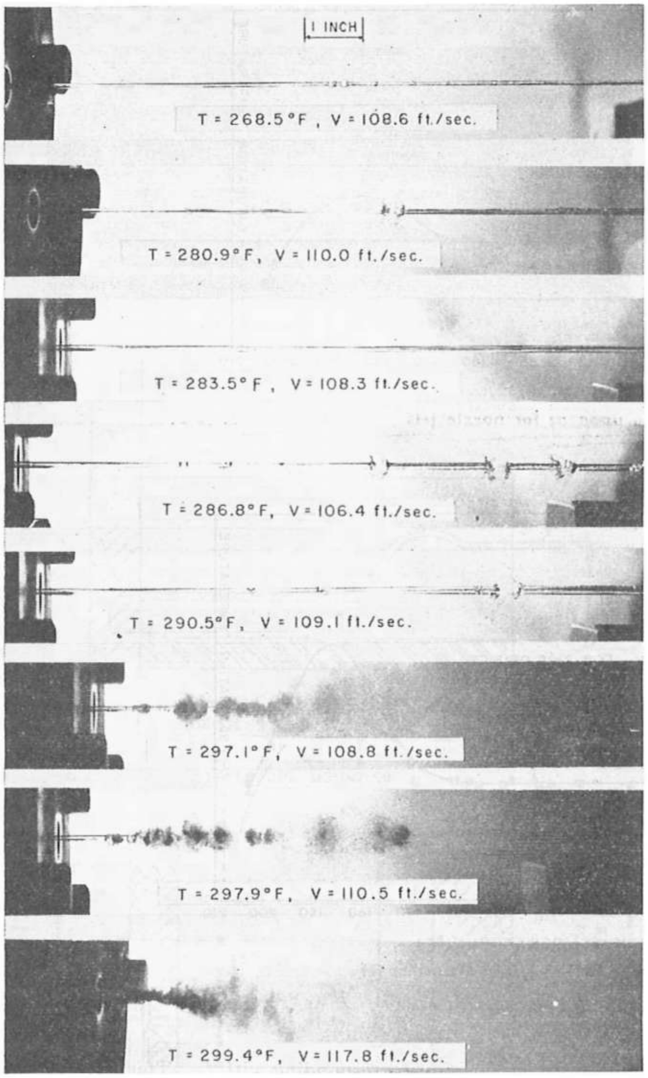

Fig. 7 Effect of increasing temperature upon a free jet issuing from a 3/32-in-dia orifice at about 110 fps

The data imply a strong effect of scale upon σ_i of the form

$$\sigma_i \sim (\text{characteristic dimension})^{2/3} \tag{16}$$

or in this case

$$\sigma_i = (\text{corrected diameter, in inches})^{2/3} \tag{17}$$

Like Hammitt, we found little serious effect of temperature upon σ_i below 160 F. At higher temperatures, however, the present values of σ_i rose to a maximum and then—near the boiling point—dropped off again. During the tests, we found that above 150 F the presence of tiny bubbles made the water in the test section appear milky. No doubt their presence promoted cavitation and raised σ_i. The following computation will show why their numbers increased so strongly in this range:

Substitution of equation (3) into equation (2) shows that if R is to be positive (in order for equilibrium bubbles to exist) the following inequality must be satisfied:

$$\alpha \geq (p_{\text{amb}} - p_v)/\beta \tag{18}$$

The solid line in Fig. 10 is the locus of minimum concentrations for which equilibrium bubbles can exist, as determined from equation (18). The experiments of Hammitt in the temperature range up to 160 F show that the air content of water can be held to $^2/_3$ of saturation by mere settling of the liquid. The concentration could be reduced to $^1/_3$ of saturation by degassing. Our loop achieved degassing in the pressurized heat exchanger but subjected the liquid to some aeration at the open test section. Thus we probably brought water into the test section between 1/3 and 2/3 saturated with air.

Fig. 10 shows that the probable air content of our water is such that near equilibrium, bubbles can persist in large numbers at temperatures corresponding with the aberrations of the σ_i versus T curves. We should thus expect that in general

$$\sigma_i > (\sigma_i)_{\text{cold water}} \quad \text{when} \quad \alpha \geq (p_{\text{amb}} - p_v)/\beta \tag{19}$$

At temperatures approaching the local boiling point, σ_i drops off sharply. In the experiments in this regime we noted that cavitation could be seen before it was heard. Collapse is so much less violent at these high temperatures that the audible method of observation is no longer valid.

The free-jet results have been correlated with equation (15) in Fig. 11. The mean t_d-values are given with the one standard deviation limits. Modal values of t_d (the "spikes" in the histograms) are also reported. The correlation is successful in correlating the existing observations of both modal and mean values of t_d.

Of the three assumptions cited in connection with equation (15) two were validated analytically: (*a*) Solution of the conduction equation indicated that, with the outside of the jet at the saturation temperature, insignificant cooling took place within the 8-in. length under observation. (*b*) Equation (12) shows that the late growth component of t_d is on the order of only 10^{-4} or 10^{-5} sec.

Acknowledgments

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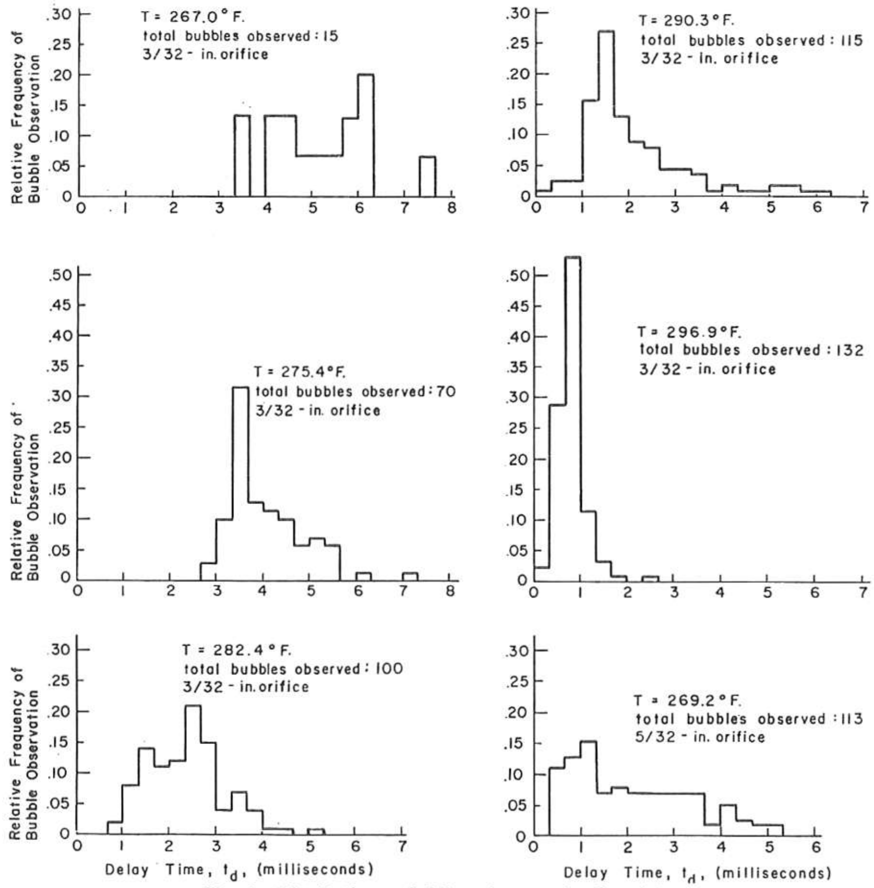

Fig. 8 Distributions of delay time, t_d, for free jets

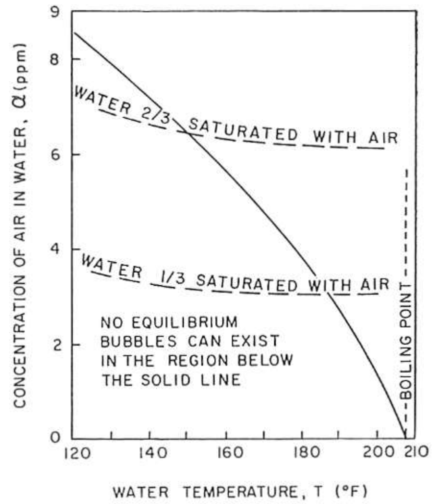

Fig. 10 Minimum air content for which equilibrium gas-vapor bubbles can exist

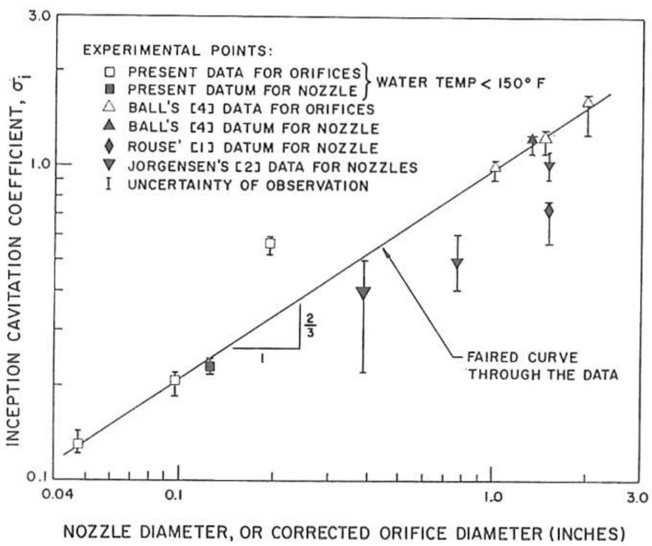

Fig. 9 Scale effect upon cavitation inception in orifices and nozzles

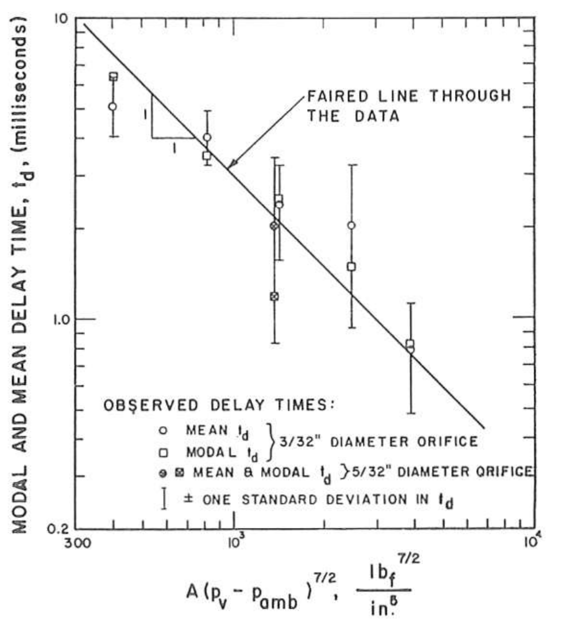

Fig. 11 Effect of scale and liquid superheat upon delay time in free jets

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