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EXPERIMENTS WITH ACOUSTICALLY LEVITATED DROPLETS*

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Abstract

The levitation by acoustic means of a droplet of one liquid in an immiscible host liquid provides a means by which a variety of droplet and bubble phenomena can be probed. With the apparatus described below the force due to the buoyancy of the droplet is balanced by a force due to the radiation pressure exerted on the droplet in an acoustic standing wave field established in a cylindrical column of the surrounding liquid. (The acoustic frequency is about 50 kHz.) By proper design the equilibrium of the droplet is stable to any perturbation in the position of the droplet; furthermore, the position in the standing wave field at which the droplet is trapped is independent of the droplet radius, but depends on the density and sound speed of both liquids as well as the acoustic pressure and pressure gradient.

The apparatus consists of a cylindrical glass column containing one liquid which is excited into acoustic resonance by a cylindrical piezoelectric transducer. A heating coil around the column provides the temperature field. A droplet of the sample liquid rising in the host liquid is trapped by acoustical means in a region of uniform temperature. Thus far this technique has been employed in a number of investigations: 1) the theory for droplet motion and droplet levitation in a sound field has been tested and has been found to provide very good predictions for experimental work, 2) the tensile strength (or acoustic cavitation threshold) of greatly superheated droplets of three liquids has been measured as a function of temperature and has been found to be in good agreement with predictions of classical homogeneous nucleation theory, and 3) levitated, superheated droplets have been exploded by a sudden increase in acoustic intensity. Moderately high speed films (about 4000 frames per second) have been taken of the resulting vapor bubble and show some interesting features associated with vapor bubble dynamics.

Experiments planned for the future include 1) radiation-induced cavitation of levitated, superheated droplets, 2) measurements of properties such as density, sound speed, and index of refraction of metastable liquids, 3) observations of the solidifi-

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cation of supercooled, levitated droplets, and 4) possible investigations of metastability of binary liquid mixtures.

INTRODUCTION

There are many instances in which it is desirable to isolate a sample from a solid container surface. For example, one much discussed application is the levitation of the nuclear fuel for a fusion reactor in order to allow the fuel to be heated to extremely high temperature. Another example is the space processing of materials. Sometimes levitation of the sample in a near vacuum is desirable whereas in other applications a fluid host medium, either gas or liquid, may be necessary. Levitation can be achieved in a number of ways. Zero gravity is the most obvious; for metallic samples magnetic levitation may be used; and fluid flow techniques (e.g. air turbine) or acoustic means have been used for a variety of materials. In this paper we shall confine ourselves to the levitation by acoustic means of droplets of one liquid in an immiscible host liquid.

It has been known for quite sometime that a progressive acoustic wave in a liquid can produce a force due to radiation pressure on an object in the liquid. But it has only been a short time since this fact has been used to practical advantage by many investigators. For instance, the recent use of ultrasonic equipment for diagnosis and therapy in medicine has lead to the need for knowledge of the safe levels of ultrasonic irradiation, and this requires adequate calibration procedures which often involve a measure of the force due to the acoustic radiation pressure on a body.

The analysis of radiation pressure for progressive acoustic waves can be generalized to standing acoustic waves, as will be outlined below. The result of the analysis can be applied to the case of the force on compressible fluid spheres.

If in an experimental situation this force is adjusted to equal the force due to buoyancy,the fluid sphere can be levitated.

Whereas gaseous bubbles are relatively easy to levitate,[1] the situation for liquid droplets is more complex.[2,3] First of all, the sample droplet material must be reasonably immiscible in the surrounding host liquid; second, it will be shown that the droplet material must be more compressible than the host liquid for stable levitation in a real situation; and third, relatively high acoustic pressure amplitudes (ranging from 1 to 15 atmospheres) may be required in order to balance the buoyancy force, implying that techniques for avoiding acoustic cavitation in the sample and host materials must be employed.

If these conditions are met, however, a number of interesting experiments can be performed. These experiments differ from zero gravity experiments in that the position of the levitated droplet is a stable equilibrium point rather than a point of neutral equilibrium. This difference can be an advantage in some situations.

In this paper we shall first review the basic considerations involved in levitating liquid droplets by acoustic means. We shall then discuss 1) experimental apparatus for levitating droplets, 2) some interesting and convenient features of droplet trapping, 3) the use of acoustic levitation in measurements of the tensile strength of liquids,[2,4] 4) the use of acoustic levitation in observing bubble dynamics associated with the explosive vaporization of a superheated droplet, and 5) some proposed experiments involving droplet levitation.

DROPLET LEVITATION

Lord Rayleigh first discussed the force on an object due to an acoustic wave, which he called acoustic radiation pressure, in 1902.[5] Since then much has been written on the subject, some of it conflicting. A lucid discussion of the basic effect can be found in an article entitled "Acoustic Radiation Pressure in a Traveling Plane Wave" by Rooney and Nyborg.[6] An excellant analysis of "The Acoustic Radiation Pressure on a Compressible Sphere" has been written by Yosioka and Kawasima.[7] Below, this analysis will be greatly abbreviated by considering the special case of the acoustic radiation force on a fluid sphere (bubble or drop) that is far more compressible than the host liquid.

Consider a compressible sphere of instantaneous volume $V(t)$. If the acoustic pressure field is described by $P_A(\underline{r},t)$, then the spatial gradient at the position of the sphere is $\nabla P(\underline{r},t)$. The acoustic force, $\underline{F}_A$, on the sphere for our special case is:

$$\underline{F}_A = - \langle V(t) \nabla P_A(\underline{r},t) \rangle_{t \text{ (time average)}} . \qquad (1)$$

If changes in the volume occur more rapidly than heat exchange can take place, then conditions tend toward adiabatic and small changes from the nominal volume of the droplet, V_o, are related to pressure changes by the adiabatic compressibility of the liquid:

$$k_A = - \frac{1}{V_o} \frac{\Delta V}{\Delta P} = \frac{-1}{V_o} \left(\frac{V(t)-V_o}{P_A(\underline{r},t)} \right) . \qquad (2)$$

But, if the liquid is not dispersive in the frequency range of interest, then the adiabatic compressibility is related to the density, ρ^*, and the speed-of-sound, c^*, of the sample liquid by the following relation:

$$k_A = \frac{1}{\rho^* c^{*2}} .$$

We have, therefore,

$$V(t) - V_o = -P_A(\underline{r},t)V_o k_A = -P_A(\underline{r},t)V_o/\rho^* c^{*2}$$

or

$$V(t) = V_o[1 - P_A(\underline{r},t)/\rho^* c^{*2}] .$$

If the time-variation of the pressure field is sinusoidal, we can write

$$P_A(\underline{r},t) = P_A(\underline{r})\sin\omega t;\ \nabla P_A(\underline{r},t) = \nabla P_A(\underline{r}) .\ \sin\omega t .$$

Therefore,

$$\underline{F}_A = -\langle V(t)\nabla P_A(\underline{r},t)\rangle = \frac{-1}{T_P}\int_0^{T_P} V_o\left(1 - \frac{P_A(\underline{r})\sin\omega t}{\rho^* c^{*2}}\right)\nabla P_A(\underline{r})\sin\omega t\, dt .$$

Here, T_P is the acoustic period ($=2\pi/\omega$). The straightforward integration yields

$$\underline{F}_A = + V_o P_A(\underline{r})\cdot\nabla P_A(\underline{r})/2\rho^* c^{*2} .$$

The droplet is also subjected to a buoyancy force:

$$\underline{F}_B = V_o(\rho-\rho^*)\, g\hat{z} ,$$

where ρ is the density of the host liquid, g is the gravitational acceleration, and $\hat{z}$ is the unit vector in the positive axial (z) direction.

In order to levitate a droplet, the z-component of the average acoustic force must be equal in magnitude and directed opposite to the gravitational force; therefore,

$$(\underline{F}_A + \underline{F}_B)_{z \text{ component}} = 0. \tag{3}$$

That is:

$$\frac{V_o P_A(z) \cdot \frac{dP_A(z)}{dz}}{2\rho^* c^{*2}} + V_o(\rho - \rho^*)\, g = 0$$

or

$$-P_A(z)\,\frac{dP_A(z)}{dz} = 2\rho^* c^{*2}(\rho - \rho^*)\, g \equiv K \ . \tag{4}$$

This result is valid if the fluid sphere is far more compressible than its host. More generally, it can be deduced from Reference 7 that for ρ and c equal to the density and sound speed of the host liquid, respectively, and for $\lambda = \rho^*/\rho$ and $\delta = c^*/c$, then

$$-P_A(z)\,\frac{dP_A(z)}{dz} = 2(1-\lambda) g \rho^2 c^2 \Bigg/ \left[\frac{1}{\lambda\delta^2} - \left(\frac{5\lambda-2}{2\lambda+1}\right)\right]$$

For the liquid combinations used in the experiments described below, Eq. 4 has been adequate. It should also be pointed out that in the experimental realization for droplet levitation described in the next section, there is, in addition to an axial pressure variation, a radial pressure distribution which serves to keep the droplet on axis.

APPARATUS FOR DROPLET LEVITATION

The essence of the apparatus used for droplet levitation is shown schematically in Fig. 1. The system is shown with the thermal control (heating wire and thermocouple), but evacuation and filtering apparatus as well as manipulating devices for the probes are deleted in order to leave the diagram uncluttered.

A pyrex glass vessel of the shape shown (30mm o.d. and 9mm o.d. tubes) holds the host liquid. The acoustic driving unit shown is a cylindrical PZT-4 lead zirconate transducer (1.5-in. o.d., 1.25-in. i.d., 1.5-in. length). The composite system, made up of this unit epoxied to the liquid-filled glass tube, resonates in the 50-60 kHz frequency range, corresponding to the (1,0,n) mode of the system, where 1 refers to the first radial mode, 0 refers to axial symmetry, and n is 2, 3, 4, and 5, corresponding to a spatial pressure distribution along the axis that can be

characterized by a wavelength of 2-10 cm. (The axial pressure distribution is not simply sinusoidal because of the irregularities in the shape of the cylinder.) The particular resonance frequency chosen is that for which the acoustic pressure amplitude along the axis of the liquid-filled tube has a maximum in the test region just below the transducer.

The magnitude of the acoustic field can be increased so as to produce a net acoustic force on the test droplet that is equal in magnitude and opposite in direction to the buoyancy force. In other words, the test droplet can be held motionless in the host liquid. By trapping the droplet at a given position, the experimenter can observe its size and can assure that the droplet has time to achieve thermal equilibrium with the immediate surroundings. The thermocouple used in this experiment consists of a ribbon junction which is designed to minimize thermal conduction errors. The acoustic monitoring system is far more complex than the thermocouple. The complexity arises from the difficulty in constructing an acoustic transducing device that has the following properties:

(a) a sufficiently small size in order that it not disturb or detune the acoustic field and so that it has a fairly flat frequency response in the frequency range of interest;

(b) a construction that can withstand temperatures as high as 200C continually, acoustic pressure amplitudes of several bars, and rough treatment; and

(c) a sensitivity that is not affected markedly by small changes in temperature.

Such a probe has been constructed. The essential element is a cylindrical PZT-5 lead zirconate cylinder (nominal dimensions: $\frac{1}{16}$" o.d., 0.0425" i.d., $\frac{1}{16}$" length). A coaxial cable of 0.040" o.d. makes electrical connection with the sensing device in the following way: The inner wire of the coax is looped so that the sensing element can be forced on the loop. A spring-type action keeps the loop in contact with the inner electrode. Some high temperature epoxy can be added to help keep the loop in place. This epoxy also makes a mechanical junction between the coaxial wire and the PZT-5 cylinder. Electrical contact between outer conductors (of coax and sensor) is made with conductive paint. A thin TFE coating protects the probe from the liquid.

SOME INTERESTING AND CONVENIENT FEATURES OF DROPLET LEVITATION

There are some interesting features of droplet levitation that are predicted by Eq. 4 and that have been confirmed using the apparatus described above: (1) Equation 4 is independent of the radius of the droplet. The experimental results complement the results of Crum in confirming this prediction.[3] (2) Equation 4 is also independent of the acoustic frequency. (The above

derivation assumes that percentage changes in the acoustic pressure amplitude are small over distances comparable to the droplet radius.)

These features make calibration of the acoustic probe possible by observing the conditions for droplet levitation. We first assume linearity in two respects: (1) The voltage output of the probe amplifier v_o is proportional to the pressure at the probe position in the liquid. (2) The pressure in the liquid increases linearly with the input voltage to the driving transducer. (This can be assured so long as the electric input impedance to the driver is constant as the voltage is increased. The waveform can also be observed for distortion.)

The first condition can be written

$$P(z) = \alpha v_o(z), \quad dP/dz = \alpha dv_o/dz,$$

$$\alpha = \text{Proportionality Const.} \qquad (5)$$

If the probe amplifier output v_o is β times the actual probe output v_p, then the acoustic probe sensitivity is

$$v_p/P = v_o/\beta P = 1/\beta\alpha. \qquad (6)$$

In logarithmic form, the sensitivity S is just

$$S = 20\log_{10}(v_p/P) = -20\log_{10}\alpha\beta. \qquad (7)$$

The experimental procedure for probe calibration is as follows: with the driver input at v_i, the acoustic field is probed along the axis; the output, as a function of z, is designated $v_o(z)$. The probe is then removed from the liquid.

A droplet of the sample liquid is introduced into the column of the host liquid. When it reaches the test region, the driver input voltage is increased until the droplet is trapped. The input voltage with the droplet trapped at the position z is designated $(v_i)_z$. Assuming linearity, this would correspond to a trapping pressure

$$P(z) = \alpha \left[\frac{(v_i)_z}{v_i} v_o(z) \right] . \qquad (8)$$

[The bracketed term is just what the probe output voltage would be if the probe were at z with the driver voltage, $(v_i)_z$.]

Substituting Eq. 8 (and the derivative of it) into Eq. 4

yields

$$\alpha^2 \left[(v_i)_z / v_i \right]^2 \cdot v_o(z) \cdot \left[-dv_o(z)/dz \right] = K \qquad (9)$$

or

$$\alpha = \frac{v_i}{(v_i)_z} \left\{ \frac{K}{v_o(z) \left[-dv_o(z)/dz \right]} \right\}^{1/2} . \qquad (10)$$

We have included the minus sign with dv_o/dz because this term must be negative if a droplet is to be trapped. Since α, v_i, and K are constant, this relation implies

$$(v_i)_z^2 v_o(z) dv_o(z)/dz = \text{Const}, \qquad (11)$$

where z equals trapping position, $(v_i)_z$ is input voltage when droplet is trapped at z, and $v_o(z)$ is probe output voltage at z when driver input voltage is v_i. As the input voltage is increased, the droplet's position will change and Eq. 11, which is one test of the theory, can be checked. Crum has indirectly confirmed that this prediction is consistent with experiment.[3] Problems of adequate resolution, however, occur in regions in which the pressure gradient is so small that errors in the measurement of $dv_o(z)/dz$ can be large. For practical purposes, therefore, Eq. 11 should be most accurate in regions of maximum pressure gradient. Once α in Eq. 10 is known, the sensitivity of the probe can be calculated using Eq. 7, and Eq. 8 can be used to give the trapping pressure.

We point out, also, that the probe calibration can be circumvented in determining the acoustic pressure at any point on the axis. This is often desirable because the calculation of α assumes that the acoustic field has been probed precisely where the droplet is trapped. Slight probe misalignment would lead to errors in the probe calibration. The following expression for the trapping pressure does not require this precise alignment. Using Eq. 5, we can rewrite Eq. 4 as follows:

$$-P \frac{dP}{dz} = P\alpha \frac{(v_i)_z}{v_i} \cdot \frac{dv_o(z)}{dz} = K,$$

or

$$P(z) = \frac{K}{\alpha} \frac{v_i}{(v_i)_z} \left[- \frac{1}{dv_o(z)/dz} \right] .$$

With Eq. 10 for α, we have

$$P(z) = \left\{ Kv_o(z) \Big/ \left[-\frac{dv_o(z)}{dz} \right] \right\}^{1/2} \qquad (12)$$

Once again, the equation is most accurate at trapping positions for which $dv_o(z)/dz$ is not difficult to measure accurately. In order to find the trapping pressure at a position z' where $dv_o(z)/dz$ is small, we just use the known trapping pressure at z and Eq. 8 to eliminate the proportionality constant, and we solve for P(z'):

$$P(z') = P(z) \frac{v_o(z')(v_i)_{z'}}{v_o(z)(v_i)_z} . \qquad (13)$$

We can summarize the above as follows:

(1) Equations 12 and 13, the formulas for converting voltage measurements to pressure measurements, are based on the assumption that Eq. 4 for the trapping pressures is accurate. The recent work of Crum[3] suggests that results within 10% of the theory are to be expected. The fact that the theory predicts (and experiment confirms) that the trapping pressure is independent of droplet radius, provided that the radius is small compared to an acoustic wavelength, is rather comforting.

(2) Since P(z) in Eq. 12 depends on the ratio $[v_o(z)/(dv_o/dz)]$, the actual magnitude of the probe output does not enter into the prediction of the trapping pressure. (For instance, if the probe is slightly off axis, this ratio will have the same value as that along the axis. The probe must, of course, move vertically.) For probe calibration, however, the actual magnitude of $v_o(z)$ is, of course, important.

Example

The procedure for measuring the conditions that cause droplet levitation is illustrated by the following example. In Fig. 2, two curves are plotted. The upper ordinate scale is the output of the acoustic probe amplifier at a given probe position in the sound field when a constant rms voltage is maintained across the acoustic driving unit. For this particular experiment, the acoustic system resonates in the (1,0,3) mode corresponding to a frequency of about 50 kHz.

Having probed the acoustic and thermal fields, we remove both probes from the liquid. A droplet of sample is introduced into the column of liquid and rises into the test region where it is trapped in the host liquid by appropriately adjusting the input voltage to the acoustic driving unit. The position of the trapped droplet above the pressure maximum and the rms voltage to the

driving unit is then changed, causing the droplet to move to a new equilibrium position closer to the pressure maximum. Input voltage and position are again recorded. This procedure is repeated.

The bottom ordinate in Fig.2 indicates the trapping input voltage versus position for four ether droplets. The host liquid in this case is glycerin.

Observations

One interesting feature of the results is that the data for droplets of different size (ranging from about 0.2-to 2.0-mm diam.) appear to lie on the same curve. This is consistent with the "trapping theory," which predicts the independence of trapping pressure on droplet size, provided that the droplet is small compared to the acoustic wavelength.

According to Eq. 11, the product of $(v_i)_z^2$, $v_o(z)$, and dv_o/dz should be a constant if the theory for droplet trapping is to be trusted. For the region z=4.4-5.0, in which most of the droplet trapping measurements are made, this product varies by less than 10%. The calculated product shows even less variation if the point at z=4.4, where the slope of $v_o(z)$ is more difficult to measure, is not considered.

MEASURING THE TENSILE STRENGTH OF LIQUIDS

Under certain conditions a liquid can sustain large tensile stresses or degrees of superheat without vaporizing. This departure from the vaporization conditions described by the relation between vapor pressure and temperature for a given liquid is a result of the absence of a flat liquid-gas interface in the system under test; that is, vaporization occurs when a vapor cavity forms in the liquid.

This cavity formation, or "cavitation", usually occurs not because of spontaneous breaking apart of neighboring liquid molecules due to fluctuations in the density at the molecular level (homogeneous nucleation) but because of the presence of something foreign to the liquid (heterogeneous nucleation). In the latter of these cases cavitation may occur at a liquid-solid boundary, at a liquid-liquid boundary, at a liquid-solid-gas interface (such as a crevice in an imperfectly wetted container surface or solid impurity suspended in the liquid), or even at a site in the liquid established by impinging radiation (as in bubble chambers).

There were, until recently, no reported measurements of the tensile strength of liquids that came close to the theoretical predictions for the ultimate strength of a liquid as described by homogeneous nucleation theory. The droplet levitation technique,

however, appears to be well suited for such measurements. In an attempt to minimize the chances of heterogeneous nucleation, small, filtered droplets of the sample liquid are immobilized acoustically in an inert host liquid.

The experimental procedure is outlined with the assistance of Fig. 1. An injected droplet of the sample rises in a cylindrical glass column containing the inert host liquid. A heating coil wrapped around the column establishes a positive and stable temperature gradient in the host ("up" positive). The droplet is superheated as it rises and when it reaches the test region it is levitated as described earlier. If the acoustic pressure amplitude is further increased, the droplet will move to a new equilibrium position closer to the acoustic pressure maximum in the standing wave field. This procedure of increasing the acoustic pressure can be continued until at some combination of superheat and acoustic stress, the droplet bursts into its vapor. This can be repeated for different test-region temperatures, thereby allowing the measurement of the trade-off between acoustic stress and superheat as causes of droplet vaporization.

The peak tensile stress experienced by the droplet immediately before vaporization (that is, the peak acoustic pressure amplitude minus the hydrostatic pressure) is plotted against temperature in Fig. 3 for two different liquids: diethyl ether and n-hexane. In both cases the host liquid was glycerin. Also plotted are the results of others who measured the limit of superheat of these liquids under positive pressure using a variety of experimental techniques. The solid lines are the predictions of classical homogeneous nucleation theory.

The experimental results complement each other despite the fact that, for n-hexane, Skripov and Ermakov[8] used a different host liquid than in the present measurements, and the fact that Wismer[9] held his ether samples with capillary tubes rather than in another liquid. These observations strongly suggest that for the liquids tested, nucleation has occurred within the sample and not at the liquid-liquid or liquid-solid interface. The results are also in good agreement with classical homogeneous nucleation theory. Thus, it appears that the droplet levitation scheme has provided a means by which the tensile strength of some liquids may be measured.

VAPOR BUBBLE DYNAMICS ASSOCIATED WITH THE VAPORIZATION OF A SUPERHEATED DROPLET[10]

The dynamics of physical explosions in liquids commands interest in a wide variety of disciplines: Examples of such phenomena are underwater explosions, explosions due to sudden contact of hot or cold liquids (such as Liquid-Natural Gas contacting water, water contacting smelt, and molten metals contacting other liquids), and cavitation explosions (and implosions).

These explosions have been observed directly and also in model systems. In the model systems bubbles have been generated employing methods such as spark-gap discharge[11] and focussed lasers.[12] Here we describe our first attempts at observing photographically the explosion of small superheated droplets of one liquid suspended in an inert host liquid. The size of the droplet and the degree of superheat give us a handle as to the energy associated with the explosion.

Above, we have described a technique for measuring the tensile strength of superheated liquids. When the liquid reaches this ultimate limit, it vaporizes explosively. We have filmed the dynamics of this explosion at moderately high speeds (about 4000 frames per second, fps) with both diffuse and shadow lighting.

The filming has been made relatively easy, because we have taken advantage of droplet levitation and positioned the camera where the droplet will be levitated and exploded. We can, therefore, adjust things so that the vapor bubble resulting from the explosion nearly fills the entire frame.

The explosion is initiated by suddenly increasing the acoustic stress on the levitated droplet. The acoustic stress serves one other useful purpose:

In the absence of the acoustic field the explosive growth of the vapor bubble produced from the initial explosion is followed by the vapor bubble collapse. This collapse process is unstable, with the single vapor bubble shattering into a multitude of smaller bubbles which are propelled, upon rebound, into the host liquid. In the presence of the acoustic field, however, the collapsing bubble is held together by the acoustic field. The tendency of small bubbles to coalesce in an acoustic field is attributed to "Bjerknes" forces.[13] Thus a single vapor bubble results from the explosion. The acoustic field has a frequency about 50-100 times greater than the natural resonance frequency of the resulting vapor bubble and represents, we believe, only a small perturbation, other than its coalescence role, to the dynamics of the initial explosion process.

The Particulars for These Experiments

Ether was the droplet material and glycerin was the host liquid for these observations. The droplets were superheated to approximately 105°C above ether's normal boiling point, or to about 140-141C. At this temperature an acoustic stress of approximately eight bars is required to nucleate the explosion.

The apparatus sketched in Figure 1 was supplemented by a

Fastex 16mm WF3 Camera with a 2 inch lens extension tube. The end of the extension tube was within three inches of the droplet. In this configuration a one millimeter diameter droplet appears on the 16mm film as an image with an approximate dimension (vertical diameter) of 1mm. Because of the cylindrical column, horizontal dimensions are magnified by about 1.6.

When the camera motor is switched on, the film accelerates to 5000 frames per second in less than a second. The film runs for little more than a second. For monitoring the frame rate an oscillator set at 1000 Hz drives a neon bubble in the camera which puts light marks on the film (2000/s, because the neon bulb flashes for positive and negative excursions in voltage). In the sequences shown in Figs. 4 and 5, the time per frame ranged from 0.24 to 0.3 ms (or approximately 3300 to 4000 fps).

Two different lighting schemes were used:

Diffuse Lighting: For the photographs in Fig.4, three 500 watt bulbs in parabolic reflectors surrounded the test region.

Shadow Lighting: For the photographs in Fig. 5, a collimated mercury arc beam was directed through the test region into the lens.

Results

An initial film sequence and radius vs. time graph of a droplet explosion is shown in Fig.4. The explosion process can be summarized as follows: The vapor bubble grows rapidly as a result of the pressure produced inside the cavity during the vaporization of the droplet. It grows past the size at which the pressure inside and outside the cavity are the same, because of the momentum imparted to the host liquid. It then collapses and rebounds several times before the energy associated with the oscillation is completely dissipated. The droplet then moves radially from the center of the tube due to acoustic forces on it.

As the photographs indicate, some of the energy associated with the growing droplet is lost during the collapse as surface instabilities grow.

In Figure 5 using shadow lighting an instability initiated during the collapse of a vapor bubble takes the form of a jet-like protrusion growing rapidly from the main bubble as it rebounds (only part of the main bubble is shown). The approximate velocity of this protrusion is 2m/s. This instability may be analogous to the jets that occur during the violent collapse of a cavitation void in a liquid far below its boiling point. In our case the instability is less violent because of the cushioning

and damping effects of the superheated vapor in the bubble.

The techniques for producing and observing droplet explosions described here may be adaptable to the study of the initial stages of physical explosions in model systems. For a given modeling application, the appropriate choice of test and host liquids is required. (Freon 114 in a host of water is being considered in modeling underwater explosions.)

This scheme should also be easily adaptable to higher speed photography. This would allow us to focus in on the region where the first vapor cavity is nucleated and would give us detailed information about the very important initial stages of growth.

PROPOSED EXPERIMENTS INVOLVING DROPLET TRAPPING

1. Radiation-Induced Cavitation

   A superheated droplet that is levitated in a sound field at acoustic pressures insufficient to cause homogeneous nucleation may explode due to some foreign matter touching the sample or some radiation incident on the sample. By using known radiation sources one should be able to study the temperature and pressure dependence of the threshold of radiation-induced cavitation. Such a study may have implications in the design of a neutron energy spectrometer.

2. The Solidification of Supercooled Droplets

   Using a photographic scheme similar to that described for observing the explosion of superheat droplets, we should be able to observe the solidification of an acoustically levitated supercooled droplet. The information obtained from these films can be compared with the results of the analysis of the retrieved solid pellets in order to shed light on the mechanisms of the nucleation and growth processes involved in solidification.

3. Properties of Metastable Liquids

   Very few properties of metastable liquids have been measured. (e.g. sound speed, index of refraction, density, compressibility, et al.). By probing at and observing the motion of these droplets in a known sound field we should be able to determine the temperature dependence of some of these properties. We, therefore, have the opportunity to increase substantially our knowledge and hopefully our understanding of the liquid state.

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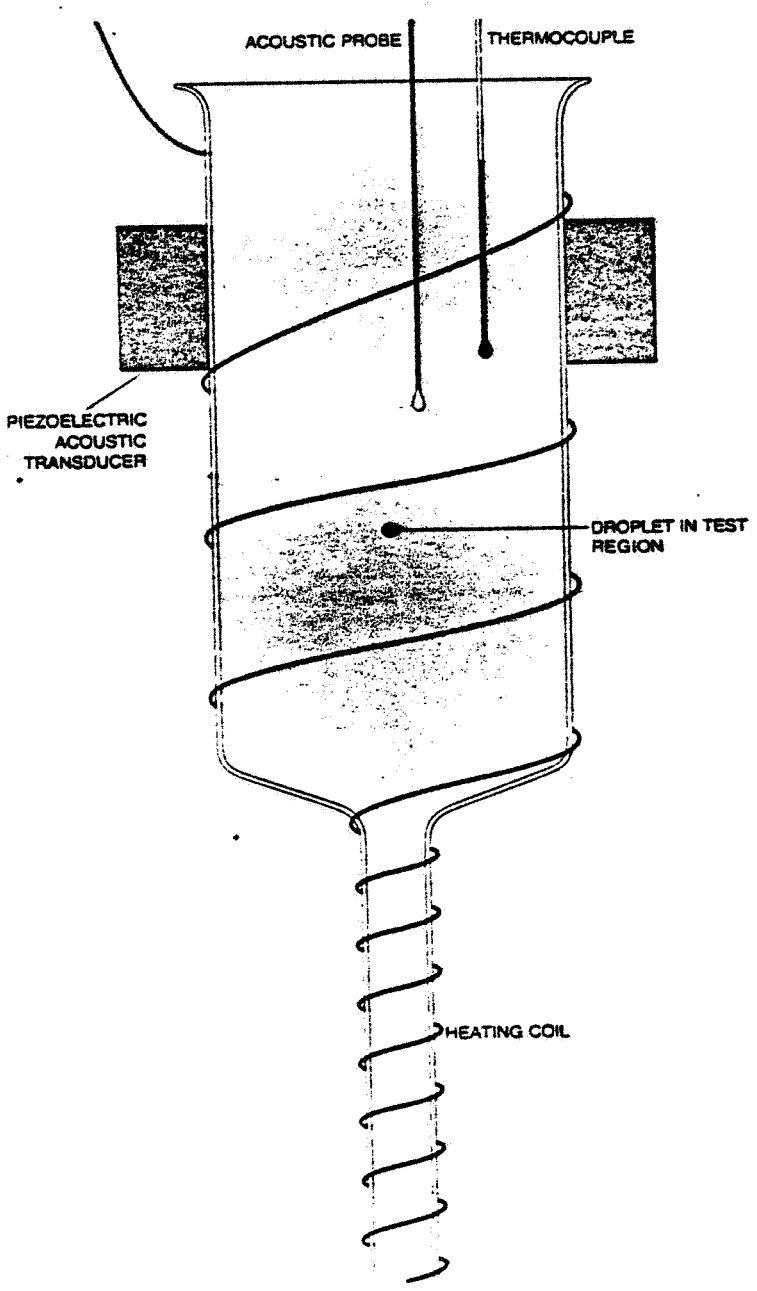


Fig. 1 Acoustic resonator for levitation experiments. Intensity of shaded region is suggestive of acoustic pressure distribution.

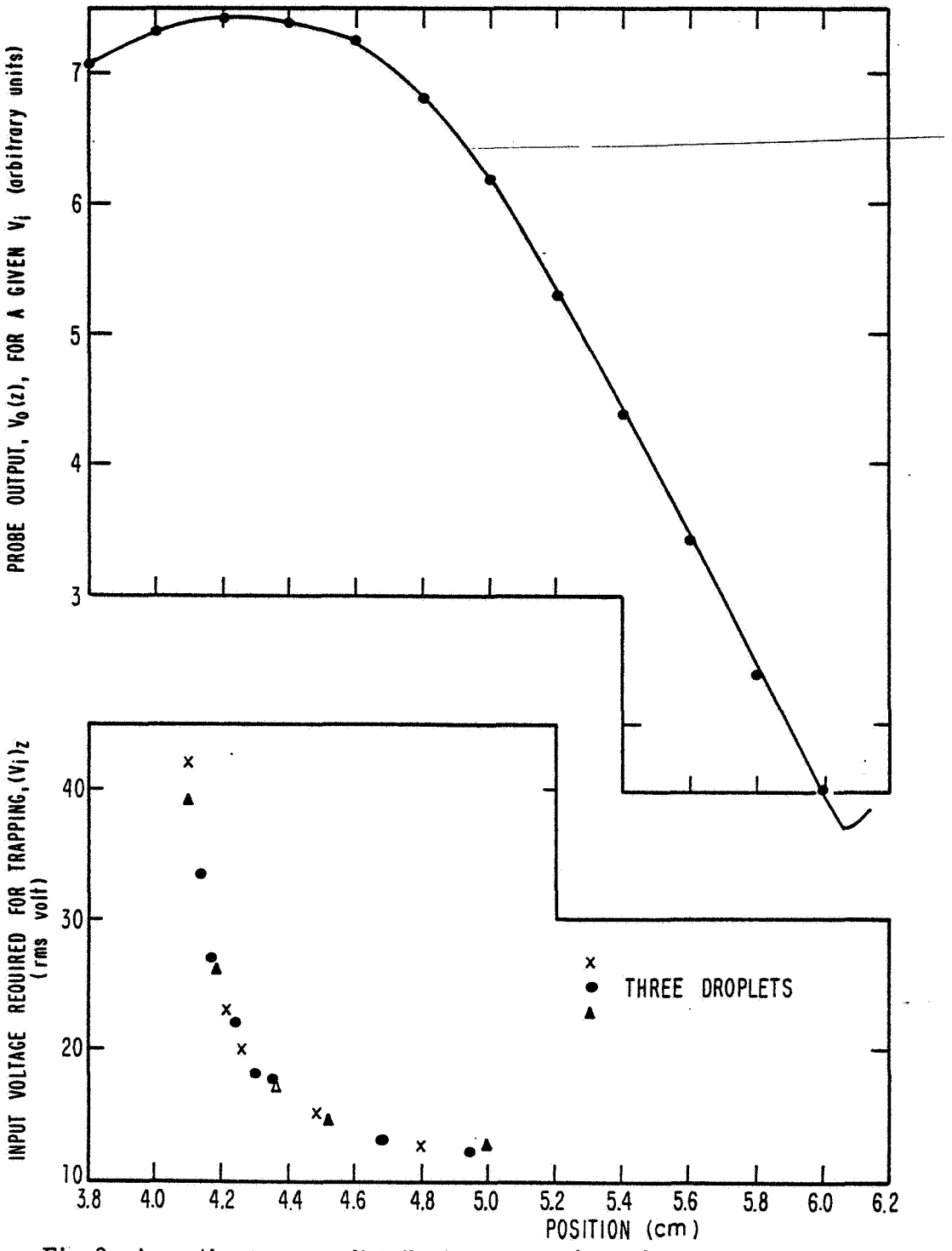


Fig. 2 Acoustic pressure distribution on axis (above) and driver input required to levitate droplets (below).

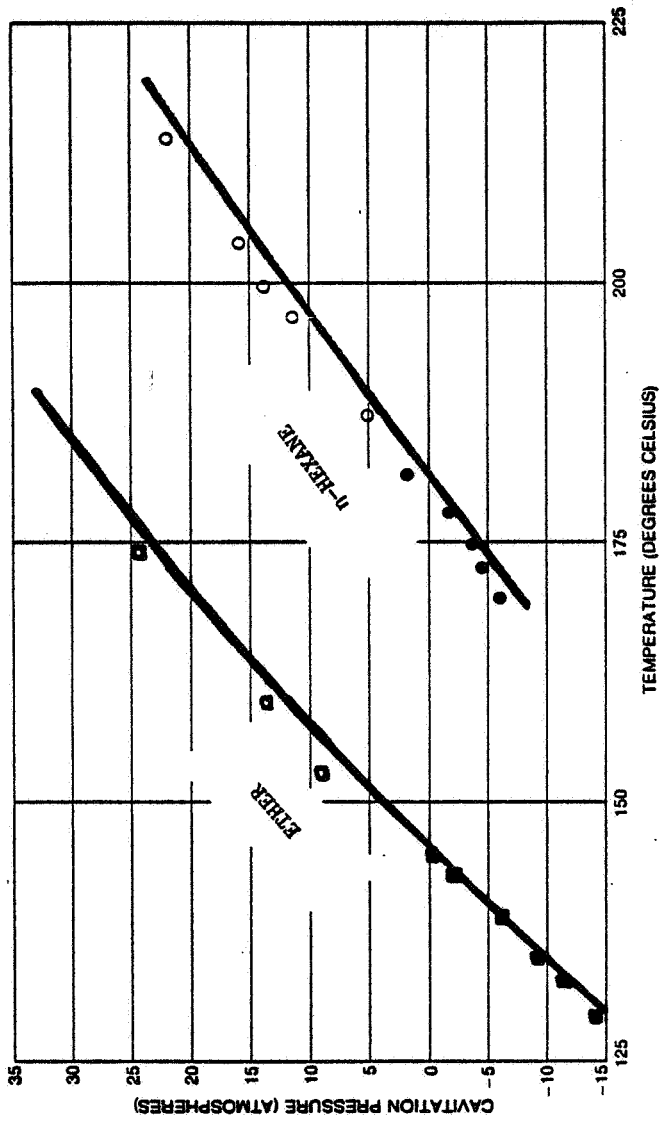
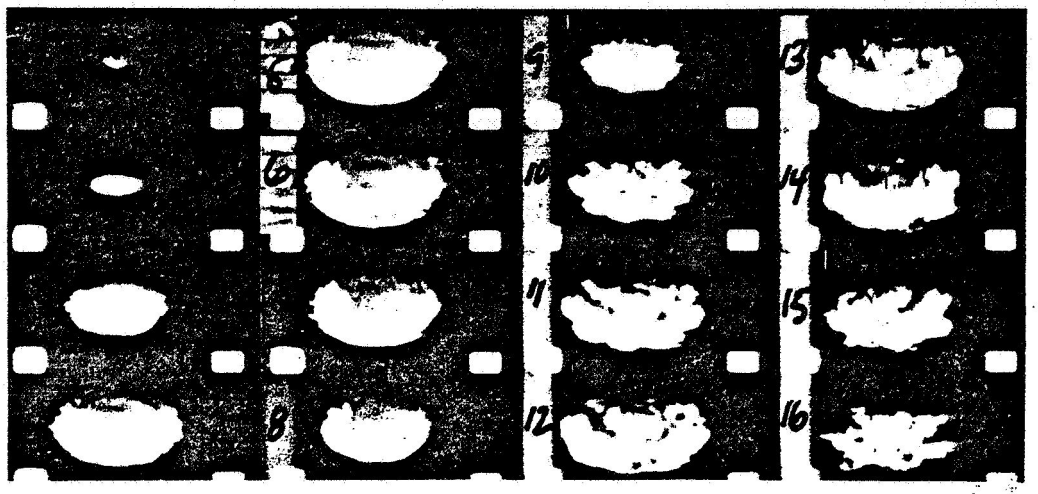


Fig. 3 Tensile strength (at negative pressures) and limiting superheat (at positive pressure) of two liquids.



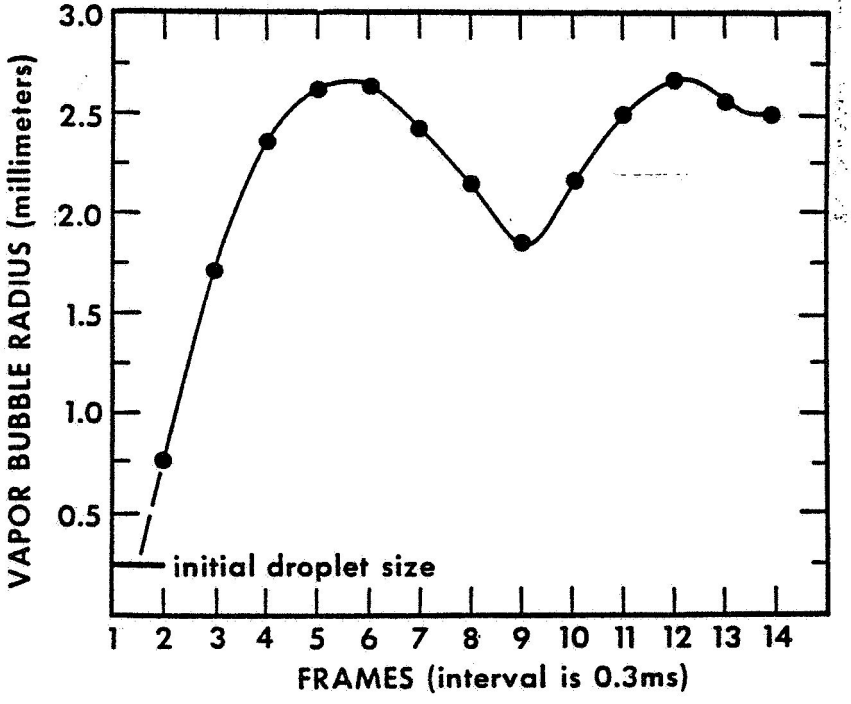


Fig. 4 Droplet explosion and resulting vapor bubble dynamics; Radius vs. time curve for initial sequence.

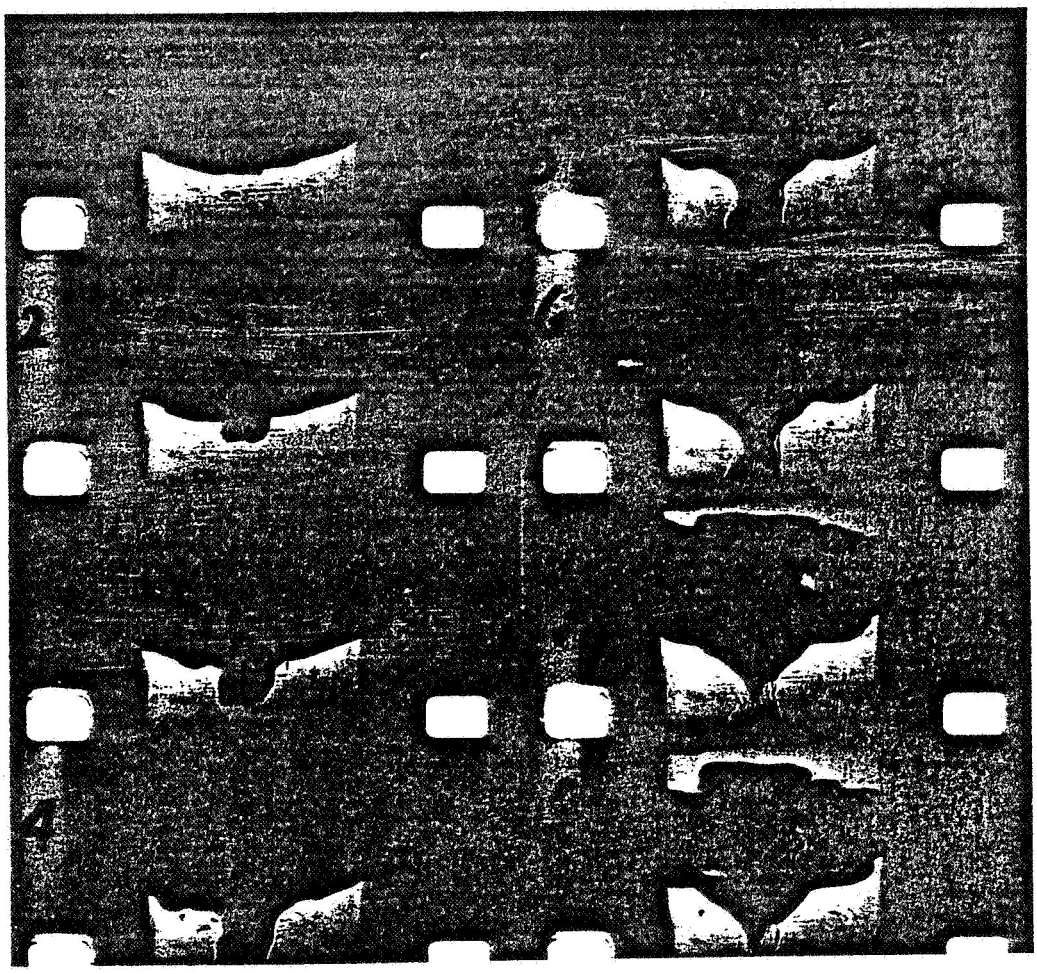


Fig. 5. Instability during oscillation of hot vapor bubble. Only part of bubble is shown.