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Cavitation in Liquid Helium*

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Ultrasonic cavitation has been induced in liquid helium over the temperature range 1.2 to 2.3°K, using a pair of identical transducers. The transducers were calibrated using a reciprocity technique and the cavitation threshold was determined at 90 kc/sec. It was found that this threshold has a sharp peak at the λ point, but is at all temperatures quite low, with an approximate range of 0.001–0.01 atm. The significance of these results is discussed.

INTRODUCTION

ESTIMATES of the tensile strengths of liquids based on the assumption that it is possible to rupture molecular bonds, are considerably higher than measured values. For example, in the case of water at room temperatures such predictions of tensile strength vary from 500 to 10 000 atm while empirical values range from a fraction of an atmosphere to 280 atm.[1,2] To explain these discrepancies it has been proposed that true rupture does not occur in practice but that the applied tension is relieved by the sudden growth of relatively large cavities from microscopic nuclei. It is possible to nucleate cavitation in normal liquids by the following principal agencies: (1) minute gas or vapor filled bubbles, mechanically or electrolytically created, (2) inclusions of gas or vapor in cracks on solid surfaces, (3) solid particles unwetted by the liquid, (4) cosmic rays and radioactivity.

The last mentioned agency was first suggested since even degassed distilled liquids have relatively low thresholds.[3] There is now a growing body of phenomena in which cosmic rays and radioactivity nucleate cavitation.[4–10]

It has been pointed out by Beams[11] that the variety of possible nuclei is much restricted in liquid helium since it cannot contain bubbles filled with anything but its own vapor, it is a very efficient wetting agent and due to its low viscosity and density cannot readily carry solid particles in suspension. If cavitation in liquid helium is nucleated, then the most likely agency would be cosmic rays.

When the vapor above liquid helium I is pumped away, evaporative cooling occurs, and bubbles rise through the liquid. On reaching the λ point the bubbling stops and below this temperature the liquid, helium II, has excellent heat transfer properties, causing the disappearance of bubbles.[12] This and other manifestations of superfluidity make it especially interesting for cavitation studies.

The tensile strength of helium II was first measured by Misener and Herbert[13] in the temperature range 1.092–2.147°K using a bellows technique. They concluded that if helium II has a tensile strength it could not exceed 0.3 atm. Beams[11] measured the tensile strength of helium II by a spinning capillary method and by a piston and cylinder method at a temperature of about 1.9°K. He found the negative pressures necessary for rupture were 0.14±0.02 atm with the first method and about one-half of this value with the second method. Since these values are much less than theoretical estimates, Beams concluded that there must have been nuclei present. During preliminary experiments for the design of a liquid-helium bubble chamber Fairbank *et al.*[14] applied negative pressures of about 100 mm to helium II and obtained photographs of bubbles. No tracks were found but there were some "double" bubbles, which Fairbank *et al.* conjectured might have some relationship to quantized vortices.

The uncertainties in these experiments arose from difficulties in the measurement of small negative pressures and in the detection of the onset of cavitation. Relatively low negative pressures can be readily applied and measured using ultrasonic techniques. Further, ultrasonic cavitation gives rise to a characteristic noise which is generated by the collapse of cavities during the positive pressure phase. This noise, when amplified, affords a sensitive means of detecting the onset of cavitation.

APPARATUS

The object of the present experiments was, then, to measure the threshold of ultrasonic cavitation in

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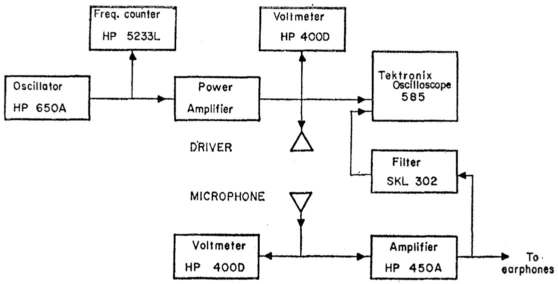

FIG. 1. Block diagram of driver and microphone circuits. With identical PZT-4 transducers as driver and microphone it was possible to deduce acoustic pressures directly from measurements of driver and microphone voltages using a reciprocity technique. The cavitation threshold was determined by the onset of noise from the microphone as heard through earphones and as displayed on an oscilloscope.

liquid helium over a temperature range. To do this two transducers were employed, one to act as a driver and the other as a microphone. A block diagram of the driving and microphone circuits is given in Fig. 1. As will be explained later, it was possible to measure acoustic pressures simply by monitoring the driver and microphone voltages, while the threshold could be detected with cavitation noise, heard in earphones and seen on an oscilloscope trace.

The two transducers were identical disks of Clevite PZT-4 ceramic, $\frac{1}{2}$ in. in radius and in thickness, with electrodes on the flat faces. The resonant frequencies of the transducers were both within 0.2% of 91.15 kc/sec in liquid helium and their capacitances were also the same to within 0.5%. Tests made with a third transducer showed that their sensitivities as microphones were also essentially the same. They were supported by threads (for vibration isolation) from a metal cradle with their opposed faces parallel, there being a separation of some 4.5 cm between them, as seen in Fig. 2. This figure also shows a carbon resistor which when immersed in helium formed one arm of a bridge so that by monitoring the off-balance current an accurate indication of temperature change was possible. The assembly shown, in Fig. 2, was suspended vertically in a standard low-temperature double-Dewar system. The assembly could be viewed through parallel vertical slits in the silvering of the Dewars. Temperatures were determined by measuring vapor pressure using Wallace and Tiernan gauges.

PRELIMINARY OBSERVATIONS OF CAVITATION

When the driving voltage was increased from zero there came a point at which intermittent bursts of noise could be hear in the earphones. This point corresponded to the cavitation threshold and could also be observed as "noise" on an oscilloscope trace of the microphone output after it had been filtered to eliminate the 91-kc/sec driving frequency. With further increase of the driving current the bursts became a steady white noise hiss, characteristic of ultrasonic cavitation, this noise being easily distinguished from that of boiling above the λ point, when the appearance of relatively large rising bubbles could be correlated with "burbling" sounds. With driving currents an order of magnitude or so higher than at threshold the cavitation noise was sufficiently loud to be heard outside the cryostat with an unaided ear. At these power levels the cavities were visible as transient bubbles of about $\frac{1}{2}$–1 mm in diameter, uniformly distributed throughout the volume between the transducers. This was the case whichever transducer was driven. It should be noted, however, that it was not easy to see these bubbles due to the low refractive index of liquid helium, and the use of photography was not practical since the cryostat could not readily accommodate optical systems of any size. With these reservations in mind it may be stated that no "double" bubbles were seen. An examination was made with an RCA 6810-A photomultiplier (cathode sensitivity: 60 μA/lumen, current gain: 12.5×10^6) but no sonoluminescence could be detected at any temperature in the operating range.

MEASUREMENT OF CAVITATION THRESHOLDS

It has been shown by Maclean[15] that using the laws of reciprocity for a four-terminal network it is possible to determine the sensitivity of a reversible transducer using only one other identical transducer. Following

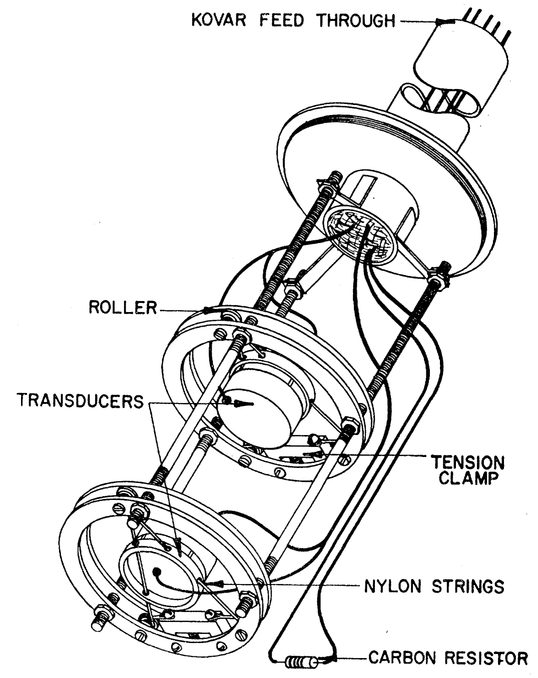

FIG. 2. Driver and microphone suspension. The PZT-4 transducers were 1 in. in diam and $\frac{1}{2}$ in. in thickness. A carbon resistor, used to determine temperature stability, is seen below the lower transducer.

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the principles laid down by Maclean it may be shown that for two identical transducers:

$$M_0=[(V_2/I_1)(1/Q)]^{1/2}, \tag{1}$$

where M_0 = sensitivity of a transducer used as a microphone in esu of potential/dyne/cm^2. V_2 and I_1 are, respectively, the microphone open circuit potential difference and driving current in esu as indicated in Fig. 3. Q is given by

$$Q=P_2/U_1S,$$

where P_2 = acoustic pressure (dynes/cm^2) at the microphone face, U_1 = particle velocity at the driver face (cm/sec) and S = area of a transducer face (cm^2).

In the present case a standing wave is set up in the volume between the transducers. However, since the driver has a high impedance the particle velocity U_1 will not differ appreciably from the free field particle velocity U_F. Suppose that due to the nondirectionality of the beam the pressure in a progressive wave is reduced by a factor r in traveling once between the transducers. The pressure at the microphone, P_2, will then be given by

$$P_2=2P_Fr/(1-r^2),$$

where P_F is the free field pressure at the driver. Thus, in this case,

$$Q=(\rho c/S)[2r/(1-r^2)],$$

where ρ and c are the density and sound velocity of liquid helium, respectively. In Fig. 3 C_T represents the capacitance of the transducer and C_g the capacitance of the cable. The capacitances of the cables had essentially the same value (within 0.5% of 524 μF) showing no appreciable change over the operating temperature ranges. Under these circumstances $V_2'I_1'=V_2I_1$ and $I_1'=V_1'Z_D$, where Z_D is the combined impedance of a transducer and its cable. A further test was made to confirm that Z_D did not vary with temperature. Hence, substituting in Eq. (1) for Q and taking values of V_2' and I_1' appropriate to the onset of cavitation then the pressure at the microphone, Pm, will be:

$$P_m=\left(\frac{\rho c}{S}\frac{2r}{(1-r^2)}\frac{10^7}{Z_D}\right)^{1/2}(V_1V_2)^{1/2},$$

where V_1 and V_2 are expressed in volts and Z_D in ohms. The pressure at the driver is then the cavitation threshold, P_t, given by

$$P_t=\frac{(1+r^2)}{2r}\left(\frac{\rho c}{S}\frac{2r}{(1-r^2)}\frac{10^7}{Z_D}\right)^{1/2}(V_1V_2)^{1/2}. \tag{2}$$

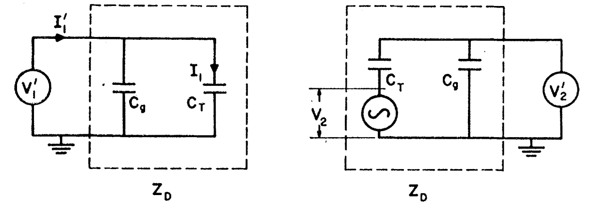

FIG. 3. Four terminal reciprocity network. C_t: capacitance of a transducer. C_g: cable capacitance. C_t and C_g were identical to within $\frac{1}{2}$% for both transducers. Z_d: combined impedance of a transducer and its cable. V_2: generated microphone voltage. V_2': measured microphone voltage. I_1: actual driving current. I_1': measured driving current. V_1' measured driving voltage.

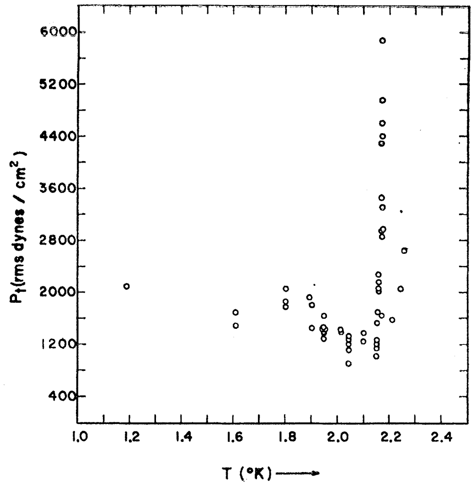

FIG. 4. Cavitation thresholds. The principal feature is a sharp peaking to a maximum value at the λ point (2.172°K). This rise all occurs within 0.01°K below the λ point. At other temperatures the threshold is comparable to the liquid pressure head, which varied smoothly from about 1600 to 1100 dynes/cm^2 at the driver face during the experiment.

The ratio r was measured by applying pulses of about 100-μsec width to the driver, without removing the assembly from the helium, displaying the microphone voltage on the oscilloscope and measuring the ratio of successive reflected pulses. This gave r^2, which was found to be 0.69 by averaging a number of measurements, so that $r=0.83$. Then, taking $\rho=0.146$ gm/cm^3, $c=2.38\times10^4$ cm/sec, $S=5.07$ cm^2, and $Z_D=2.75\times10^3$ Ω, from Eq. (2), $P_t=3.72\times10^3$ $(V_1V_2)^{1/2}$. Thus the threshold at any temperature could be deduced directly from two voltage readings.

The procedure adopted was to increase the driving voltage until cavitation noise could just be heard continuously. Then by gradually reducing the driving voltage a point was reached with careful tuning where a burst of noise could not be heard more than once every five seconds. The voltage readings were then made. Certain precautions had to be observed to obtain consistent readings. To begin with, care was taken to ensure that particles of frozen air did not get into the helium. Secondly, it was found that the process of temperature stabilization (achieved by balancing the heat input from the transducer against the pumping rate) had to be truly effective and the threshold measurement not made too hurriedly after stabilization. The results shown in Fig. 4 were obtained only after the temperature had remained stable for some ten to fifteen minutes. The liquid level was 7.2 cm above the face of the top transducer during this run and the bottom transducer was used as the driver.

Some calorimetric measurements were carried out by timing the temperature rise from 1.53 to 1.73°K with the sound pressure maintained just above threshold level, and then with no sound at all. The time intervals in the two cases did not differ by more than about 5%, so that the threshold could not be determined accurately. However, it was found that the total power flux due to self-heating and sound across the surface of the transducer was of the order of magnitude of one mW/cm^2.

DISCUSSION OF RESULTS

In the first place, it is necessary to establish that the phenomenon observed was truly cavitation and not boiling at the surface of the transducer. In order to boil helium II it is necessary to generate a heat current of sufficient magnitude to convert the liquid surrounding the source into helium I after which the boiling occurs. A number of workers have found that this heat current is of the order of 1 W/cm^2 [16,17] and that heat currents of the same order of magnitude are required for nucleate boiling of helium I.[18] In the present experiments the heat current at threshold was of the order of a mW/cm^2. Only when driving the transducer at full power could the heat flux have attained 1 W/cm^2. This is strong evidence that boiling was not present, a conclusion corroborated by a number of facts. For instance the white noise obtained was quite distinct from the sounds of nucleate boiling and typical of ultrasonic cavitation. Again, at high ultrasonic power transient bubbles could be seen uniformly distributed in the space between the transducers, even when driving the upper one. Whereas if the phenomenon were boiling the vapor phase might be expected to occur in the locality of the driving transducer or as stable bubbles rising from it.

A significant aspect of the results is the fact that the threshold is very low at all temperatures. Apart from the λ point the situation is similar to the case of gassy water where the threshold is determined by the static pressure head. However, the methods for estimating the tensile strength of a normal liquid may not be applicable in the case of helium, so that the values of 4 atm and over, as cited by Beams[11] should be treated with some reserve.

The other remarkable feature of the results is the sharp peak at the λ point. Many of the properties of liquid helium show pronounced effects in this vicinity, especially the thermal properties. There is for instance the well-known behavior of the specific heat which rises sharply to very high values at the λ point. One possible tentative explanation of this apparent correlation between the threshold and thermal properties can be given in terms of the Seitz theory of the bubble chamber.[19]

As has been mentioned in the Introduction, of the agents that are known to nucleate cavitation in normal liquids, cosmic rays and radioactivity are the most likely to be operative in liquid helium. That the passage of high-energy particles in liquid helium can give rise to bubbles is evidenced by the successful operation of helium bubble chambers. According to Seitz, the particle produces highly localized energy deposits or "thermal spikes" in the liquid. The thermal spikes then cause the growth of microbubbles whose equilibrium size is partly determined by the thermal properties of the liquid. Possibly it is these microbubbles which nucleate the cavitation event. If the threshold is a function of nucleus size, as in normal liquids, then a relationship might be expected between the threshold and the thermal properties.

ACKNOWLEDGMENT

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