ULTRASONIC INSTRUMENTATION IN CAVITATION RESEARCH

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INTRODUCTION

In the study of cavitation, a problem of fundamental interest is an understanding of the conditions required for its onset. The conditions to which I refer are the local conditions which must exist at any point in the water, such as the local pressure and temperature, for the formation of a cavity at that point in the water. This problem is of interest to both the hydraulics engineer and the hydrodynamicist, in the design of cavitation-free equipment and in determining the conditions and scaling laws for cavitation model testing.

At the Taylor Model Basin we are utilizing electro-acoustic equipment, operating at ultrasonic frequencies, to investigate the influence of undissolved air cavities in the water on the conditions required for cavitation. Before describing our equipment, it may be useful to review briefly some of the contemporary ideas on cavitation inception, to provide the background for an understanding of the purpose of our apparatus.

For many years it was assumed that cavitation occurred in a hydraulic flow when the local pressure dropped to the vapor pressure of the water. However, it is now recognized that the cavitation inception pressure does not have a fixed value. Indeed, under certain circumstances, particularly those found in water tunnels, inception may require a negative pressure or tension [1, 2].

Measurements of the inception pressure made under static conditions, by applying steady suction or tension to undisturbed water, have resulted in an amazing range of values, ranging from vapor pressure to minus 300 atmospheres [3]. On the other hand, theoretical estimates made by the physicists, based on calculations of the inherent strength of water, predict negative pressures as large as —500 to —10,000 atmospheres for inception. However, such large negative values have never been observed experimentally by any method.

To explain why the measured inception pressures are so variable and yet less negative than the theoretical values, it has been postu-

lated that the onset of cavitation requires the existence of microscopic non-homegeneities or nuclei in the water [4]. The nuclei are generally assumed to be undissolved air cavities whose sizes may range from 10^{-3} to 10^{-5} inches. The cavitation process is considered to be the growth of these air-filled nuclei to visible size. The variation of the inception pressure is attributed to a variation in size of the original nuclei.

AIR-FILLED NUCLEI

A nucleus can grow to visible size in two ways: (1) by the relatively slow diffusion of dissolved air out of the water into the nucleus, or (2) by its sudden explosive expansion into a large cavity. The slow growth by diffusion results in a permanent bubble filled primarily with air, and is accordingly called "gaseous cavitation". The sudden explosive expansion, on the other hand, results in a cavity filled primarily with water vapor, since diffusion of air cannot keep up with the expansion, and is accordingly called "vaporous cavitation". In vaporous cavitation, the cavities collapse and disappear, due to the condensation of the water vapor, after leaving the low-pressure cavitating region.

Sometimes a collapsing vapor cavity does leave a permanent air bubble, much smaller than the original cavity, as a result of the diffusion of some air into the vapor cavity during its short life [5].

If it is assumed that these air nuclei are small free bubbles of air, it is possible to estimate theoretically the critical pressure for inception of either gaseous or vaporous cavitation. Theoretical values of the critical pressure are shown in Fig. 1 as a function of the radius of the bubble nucleus. The critical pressure for gaseous cavitation depends not only on the nucleus size but also on the amount of air dissolved in the water; curves are shown for three air contents. The critical pressure for vaporous cavitation depends only on the size of the nucleus. (It is possible, however, that the nucleus size itself may depend on the air content of the water.)

If the nuclei are small, both gaseous and vaporous cavitation require negative pressures of equal magnitude. If the nucleus bubbles are large, gaseous cavitation can occur at pressures above the vapor pressure provided the bubble remains at the required pressure long enough to accommodate the slow diffusion process. Vaporous cavitation, in contrast, always requires pressures below vapor pressure, but the growth is rapid.

Photographs of cavities growing rapidly by vaporous cavitation

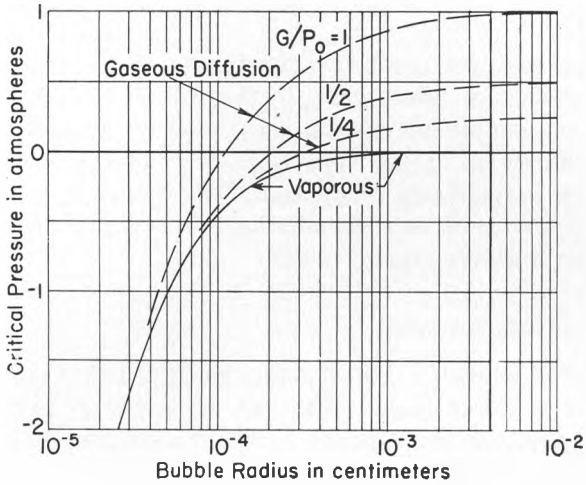

FIG. 1. THE CRITICAL PRESSURE FOR GASEOUS AND VAPOROUS CAVITATION AS A FUNCTION OF THE RADIUS OF THE AIR-FILLED NUCLEUS. THE NUCLEUS SIZE IS THE SIZE AT ATMOSPHERIC EXTERNAL PRESSURE. THE CRITICAL PRESSURE IS GIVEN RELATIVE TO THE VAPOR PRESSURE. THE THREE CURVES FOR GASEOUS CAVITATION ARE FOR THREE VALUES OF AIR CONTENT, THE SATURATION PRESSURE OF THE DISSOLVED AIR BEING INDICATED ON THE CURVES.

are fairly common, those of Knapp and Hollander [6] being typical. Recently, some photographs showing the slow growth typical of gaseous cavitation were published by Parkin and Kermeen [3].

The hypothesis that water contains air-filled nuclei, whose sizes may vary from one batch of water to another, thus explains the observed variations in the measured values of the inception pressure. However, there is no direct evidence that such nuclei actually exist in water. On the contrary, it would ordinarily be assumed that air cavities would spontaneously disappear by dissolving in the water.

According to diffusion theory, an air bubble of 10^{-3} cm radius should dissolve in about 7 seconds, even in saturated water; smaller bubbles should dissolve even faster [7].

Accordingly, it is of interest to find some direct method for detecting air-filled cavities in water, and for determining their effect on the onset of cavitation. The apparatus to be described was developed to perform these functions.

APPARATUS

The apparatus performs two functions:

1. To detect air-filled nuclei in the water.
2. To determine the critical pressure for cavitation.

In the present form of the apparatus, both of these measurements are made on a relatively small sample of undisturbed water. The detection of air nuclei and the setting-up of cavitation are both performed with high-frequency sound.

Detection of Air Cavities

Air cavities in water absorb sound energy, and it is this property that is used to detect them. When an air cavity is in a sound field, the cavity pulsates in response to the fluctuating sound pressure. The resulting expansion and contraction of the air converts some of the sound energy into heat. The quantitative theory of sound absorption is well understood [8], and only the results pertinent to the apparatus need be discussed here.

The amount of absorption of a body of water containing air cavities may be determined by putting some sound energy into the water and measuring the rate at which sound energy decays, i.e., by observing the reverberation decay. The principle of the method may be illustrated by a simple experiment. If a glass of water is tapped, it will ring with a clear note of perhaps one-second duration. If bubbles are now formed in the water by inserting an "Alka-Seltzer" tablet, tapping will only result in a dull thud. The difference is due to the absorption of the sound energy by the bubbles. This principle, in refined form, is utilized in our apparatus.

Electro-acoustic apparatus for measuring sound absorption is relatively conventional in acoustics, that described by Moen [9] being typical. Our equipment is shown schematically in Fig. 2. The water sample is contained in a 12-liter spherical Pyrex flask about 12 inches in diameter. Two small piezo-electric ceramic cylinders, ¼-inch diameter and ¼-inch long are cemented to the outer wall of the sphere. One of these cylinders acts as the sound source and is supplied with electrical random noise from a noise generator and power amplifier. The second piezo-electric cylinder acts as sound receiver. Its output is amplified, passed through an attenuator and then rectified into a DC signal by a tuned loga-

The piezo-electric cylinders are cast ceramics consisting principally of barium titanate. They are obtainable commercially from sources such as the Brush Development Company and the Gulton Manufacturing Company.

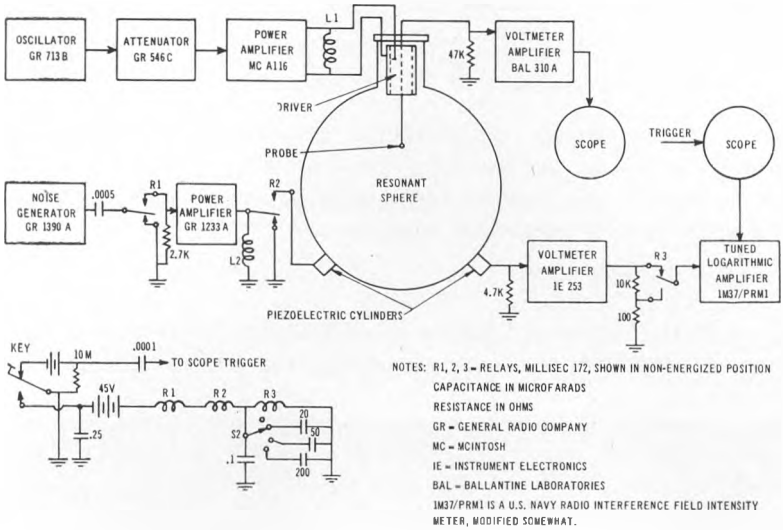

FIG. 2. BLOCK DIAGRAM OF THE ELECTRONIC EQUIPMENT. THE LOWER PORTION SHOWS THE EQUIPMENT FOR MEASURING THE ACOUSTIC ABSORPTION OF THE WATER, WHEREAS THE UPPER LINE SHOWS THE EQUIPMENT FOR CAUSING CAVITATION WITH HIGH-INTENSITY ULTRASONICS. ALL THE COMPONENT INSTRUMENTS ARE COMMERCIALLY AVAILABLE, EXCEPT FOR THE TUNED LOGARITHMIC AMPLIFIER WHICH IS A SOMEWHAT MODIFIED ITEM OF NAVY EQUIPMENT.

rithmic amplifier. The DC output of this amplifier, which is proportional to the logarithm of the AC voltage from the sound receiver, is observed as a trace on a DC cathode-ray oscilloscope. Three relay switches are arranged in the circuit so that depressing a hand key turns on the noise signal to the sound source and inserts attenuation into the receiving circuit. Releasing the key cuts off the noise source, triggers the horizontal time base of the oscilloscope and, after an adjustable time delay, removes the attenuation from the receiving circuit. When the key is released, the resulting display on the 'scope shows the decay of the sound in the sphere. Since the sound decays exponentially with time, the logarithm of the sound amplitude falls linearly with time, so that the logarithmic amplifier provides a decay trace on the 'scope which is approximately a straight line. The decay rate is given by the slope of the trace, in terms of the known sweep rate of the horizontal time base and the known logarithmic sensitivity of the vertical axis.

A photograph of the apparatus appears as Fig. 3.

Absorption of sound at a given signal frequency is associated primarily with bubbles which resonate near that frequency. The

resonant frequency f_r of an air bubble in water is given by the numerical relation

$$f_r R = 330 \text{ cm/sec} \tag{1}$$

where R is the radius. Accordingly, by varying the frequency it is possible to detect bubbles of different sizes. The rate of sound decay caused by gas bubbles resonating at a frequency f_r is given by the approximate numerical relation

$$d_r \simeq 10^{-14} N_r/f_r^2 \tag{2}$$

where f_r is the signal frequency in cycles per second and N_r is the number of bubbles per cm^3 resonating in the frequency range

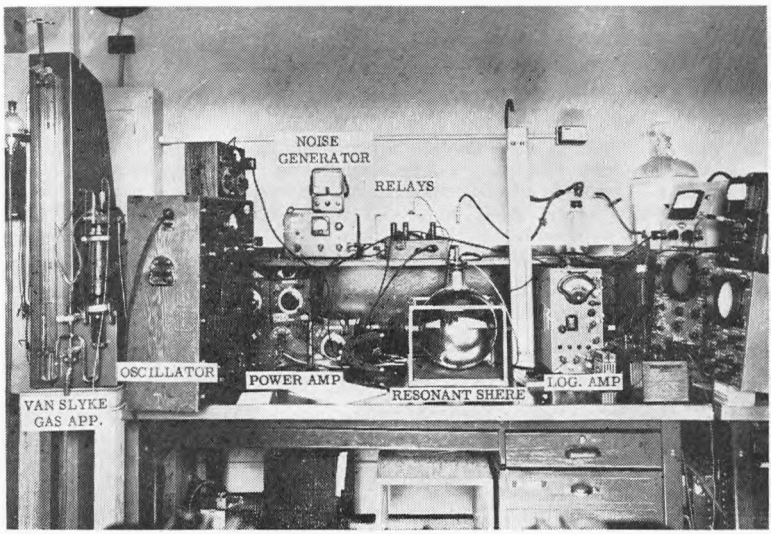

FIG. 3. PHOTOGRAPH OF THE APPARATUS

$\frac{2}{3} f_r$ to $2f_r$. It is apparent that the smaller the bubbles, the more of them are required for a given decay rate. The decay rate d_r is in decibels per second, an increment of 10 decibels corresponding to a factor of 10 in sound energy; e.g., 50 decibels per second means that the energy drops to 10^{-5} of its original value in a second.

Sound decay is caused in the apparatus not only by bubbles but also by sound absorption inherent to the water itself and in the walls of the sphere. Accordingly, the total decay rate d is equal to $(d_r + d_o)$, where d_o is the minimum or background decay rate of the apparatus in the absence of bubbles. This background decay sets a limit to the sensitivity of the apparatus for detection of

bubbles. The background decay may vary erratically from day to day by as much as 20%. To detect bubbles with certainty, enough must be present to increase the decay rate by a substantial amount, say by 50% over the average background rate. The number of bubbles which will cause such an increase can be estimated by equating d_r in Eq. (2) to $\frac{1}{2}\, d_o$. Accordingly, the minimum detectable number of bubbles, or threshold of detectability, is given by

$$(N_r)\ \min = 5 \times 10^{-15}\, d_o\, f_r^2 = 5 \times 10^{-10}\, d_o/R^2 \qquad (3)$$

where again N_r is the number of bubbles per cm^3 with radii ranging from $\frac{1}{2}$ to $3/2\ R$, R being in cm, and f_r is the resonant frequency of the bubble in cycles per second. If fewer bubbles are present than the quantity given by Eq. (3), they will not be detected.

Ultrasonic Cavitation

The measurements of cavitation inception are made in the same apparatus, simultaneous with the bubble detection. The cavitation is induced by setting up a high-intensity sound field in water. If the sound pressure has an amplitude p_s, the instantaneous total pressure is $P_o + p_s \sin 2\pi ft$, where P_o is the static pressure. If this oscillating pressure drops to the critical pressure P_c for cavitation, cavitation occurs. Accordingly, the critical pressure is given in terms of the sound pressure at cavitation by the relation $P_c = P_o - p_s$.

The sound field is generated by a large driver consisting of a $1\frac{1}{2}$-inch diameter piezo-electric ceramic cylinder held in the neck of the spherical flask. The open bottom end of the driver cylinder projects about $\frac{1}{4}$ inch below the water surface. The sphere is filled with water just to the neck, to keep the shape of the water as nearly spherical as possible. The driver receives its electrical power from a 30-watt power amplifier excited at a frequency of about 25 kc/sec by a controllable oscillator. This section of the equipment is similar to that used by Galloway [10] for cavitation studies.

By proper choice of the sound frequency, a sound field is generated with maximum sound pressure at the center. This has the advantage of causing cavitation only at the center of the sphere, away from any solid boundaries. The spherical body of water is highly resonant at these frequencies. The exact frequency is found by experiment, slowly tuning the oscillator to resonance. For our apparatus, a resonance near 25 kc/sec is used. The half-power bandwidth of the resonance is only about 1 c/sec; an extremely stable

oscillator is necessary to hold the resonance. The large amplification at resonance results in high sound pressures with relatively small electrical power.

The sound pressure in the water is measured with a sound probe. The probe consists of a tiny piezo-electric cylinder $\frac{1}{16}$ inch in diameter, at the end of a brass tube. The electrical output of the probe is measured with an electronic voltmeter and also observed on an oscilloscope. The sensitivity of the probe is known from a calibration performed by conventional acoustic techniques, so that its voltage output can be converted to sound pressure. The probe is not placed at the center of the sphere, for this would cause the cavitation to form on the probe rather than in the water. The probe is held several inches off center, and the indicated pressure at this point is multiplied by a correction factor to obtain the pressure in the cavitation zone at the center.

It may be well to consider how the value of critical pressure for ultrasonic cavitation is related to the critical pressure for hydraulic cavitation. In hydraulic cavitation the water is at a low pressure for a time which may vary from 1 to 100 milliseconds, depending on the velocity and the size of the cavitating region. In ultrasonic cavitation, on the other hand, the water is at low pressure for very short periods which repeat periodically; at 25 kc/sec, for example, the low pressure exists for periods shorter than 0.012 milliseconds.

The critical pressure for vaporous cavitation, plotted in the previously-discussed Fig. 1, was calculated with the assumption that the pressure changes are very slow so that the water is at the low cavitation pressure for a long time. A calculation of the critical pressure for ultrasonic cavitation, taking account of the rapid fluctuations in pressure, [11] leads to the same values of critical pressure as for the slow pressure changes. This is an important result, for it indicates that the critical pressure for vaporous cavitation does not depend on the duration of the low pressure.

This is not true, of course, for extremely short durations or extremely high ultrasonic frequencies, say durations less than 5 microseconds or frequencies over 100 kc/sec.

Accordingly, the critical pressure for ultrasonic vaporous cavitation should be equal to the critical pressure for hydraulic cavitation.

For gaseous cavitation, however, there is no relation between ultrasonic cavitation and hydraulic cavitation. Although gaseous cavitation can be induced by ultrasonics, the process is more complicated than that of hydraulic gaseous cavitation.

PROCEDURE AND TYPICAL RESULTS

For a typical set of measurements, tap water is drawn directly from the city supply into the spherical flask. The decay measurements for bubble detection are made over a period of several days as the water stands undisturbed in the sphere. Simultaneously, measurements are made of the inception pressure for ultrasonic cavitation.

The onset of cavitation is determined by increasing the sound pressure in small increments until cavitation starts. The voltage from the sound probe, just before the onset of cavitation, indicates the inception sound pressure. Both gaseous and vaporous cavitation are observed. For gaseous cavitation, the onset is observed visually by the appearance of a small bubble at the center of the sphere. The onset of vaporous cavitation is apparent by the sudden explosive formation of a cavity, accompanied by a "ping" which can be heard in the air.

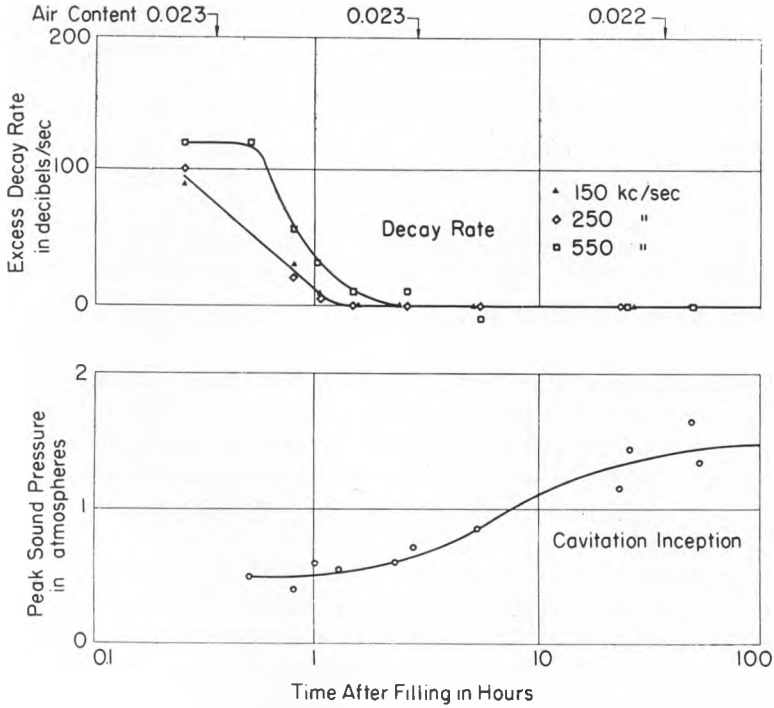

FIG. 4. THE DECAY RATE AND THE INCEPTION PRESSURE FOR ULTRASONIC CAVITATION, AS A FUNCTION OF THE TIME AFTER FILLING THE SPHERE WITH FRESH TAP WATER

Some typical results are shown in Fig. 4. The upper curves

These results were obtained in the course of measurements performed in partial fulfillment of the requirements for the Ph.D. at the Catholic University of America.

show the decay rate measured at three frequencies as a function of the time after filling. The plotted "Excess Decay Rate" is the measured total rate minus the background rate inherent to the apparatus. The excess decay falls to zero in several hours. This means that the content of air bubbles has become too small to be detectable. An upper bound on the number of bubbles which can be present and yet avoid detection can be estimated by substituting into Eq. (3) the measured background decay rates. Upper bounds on the number of bubbles N_r and their volume concentration V_r are indicated in the table below. These values may be considered to be the thresholds of detectability for our apparatus.

TABLE I
Thresholds of Detectability for Bubbles

Frequency kc/sec	Background Decay db/sec	Bubble Radius R cm	Number* N_r per cm³	Volume** V_r cm³/cm³
150	20	2.2×10^{-3}	0.002	1×10^{-10}
250	40	1.3×10^{-3}	0.01	1×10^{-10}
550	200	6×10^{-4}	0.3	2×10^{-10}

*N_r is the number of bubbles per cm³ with radii ranging from 1/2 to 3/2 R.
**V_r is the total volume per cm³ of bubbles whose radii range from 1/2 to 3/2 R.

The lower curve of Fig. 4 shows the sound pressure for cavitation, measured with the same sample of water. The inception pressure changes with time. The measurements during the first few hours resulted in gaseous cavitation, whereas the later measurements at negative critical pressure resulted in vaporous cavitation.

These results, showing how the cavitation characteristics of the water change as it stands, are only illustrative of the type of data obtainable with the apparatus.

For determining the effect of dissolved air, the water can be deaerated without removal from the sphere. The sound intensity is set at a maximum while applying a vacuum to the water in the sphere. This results in violent gaseous cavitation. The appearance of the water during deaeration is shown in Fig. 5. The total air content after partial deaeration is determined by syphoning a 10 cm³ sample into the Van Slyke Gas Apparatus visible at the left side of Fig. 3.

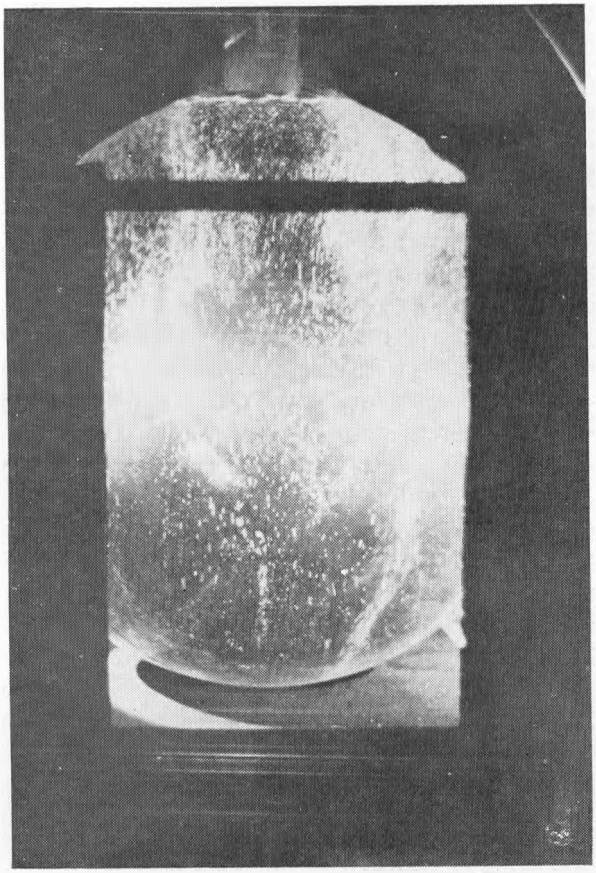

Fig. 5. Ultrasonic Deaeration of the Water within the Spherical Flask

Future Development

The present apparatus is limited to measurements on a batch of water standing undisturbed. For hydraulic applications it would be desirable to detect bubbles and measure the cavitation inception pressure in a stream of moving water.

For measurements in a stream of water, the spherical resonator could be replaced by a cylindrical resonator open at both ends. The water could then stream axially through the cylinder. The bubble detection and the onset of ultrasonic cavitation could be observed in the flowing water. Such a device might be useful for characterizing the water in a water tunnel.

DISCUSSION

Mr. Eisenberg added some comments to clarify the question of bubbles and stability, stating that bubbles will be in equilibrium over a specific range of sizes which are related to the vapor pressure and partial pressure (of air). Bubbles larger than this range of sizes will remain, while the smaller ones will dissolve. Those within the range will be dynamically unstable so that they will grow, and when pressure is applied these bubbles are actually in a state of equilibrium in which the required pressure is somewhat less than vapor pressure. This is demonstrated by the same conditions of stability holding. Though the mechanism by which such nuclei are stabilized is still an open question, long before Harvey, Herzfeld, etc., suggested these mechanisms, people working with problems of surface chemistry had pointed out that certain materials such as detergents may provide stability. He mentioned the cases where air is not needed for stability and stated that infinite energies would be required to dissolve a vapor on that premise even without air.

Regarding the maximum tensions attainable in liquids, he said that the value of 10,000 atmospheres mentioned by Mr. Strasberg was based on the old theory of a ruptured molecule, while according to modern theories—he mentioned the "hole theory"—fluctuations are possible and explained in terms of the crystal structure. In most materials the estimates of 1000 atmospheres which are made seem to be more realistic, although, as Mr. Strasberg pointed out, even this magnitude has never been experimentally observed.

Mr. Eisenberg mentioned, without wishing to discuss, the experiments 3 or 4 years previously by Dr. Glaser at the University of Michigan in which he used a "bubble chamber" to detect sub-atomic particles. This is the liquid analog of a cloud chamber, and in it, paths of the particles are shown by nuclei that open up in superheated water when it is bombarded. His main point was to express the possibility that cosmic radiation in the atmosphere may determine the limit of tension attainable in experiments with the rotating tube and other devices.

Mr. Strasberg emphasized the fact that the critical pressure in his curve was corrected for vapor pressure of the water. With regard to the possibility of the cavities containing only water vapor, he didn't wish to exclude it entirely but stated that his data show a very definite variation in critical pressure with air content which would seem to require that the cavity itself contain air which varies with air content.

Mr. Ripken expressed the opinion that the techniques discussed

in the paper furnish a good example of the effective use of an indirect method where the dimensions of the things to be examined are extremely minute and apparently direct methods are impossible. In view of the indirectness, the good correlation of the data is a high tribute to what has been done. It should be noted that the experiments described herein more or less describe the static scale of things and that there is a broad area of obscurity as to what happens when we transfer to dynamic problems, particularly with regard to derivations based on surface-tension phenomena which have been measured only in the steady case. We have no knowledge which would indicate that surface tensions could not be drastically different as functions of time when fluids are in motion. Mr. Strasberg replied that he usually referred to instantaneous variations or to the fact that water might be flowing.

Mr. Ripken concluded by saying that anything which disturbs the rate at which energy can be transferred through the surface is important, since surface tension is an energy condition and an energy exchange must take place with the bulk of the fluid to cause a change at the surface.

Mr. Strasberg stated that the equipment could be redesigned to permit its use with flowing water by replacing the sphere with an open-ended cylinder. By using the resonant frequency of the cylinder, exactly the same kind of measurements could be performed and the results could be checked using flowing water.

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