Tensile Strength of Liquid Helium II*

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The tensile strength of liquid helium II was measured by the spinning capillary method and by a piston and cylinder method. The first method gave a tensile strength of 0.14±0.02 atmos and the second about half as much. These values are smaller than that expected from the present theories of the tensile strength of liquids.

IT is well known that most pure liquids show tensile strengths of considerable magnitude.[1] However, assuming that the fracture of the liquid takes place simultaneously into two portions along a plane surface,[2,3] in all cases so far reported the measured values are much less than those estimated from theory. This lack of agreement between theory and experiment is perhaps not surprising when it is considered that a liquid under high enough negative pressure is probably metastable and in time will change spontaneously into a two-phase system of liquid plus vapor. Consequently, vapor bubbles will form and grow until the pressure of the system reaches the equilibrium value during which process the liquid may fracture. Fisher[4] has applied nucleation theory to this problem and has derived the following expression for the fracture pressure p_t:

$$p_t=-\left[\frac{16\pi}{3}\frac{\sigma^3}{kT\ln(NkTt/h)-f_0}\right]^{\frac{1}{3}}, \qquad (1)$$

where σ is the surface tension, f_0 is the free energy of activation for the motion of a molecule of the liquid into or away from the bubble surface, and t is the waiting time. Values calculated by Eq. (1), while very much smaller than those estimated by use of the Van der Waals equation,[2] are still larger than the observed values for liquids near room temperature. It is generally believed that the low values observed experimentally are due to the presence of impurities or nuclei in the liquid or on the interface between the liquid and its container around which vapor bubbles may form. Vapor or gas bubbles also may exist in cracks or roughnesses on the surfaces of the container. In practice it is extremely difficult to free a liquid and its container surfaces of these nuclei except perhaps in the case of liquid helium II where, because of its superfluid properties and low surface tension, it should flow into the cracks and wet most of the surfaces in contact with it. Consequently, a determination of the tensile strength of liquid helium II might give a test of nucleation theory as well as provide further information concerning the properties of the liquid itself. It was with this in mind that the present work was undertaken.

Recently, Misener and Hebert[5] have attempted to measure the tensile strength of liquid helium II, and have concluded that if there is a tensile strength it cannot exceed 0.3 atmos, which was the least they were able to observe with the bellows method used. With the same type of apparatus, Misener and Hedgcock[6] previously had found a value of 3.5 atmos for the tensile strength of liquid nitrogen at 71°K.

The fact that liquid helium II has a finite tensile strength was demonstrated by a siphon experiment. A cylindrical glass beaker about 3 cm i.d. and 15 cm high containing, say, a 3 or 4 mm i.d. glass inverted U-tube hanging from its top with one leg (14 cm long) of the U inside the beaker, and the other in the bath, was completely immersed upright in liquid helium II so that the U-tube was completely filled. The beaker was then carefully raised vertically. When it was raised above the liquid surface of the bath, the liquid rapidly siphoned out of the beaker through the U-tube into the bath. Without a finite tensile strength the liquid would not siphon. By giving the beaker various accelerations upward until the liquid column in the U-tube breaks, a very rough lower limit in the tensile strength could be estimated.

Another attempt was made to determine the tensile strength of liquid helium II by measuring directly the force necessary to break the liquid column. A 2-cm³ glass hypodermic syringe with a glass plunger 0.9 cm in diameter was immersed several cm below the surface of the liquid. A special valve which could be opened or closed from the outside of the cryostat was fitted into the opening where the hypodermic needle normally is fastened to the syringe. The glass plunger could be pulled upward by a small stainless steel rod attached to a calibrated solenoid arrangement situated well above the liquid helium surface but in the same container. With the syringe completely full of the liquid helium II and the valve closed, forces lasting for the order of one second were applied to the glass piston by the solenoid. It was found that after allowances were made for friction, etc., observable vapor bubbles formed

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[1] L. J. Briggs, J. Appl. Phys. **21**, 721 (1950).
[2] J. H. Hilderbrand and R. L. Scott, *Solubility of Nonelectrolytes* (Reinhold Publishing Corporation, New York, 1950), third edition, pp. 94–401.
[3] H. N. V. Temperley, Proc. Phys. Soc. (London) **59**, 199 (1947).
[4] J. C. Fisher, J. Appl. Phys. **19**, 1062 (1948).
[5] A. D. Misener and G. R. Hebert, Nature **177**, 946 (1956).
[6] A. D. Misener and F. T. Hedgcock, Nature **171**, 835 (1953).

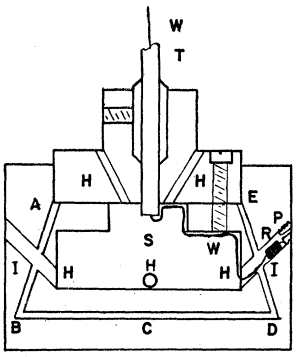

FIG. 1. Cross section of rotor.

inside the syringe when the negative pressure on the column reached between 0.07 and 0.08 atmos, when the temperature was approximately 1.9°K. As far as could be determined, the vapor always formed on or near the surfaces of the plunger. It is also possible that the vapor bubble started between the wall and the plunger. Although this method demonstrates the presence of a tensile strength, it did not give reliable quantative measurements because of the difficulty of estimating the corrections for static friction, etc., and the fact that the vapor bubble always formed near the plunger.

The apparatus finally used for determining the tensile strength of liquid helium II was an adaptation to low temperatures of the spinning capilliary method used by Reynolds,[7] and more recently by Briggs[1] in his classical measurements of the tensile strength of various liquids near room temperature. The method consists of spinning a capillary filled with the liquid around an axis through its center and perpendicular to its length until the liquid ruptures near the axis of rotation. This method is particularly suited for studying the tensile strength of liquid helium because the impurities are solid at this temperature and have a density greater than that of liquid helium. As a result, they are centrifuged out of the liquid. Also, liquid helium has a relatively low surface tension and thus wets most substances.

Figure 1 shows a schematic cross-sectional diagram of the stainless steel rotor. *ABCDE* is a 1.7-mm capillary bored in the solid metal. This capillary is intersected at the points *I* by 4 mm i.d. channels which connect the hollow space *S* with the periphery of the rotor. *A* 3-mm i.d. and 5-mm long insulated 51-ohm carbon resistor fits loosely in one of these channels as shown and is prevented from flying out of the rotor by the tubular metal plug *P*. One terminal of the resistor is soldered to *P* and the other to an insulated manganim wire *W*. The wire *W* passes along the wall of the chamber *S*, in such a way as to avoid as much radial stress as possible, and then out through the stainless steel rotor shaft. The insulated wire and the tubular shaft itself

[7] J. H. Poynting and J. J. Thomson, *Properties of Matter* (Charles Griffin and Company, London, 1902), p. 122.

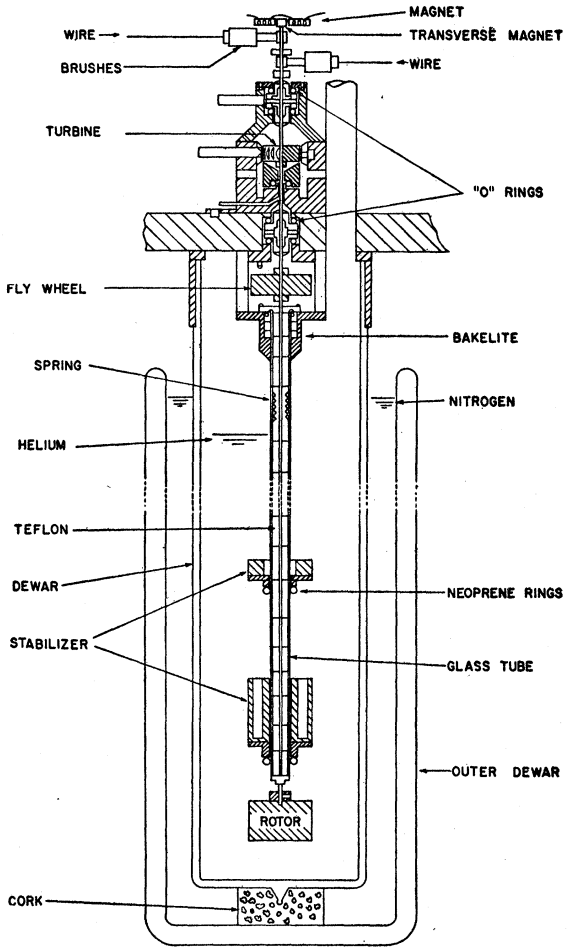

FIG. 2. Apparatus for spinning rotor in liquid helium.

are the two leads to the resistor *R*. Figure 2 shows the method of driving the rotor while it is immersed in the helium bath. The rotor is supported and spun on the end of an 0.122-cm i.d., 56-cm long stainless steel tubular shaft. The rotating parts are both supported and driven by an air turbine situated above and outside the liquid helium bath. The shaft passes through a vacuum-tight oil gland in the top of the vacuum-tight helium bath. In order to prevent the long flexible shaft from vibrating with appreciable amplitude it is surrounded by loose Teflon bushings mounted in a Pyrex glass tube. In order to absorb any vibrations transmitted to the glass tube, dampers or stabilizers are mounted along the length of the tube. A damper consists of a metal platform rigidly mounted on the tube which supports a ring of brass. The bottom stabilizer platform supports a metal cup which fills with liquid. The cup and metal rings have at least 5 mm clearance around the glass tube and, by rubbing on the platform, they damp vibrations. The rotor thus spins smoothly on the end of a shaft of very low thermal conductivity. The electrical connections to the leads of the resistor are

made to the rotating shaft by small brushes above the turbine. The rotor speed is measured by an electromagnetic pickup situated above the brushes.

The inner glass Dewar is first evacuated and filled with helium gas at atmospheric pressure. The outer silvered glass Dewar is next filled with liquid nitrogen. After the rotor has had time to cool sufficiently, it is started spinning very slowly while the inner Dewar is filled with liquid helium. Great care must be taken to avoid air leaks or air condensation inside the helium bath. The rotor is then stopped spinning and the pumps applied to the helium bath until the temperature falls below the lambda point as determined by the vapor pressure, the resistance of the carbon resistor, and by visual observation. Since the rotor is immersed in liquid helium II at least to a depth of a few cm, the capillary and all other rotor chambers should be completely filled. The rotor is next accelerated at the rate of about 9 rps per sec. This forms a slight cavity in the liquid around the rotor and causes the liquid helium to fly out of the channels H in the rotor. The liquid around the resistor is thrown out through an axial channel in the plug P. The resistance-measuring circuit passes a current through R of sufficient magnitude to heat it slightly and its resistance starts to fall. This continues until the liquid helium in the capillary ruptures near C and is thrown out on the resistor R. The liquid momentarily cools the resistor which in turn increases its resistance. The resistance-measuring circuit records this abrupt temperature change because of the well known resistance sensitivity to temperature of carbon in this temperature range. From the rotor speed, when the resistance abruptly increases the effective length of the capillary (distance I to I in Fig. 1), and the density of the liquid, the tensile strength of the liquid helium is calculated. It was observed that the liquid in the capillary ruptured when the rotor speed reached between 150 and 160 rps. The temperature of the bath as measured by the vapor pressure was between 1.8°K and 1.9°K. However, the temperature of the rotor was above this and may have exceeded that of the lambda point in some of the experiments. The effective length of the capillary was 2.8 cm and the rotor diameter 4.4 cm. This gives a tensile strength of 0.14 ± 0.02 atmos. The experiments were repeated with a brass rotor similar to Fig. 1 except that it contained a compartment below the rotor which carried about 30 cc of the liquid helium to reduce temperature change in the rotor while it was spinning. The compartment contained radial baffles to prevent relative motion of the liquid and the rotor during the period of acceleration as well as to give good thermal contact. The results were roughly the same as with the rotor of Fig. 1. A special rotor with a glass capillary with the same shape as $ABCDE$ (Fig. 1), mounted so that it could be observed optically, also was tried. Unfortunately, the refractive index of liquid helium is so small that the observations were inconclusive.

The value of the tensile strength of liquid helium II at 2°K calculated from Eq. (1) is the order of 4 atmos, assuming f_0 vanishingly small, and taking the value of the surface tension[8] σ as 0.3 (dynes/cm^2). The tensile strength calculated from Van der Waals' equation is several times this. Therefore, the experimental values found are smaller than expected from Eq. (1) which was derived from nucleation theory. This may be due to the fact that Eq. (1) cannot be extrapolated to this temperature or that there still may be nuclei in the liquid or on the walls around which vapor bubbles can form. Also, there always are ions present due to radioactivity and cosmic rays. This might affect the hypodermic syringe experiment because of the larger volume of liquid, but there should be too few ions formed in the capillary near the axis of rotation to change the results appreciably. On the other hand, the values calculated from Eq. (1) decrease very rapidly with increase in temperature, and there is some uncertainty in the temperature of the spinning rotor as measured by the carbon resistor and the vapor pressure of the helium bath. This arises from the fact that the carbon resistor is covered with a thin coating of electrical insulation and the spinning rotor forms a cavity of vapor around it in the liquid helium bath. It is planned to repeat the experiment under conditions where there is no relative motion of the rotor and helium bath in order to check this possibility.

ACKNOWLEDGMENTS

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[8] W. H. Keesom, *Helium* (Elsevier Publishing Company, Amsterdam, 1942), p. 263.