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Film Flow and Bulk Formation of Helium II in Capillaries*

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The formation and maintenance of bulk liquid in capillaries caused by the mobile film flowing from a liquid helium II bath below the capillaries has been observed. Experiments with parallel plates, cylindrical capillaries, and annular capillaries indicate that bulk will form initially only when the width of the capillary space is below some critical value, depending on the geometry. However, bulk liquid once present in a capillary will be maintained by the film even if the width is greater than the critical value for initial formation. Measurements of film flow rates and equilibrium capillary rise in these capillaries give values in agreement with measurements of these quantities, under other experimental conditions, made by various other observers. The effects observed are discussed in terms of the known properties of liquid helium II.

INTRODUCTION

THE principal flow properties of the mobile helium film have been established by extensive investigation over the past fifteen years. The mass rate of flow of the film between two baths of bulk helium II has been found to be directly proportional to the smallest perimeter crossed by the film above the upper level of the bulk liquid; it has also been found to be independent of either the gravitational potential gradient or the temperature gradient driving it, except under certain very special conditions. Such flow at a constant rate, independent of the driving force, indicates the absence of frictional forces in the fluid for velocities of flow up to a certain critical velocity corresponding to the velocity at the perimeter controlling the mass rate of flow. Atkins[1] has shown that this film behavior can be regarded as a limiting case of the flow of helium II in narrow channels, in which there is a critical velocity for frictionless flow which increases as the channel width is decreased, and where flow subject to frictional retardation tends to become vanishingly small as the channel width is decreased. In the case of the film, the thickness of the film ($\sim 10^{-6}$ cm) corresponds to the channel width.

It has been observed that when the perimeter crossed by the film at some point below the upper bulk level is made smaller than the controlling perimeter, the film retains its equilibrium thickness (which is a function of the height above the level, and possibly of the nature of the substrate), and the excess flow is converted into droplets of bulk liquid. According to Jackson and his co-workers[2,3] these droplets are several tenths of a millimeter in diameter and move with a velocity of about one cm/sec, considerably below the critical velocity of the film, which is of the order of 20 cm/sec. The appearance of such droplets is consistent with a reduced critical velocity and with the appearance of some frictional flow associated with a substantial increase of channel width.

EXPERIMENTS WITH CAPILLARIES

We have recently performed some experiments with capillaries held vertically above an evaporating bath of helium II and connected to it by a surface over which the mobile film can flow. We have found that, under appropriate conditions, the film can form bulk liquid in such capillaries and a report based on preliminary experiments with a pair of parallel plates was published earlier.[4] We have now varied the experimental conditions and we have also verified that the flow rate of the film, and the capillary rise of liquid helium, in

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[1] K. R. Atkins, Proc, Roy. Soc. (London) **A203**, 241 (1950).
[2] L. C. Jackson and D. G. Henshaw, Phil. Mag. **41**, 1081 (1950); **44**, 14 (1953).
[3] A. C. Ham and L. C. Jackson, Phil. Mag. **44**, 214 (1953).
[4] C. T. Lane and R. V. Dyba, Phys. Rev. **92**, 829 (1953).

capillaries of the dimensions used here, are in agreement with values obtained from measurements made under other conditions.

The various capillaries were suspended vertically just above the level of the liquid helium bath. They were attached with special holders to the bottom of a stainless steel tube that passed through an O-ring seal in the Dewar cap; the vertical position of the capillaries was adjusted by moving this tube up and down. The holders were designed to present to the film a constricted periphery so there would not be a large film flow up the stainless steel tube. A low-power fluorescent light with heat-absorbing glass filters provided illumination for viewing of the bath level and the meniscus in the capillary through a cathetometer telescope. Measurements of the height of the two levels were usually taken as a function of time as the bath level dropped by evaporation.

I. Parallel Plates

In our preliminary report,[4] we described the results of experiments with parallel plates having a 36-micron spacing, and with one plate extending below the other.[5] A similar pair of plates with 47 micron spacing was also used. The behavior of each was found to be essentially the same. That is, a meniscus appeared in the capillary space when the lower plate was immersed in the liquid even though the bath level was below the bottom of the capillary gap. The meniscus rose rapidly to an equilibrium height above the bath, equal to the ordinary surface tension rise, as confirmed when the plates were immersed further such that the bath level was above the bottom of the gap. Then, as the bath level dropped by evaporation, the meniscus remained at this same height above the bath level, until the meniscus reached the bottom of the capillary space.

However, with a pair of similar plates with a gap of about 90 microns the meniscus did not form until the bath level was brought into contact with the bottom of the capillary space. Only then was there a rapid rise to the equilibrium height. But again, when the bath level dropped by evaporation, the meniscus maintained this equilibrium height above the bath level.

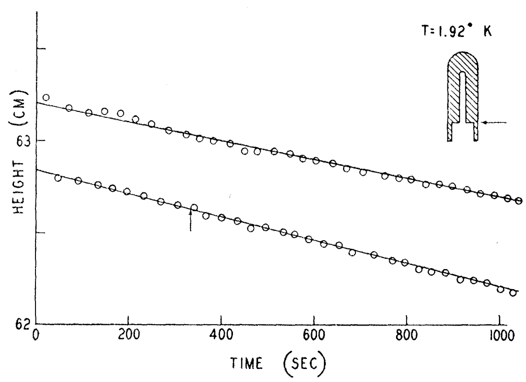

FIG. 1. The height of the meniscus and bath (lower curve) as a function of time for a circular capillary 226 microns in diameter. The arrow indicates the point at which the evaporating bath just reaches the bottom of the capillary. Temperature 1.92°K.

[5] The statement in reference 4 about the effect in spaces of 75 microns width is incorrect to the extent indicated by the details of the experiment described here.

II. Cylindrical Capillaries

A cylindrical capillary was constructed by joining a Pyrex tube with a 226-micron bore to another Pyrex tube with a 1.15-mm bore without distortion at the joint. The end of the narrow bore was sealed off.

When the open end of the wide bore was dipped into helium II, the meniscus appeared in the narrow bore although the liquid level was below the bottom of the latter. The meniscus rose in a few seconds to a height corresponding to the equilibrium capillary rise, as determined by immersing the narrow bore in the bath. After such an immersion, the heights of the meniscus in the capillary and of the bath level were measured as a function of time while the bath level dropped by evaporation. A typical plot of the data is shown in Fig. 1. The meniscus remained at the same height above the bath level even after the latter had dropped

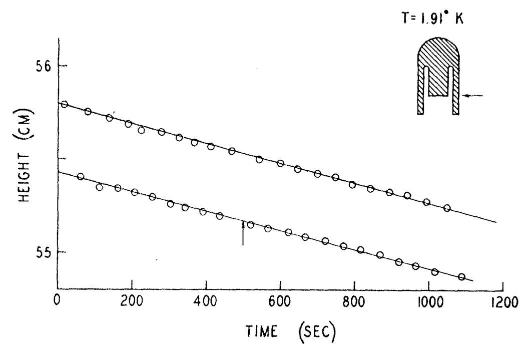

FIG. 2. The height of the meniscus and bath (lower curve) as a function of time for an annular capillary 100 microns wide. The arrow indicates the point at which the evaporating bath just reaches the bottom of the annular space. Temperature 1.91°K.

below the capillary region, and the same relative position of the meniscus and bath level was maintained until the meniscus reached the bottom of the capillary. The measurements were repeated at several different temperatures, and the equilibrium height was consistent with that calculated from the known surface tension.

A similar capillary using a 1-mm bore for the capillary space and a 2-mm bore for the lower tube was also tested. However, the small capillary rise of liquid helium in a 1-mm tube (order of 0.5 mm) made it impossible to determine whether the effects observed with the 226-micron bore were present or not.

III. Annular Capillaries

The desirability of performing the experiments with a geometry equivalent to that of the parallel plates, yet with the top of the capillary space sealed so that the paths available to the film could be controlled, led to experiments with annular capillaries. Several such capillaries were made from Pyrex rods centrally aligned in Pyrex true-bore tubing of slightly larger diameter; the annular gaps were of the order of 100 microns and less in width, while the over-all diameter of the tubes was about 6 mm. The upper end of these capillaries was sealed off and because the gap width was so small compared to the radius, these annular capillaries corresponded essentially to parallel plates sealed off at the top. A sketch of one of these devices is shown in Fig. 2.

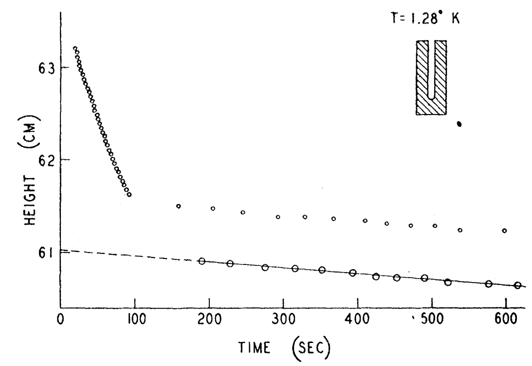

FIG. 3. An "emptying" process for a 185-micron circular capillary beaker. The bath level (lower curve, large circles) was, at all times, in contact with the outside of the beaker. Temperature 1.28°K.

In the first such capillary, with a gap width of about 100 microns, the outer tube was longer than the inner rod; therefore, the inner surface of the tube provided the path for film flow from the liquid helium bath to the annular gap. When the outer tube was immersed in the bath, no meniscus appeared in the annular gap until the bottom of the gap was in actual contact with bulk liquid. However, after the annular space was immersed, a meniscus appeared due to ordinary surface tension rise. Then alternate readings of meniscus and bath level were taken as the latter dropped by evaporation. A typical result is shown in Fig. 2. The meniscus remained at the equilibrium surface tension height above the bath even when the latter dropped below the bottom of the capillary bore, until the meniscus reached the bottom of the bore.

In the second annular capillary, the inner rod was longer than the outer tube; therefore the surface of the rod, instead of the inner surface of the tube, now provided the path for film flow from the bath to the annular space which was again about 100 microns wide. However, the behavior of the meniscus was essentially the same as in the first annular capillary.

In the third annular capillary, rod and tube were of the same length, but 1 cm of the lower end of the rod was reduced in diameter so the lower annular space was 1 mm wide, the capillary gap being about 75

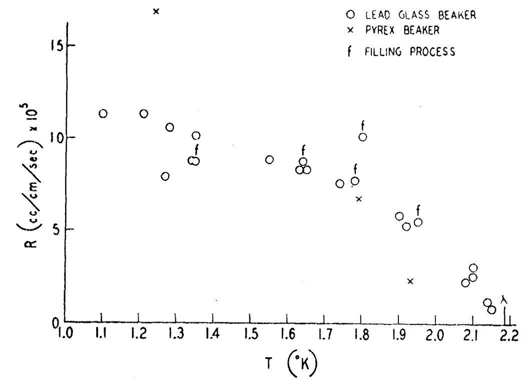

FIG. 4. The film transfer rate (R) as a function of temperature deduced from the capillary beaker experiments.

microns. In this case, therefore, the film could flow over both the surface of the rod and the inner surface of the tube from the bath to the annular capillary space. However, again the behavior of the meniscus was the same as in the other two arrangements.

From these experiments on annular capillaries it was concluded that the particular path available for the film had no effect on whether or not bulk formed in the annular capillary space.

The fourth annular capillary was similar to the first, except that the gap width was reduced to approximately 50 microns. When the outer tube was immersed in the bath, a meniscus appeared in the capillary space even though the bath level was below the bottom of this space. When the bath dropped by evaporation after the capillary was immersed, the meniscus remained at the surface tension equilibrium height above the bath level as in all the other cases.

From the experiments with the annular capillaries and the parallel plates, there therefore appears to be a critical spacing for the formation of bulk liquid from the film. For these geometries, it appears to be between 50 and 100 microns.

IV. Capillary Beaker Experiments

Since measurements of film flow rates have been made in the past using beakers with larger internal diameters than those of the capillaries in the preceding experiments, it was thought advisable to verify that the flow of the film was not significantly different in such capillaries. Consequently, flow rates were determined in a lead glass beaker with a 184-micron bore and a Pyrex beaker with a 185-micron bore, by the usual technique of measuring the rate of rise or fall of the liquid level in the beaker as the latter fills or empties by film flow. It was observed that, in general, a beaker raised partly clear of the bath after filling emptied only until the level in the beaker was at a height corresponding to the equilibrium surface tension rise above the bath level;[6] a similar effect was

[6] The same effect occurred for a "filling" process.

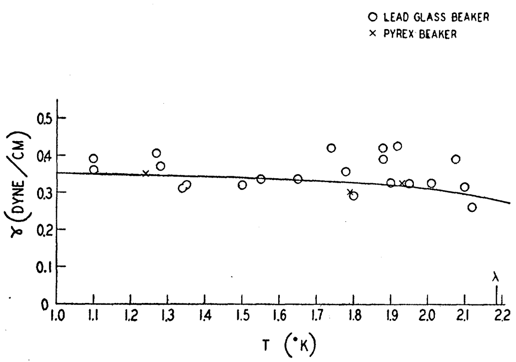

FIG. 5. Surface tension of helium II as a function of temperature. The solid curve represents smoothed values given by reference 9.

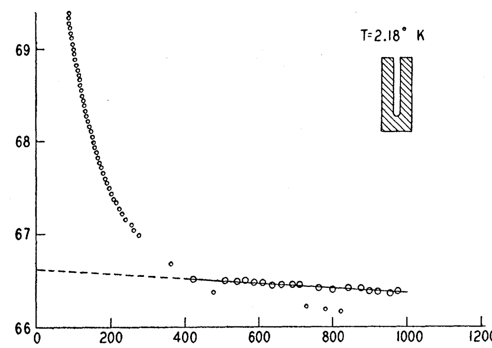

FIG. 6. An emptying process, very close to the λ point, for a 185-micron circular capillary beaker. The bath level (large circles) was, at all times, in contact with the outside of the beaker. Temperature 2.18°K. Ordinate: height in cm. Abscissa: time in sec.

observed by Atkins[7] in his determination of film thickness from the oscillations of the liquid level about its equilibrium position. A typical emptying curve is shown in Fig. 3. The deduced flow rates (in cm^3/sec cm periphery) are shown as a function of temperature in Fig. 4; they are in fair agreement with the published results of Mendelssohn[8] and others for beakers with larger internal diameters. Surface tension as a function of temperature and calculated from the equilibrium heights is shown in Fig. 5 and compared with the smoothed data of Allen and Misener;[9] the agreement is satisfactory within the estimated error of about 10 percent.

Above about 2.15°K the meniscus (indicating the level in the beaker) did not remain at the expected equilibrium height above the bath but instead continued to drop below it; a typical run of this type is shown in Fig. 6. The rate of evaporation would not be expected to change much with small changes in temperature just below the λ point at which temperature the flow rate rapidly approaches zero. Hence, above 2.15°K the film flow cannot compensate for the loss of liquid from the beaker by evaporation. At the somewhat lower temperature where the equilibrium height is maintained (e.g., at 1.28°K, Fig. 3) the film flow must therefore have reversed direction, when this equilibrium height was reached, to compensate for evaporation. In the case of capillary rise, in general, the meniscus and the bath level must be at the same gravitational potential once the equilibrium rise is attained. This is true also for the special case presented by these capillary beakers; here the mobile film connects two liquid surfaces at the same potential. Normal evaporation of the meniscus will tend to lower the potential here as compared to that of the bath. Hence, the film reversal strongly suggests that the mobile film, in beaker experiments in general, is driven by a gravitational potential difference only.

[7] K. R. Atkins, Proc. Roy. Soc. (London) **A203**, 119 (1950).
[8] K. Mendelssohn and G. K. White, Proc. Phys. Soc. (London) **A63**, 1328 (1950).
[9] J. F. Allen and A. D. Misener, Proc. Cambridge Phil. Soc. **34**, 299 (1938).

CONCLUSIONS

The formation of bulk liquid via the mobile film,in these experiments, takes place only in capillary spaces that have a width smaller than some critical value, between 50 and 100 microns for parallel plates and annuli and over 200 microns for cylindrical capillaries. However, as we have seen, once bulk liquid is present in any capillary space the film will maintain it even though the bath level drops below the bottom of such a space. If one takes into account the surface tension, this latter effect is simply an example of the fact that the film connecting two quantities of bulk liquid flows until each is at the same gravitational potential, whence the film flow ceases. The only problem that remains, therefore, is to account for the initial formation of bulk liquid in the capillaries in those cases where this occurs.

Our capillary beaker experiments indicate that the film flow rate and the equilibrium height of the bulk liquid in such capillaries are, in general, consistent with the corresponding properties of liquid helium II under other conditions. One might expect the formation of bulk liquid in the capillary to be associated with some excess film flow, as in the other known cases of bulk formation from the film. (See reference 2.) In the cylindrical capillary, the formation of an initial droplet of bulk liquid covering the bottom of the gap could possibly be accounted for by the initial excess flow caused by the contraction of the periphery at the bottom of the capillary bore (see the reverse case in reference 2). This explanation, however, cannot hold in the cases of either the parallel plates or the annular capillaries since here no abrupt change in periphery takes place at the bottom of the capillary gap. Hence, the way in which bulk liquid is formed from the film in these capillaries remains unclear.

We wish to thank H. N. V. Temperley for first suggesting to us the possibility of a critical spacing with regard to the formation of bulk liquid from the film. We are also indebted to R. G. Wheeler for valuable assistance with the experiments.