foregoing occurs, a genuine sound wave of neutral molecules will be excited on account of the collisions between ions and molecules. If such a genuine sound wave is excited, the ions will "ride on" this wave, i.e., they will participate on this wave.

The drift velocity determined in Eq. (2) is essentially the terminal velocity in the presence of friction between the neutral molecules and ions due to the relative drift velocity. The calculation given in this paper is based on the assumption that the drift velocity of the neutral molecules is zero. If the neutral molecules perform sound motion, then the friction will be proportional to the difference between the ion drift velocity and the molecule drift velocity accompanying the sound. When these two drift velocities coincide, the friction will disappear and a "resonance" will set in. This situation, which is outside the scope of Eqs. (1) and (2), may explain the fact that the actual propagation velocity of positive striations is found to lie between the value as given by Eq. (28) and the velocity of sound in the gas. We are now undertaking an investigation in this direction.

PHYSICAL REVIEW VOLUME 99, NUMBER 6 SEPTEMBER 15, 1955

Helium Film Transfer Rate from 0.14 to 2.19°K*

R. K. WARING, JR.†
Sloane Physics Laboratory, Yale University, New Haven, Connecticut
(Received May 27, 1955)

The transfer rate of the mobile helium film, over Pyrex glass, was measured as a function of temperature in the range from 0.14°K to the lambda point. The bulk of the observations was concerned with film transport due to a thermal gradient but a measurement, using the same apparatus, was made at 1.1°K under a gravitational potential as a comparison. At this temperature it was found that the transport rates, in the two cases, differ by a factor of nearly two, and below 1°K the rate was found to increase with decreasing temperature by about 10%.

INTRODUCTION

AMBLER and Kürti[1] have recently measured the rate of transfer by the helium film, under a gravitational potential difference, at temperatures below 1°K. They observed a 30% increase in the rate as the temperature was reduced from 0.85°K to 0.15°K. The only other data, that of Lesinsky and Boorse,[2] whose lowest temperature point was 0.75°K, lend some support to this result. Since all but about one percent of the liquid is already superfluid at 1°K, these observations seem to negate the hypothesis that the temperature dependence of the transfer rate is given by

$$R=(\rho_s/\rho)v_c d,$$

where the product $v_c d$ is a constant approximately equal to $\hbar/2m$. Here R is the flow rate in $cm^3\ cm^{-1}\ sec^{-1}$, v_c is the critical velocity of the superfluid, d is the film thickness, and ρ_s/ρ is the fraction of the liquid which is superfluid.

Liquid helium may also be transferred, by the mobile film, from a position at low temperature to a position at a higher temperature providing that no portion of the surface over which the helium must flow is above the lambda point. Thus thermal film transfer rates may be measured by allowing the film to flow into a region where it evaporates, the rate of vapor efflux then being determined. In view of the results of Ambler and Kürti it appeared desirable to investigate the thermal transfer rates at temperatures below 1°K, and this method offered a convenient means for observing these as well as rates above 1°K.

THE APPARATUS

The portion of the apparatus contained in the helium cryostat is schematically represented in Fig. 1. The bulk liquid helium II, which supported the film flow, was contained in a small Pyrex reservoir (*a*), the flow being constricted by a 211-micron i.d. Pyrex capillary (*b*). Except for a baking process to be described, this capillary was untreated. The surface of the liquid in reservoir (*a*) was always farther from the lower end of the Pyrex capillary than the surface tension rise appropriate to a 211 micron tube (~5 mm). This prevented the Pyrex capillary from filling with bulk liquid via the film.[3]

Above this constriction was a glass to Kovar seal (*c*) leading to a 0.014-inch i.d. stainless steel tube (*d*) with a 0.003-inch wall. A tube this fine was used in order to inhibit recondensation, into the reservoir, of helium evaporated from the film. It was necessary, since excessive recondensation would have caused the salt to warm up too rapidly after a demagnetization,

* Assisted by the Office of Ordnance Research, U. S. Army.
† This work formed part of a Ph.D. dissertation.
[1] E. Ambler and N. Kürti, Phil. Mag. **43**, 260 (1952).
[2] L. Lesinsky and H. A. Boorse, Phys. Rev. **87**, 1135 (1952).
[3] Dyba, Lane, and Blakewood, Phys. Rev. **95**, 1365 (1954).

and in addition would have introduced an error into the transfer rate measurements.

Upon leaving the stainless steel capillary the film entered the valve (*f*), which was adapted from a commercial needle valve. This was included, because at temperatures above 1°K the vapor pressure of helium in the reservoir becomes high enough so that large amounts of vapor (apart from that produced by the film) could enter the measuring system and thus create an error. When the valve was "closed" it acted as a superleak preventing the escape of any significant amount of vapor from reservoir (*a*) but offering free passage to the mobile film. A nonopening superleak could not have been used, since it was necessary to pump out the reservoir and constriction thoroughly before cooling them to liquid helium temperatures. Had this not been done, air present would have solidified onto the surface of the constriction giving rise to anomalous results.[4] Further, the valve made possible certain precautions and tests which will be described hereafter. It was actuated from outside the cryostat by means of a thin-walled stainless steel tube (*g*) which was soldered at the top to a brass rod, which in turn passed through an O-ring seal (*h*) in the Dewar cap. The copper tube (*i*) served to bypass the threaded portion of the valve, since this would have acted as a severe constriction in the pumping line.

The film arising in the reservoir was rendered mobile by the thermal gradients in the vicinity of the outer bath level. When the reservoir was below 1°K, there were, of course, other gradients. It passed up to a point at which the temperature was 2.19°K, and here any liquid which had not already evaporated at lower temperatures became vapor. It then passed out of the cryostat through the stainless steel tube (*j*) and into the pumping system. This consisted of a 50-liter/second oil diffusion pump backed by an adequate forepump.

A method which has been used to measure the efflux rate of helium evaporating from the film[5] is to allow it to flow into a previously evacuated bulb and, simultaneously, to measure the time rate of pressure rise in the bulb. For the present experiment, however, instantaneous measurement of the rate was desirable, since the temperature of the helium changed with time in the demagnetization range. The method chosen for this investigation consisted of measuring the fore-pressure in the pumping system as a function of the rate at which helium gas entered the system through a calibrated leak. This leak consisted of an ungreased stopcock with the plug waxed in at top and bottom to prevent the entrance of air. The leak rate through it was varied by changing the pressure on one side of it, the other side leading into the high-vacuum side of the diffusion pump. In order to calibrate the device, a large, accurately known volume was attached to the

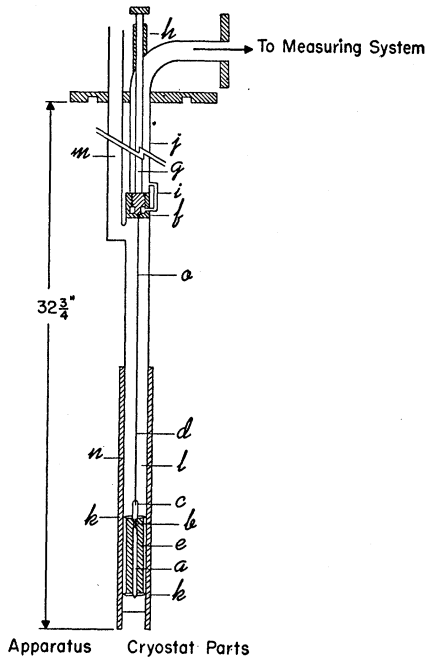

FIG. 1. Schematic diagram of the apparatus contained in the cryostat.

vacuum system; and, with the fore pump closed off and the diffusion pump not operating, the rate of pressure rise in the vacuum system was measured as a function of the pressure of helium on the other side of the leak. A simple calculation converts this to the units in which film transfer rates are expressed. The volume of the part of the vacuum system involved in this measurement was calculated from its dimensions. Since these were small compared with those of the attached container, any errors in the computation resulted in a negligible error in the total volume. The pressure on the leak was measured with a mercury manometer, and the position of the plug in the stopcock was adjusted so that the range of leak rates desired corresponded to a pressure range of about one atmosphere. The pressure in the known volume was measured with a McLeod gauge and did not rise above 100 microns.

In order to calibrate the pumping system, the large known volume was removed, and helium was admitted into the pumping system at known rates, via the leak, with both the diffusion pump and the fore pump operating. The fore pressure was then measured as a function of the known leak rate, and the fore pressures observed during the film flow measurements were then compared with this calibration. A valve between the cryostat and the diffusion pump permitted a pumping system calibration to be made at any time during a run.

Manganous ammonium sulfate was chosen as the paramagnetic salt for this work, since it is known to have a very high specific heat in the neighborhood of 0.15°K. To make the salt pill (*e*) powdered salt was

[4] R. Bowers and K. Mendelssohn, Proc. Phys. Soc. (London) A63, 1318 (1950).
[5] H. A. Fairbank and C. T. Lane, Phys. Rev. 76, 1209 (1949).

pressed onto a copper tube in $\frac{1}{32}$-inch sections interspaced with 0.005-inch-thick copper disks.[6] These had central holes about 0.010 inch smaller in diameter than the central tube, and thus they had to be forced onto it. These measures insured good thermal contact between salt and copper. A small amount of silicone vacuum grease was mixed with the powdered salt to act as a binder.

The salt pill assembly fitted closely over the glass reservoir in the position shown in Fig. 1, and silicone grease was used to establish thermal contact. On each end of the pill was placed a "spider" (*k*) consisting of eight evenly spaced quartz points projecting from a brass ring. These served to isolate the salt from the exchange gas cavity wall (*l*).

In order to determine the magnetic temperature of the salt its magnetic susceptibility was measured using the mutual inductance coil (*n*). No conversion of the magnetic temperatures to Kelvin temperatures was attempted, but the shape correction for a 3:1 ellipsoid, as calculated by Kürti and Simon,[7] was applied. Thus the temperatures quoted below 0.95°K actually approximate the magnetic temperatures of a sphere of the salt used. The measuring coil had two bucking secondaries, and the short ferromagnetic Kovar section (*c*) of the capillary line (*d*) was placed accurately between them. In this position it proved to have a negligible effect upon the mutual inductance. The exchange gas pressure was controlled with a standard vacuum system employing a five liter per second oil diffusion pump. Warm-up times were on the order of two hours. The apparatus shown in Fig. 1 was contained in a liquid helium bath whose temperature was controlled and measured in the usual manner.

RESULTS

The transfer rates observed are plotted against temperature in Fig. 2. The scatter may be partly a result of day-to-day variations in the pumping speed of the measuring system. Two features of the curve appear of particular interest. First, it displays partial agreement with the results of Ambler and Kürti. The increase observed below 1°K is, however, in the neighborhood of 10% rather than 30%, and it saturates at about 0.5°K. It should be emphasized that these measurements were made under entirely different experimental conditions than were those of the above mentioned authors. In the present work the film was rendered mobile by thermal means, and radiation was completely excluded.

The second noteworthy fact is that the rates above 1°K prove to be considerably higher than accepted gravitational rates in the same region. This is in disagreement with the often repeated statement in the literature that critical thermal flow rates are identical

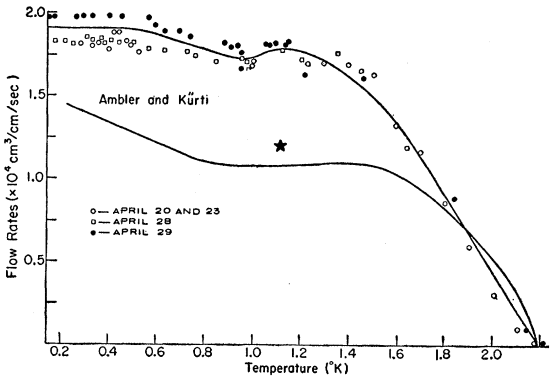

FIG. 2. Dependence of critical film transfer rate upon temperature. The upper curve presents the results of the present work. The star signifies the gravitational flow rate obtained with the same equipment. The lower curve shows the smoothed values obtained by Ambler and Kürti (reference 1).

with the gravitational ones. In the next section we shall present certain arguments to support the validity of the present measurements.

SUPPORTING ARGUMENTS

Extensive precautions were taken in order to avoid contaminating the surface of the constricting Pyrex capillary. The entire vacuum apparatus, including the system for condensing helium into the reservoir, was tested for leaks using a helium mass spectrometer leak detector. Before cooling down the system was pumped out for about 48 hours. A cold trap was used at all times to prevent migration of pump oil. The pressure reached 5×10^{-6} mm as measured with an ion gauge between the cold trap and the diffusion pump.

After cooling down to about 1°K, helium was slowly injected into the system through a charcoal trap held at liquid air temperature. During the process the valve (*f*) was closed in order to prevent the passage into the reservoir of any impurities remaining in the helium. To preclude the possibility of low vapor pressure contaminants which might have been condensed onto the constricting surface during soldering operations on the vacuum system the reservoir and capillary were baked at 300°C for two hours while the system was evacuated through a liquid air trap. That temperature was regarded as high enough, since the only joints made after the glass was attached were soft soldered. Actually, this operation was performed after the runs of April 20–23 (see Fig. 2) and no significant change resulted.

As a-final check the reservoir was broken off above the 211-micron constriction, and a gravitational film flow measurement was made with it at 1.1°K. No exceptional precautions were taken to avoid air contamination, but the result (indicated by the star on Fig. 2) falls within the range of the latest reported rates for gravitational flow over Pyrex.[8]

[6] J. C. King and H. A. Fairbank, Phys. Rev. **93**, 21 (1954).
[7] N. Kürti and F. Simon, Phil. Mag. **26**, 849 (1938).
[8] B. Smith and H. A. Boorse, Phys. Rev. **98**, 328 (1955).

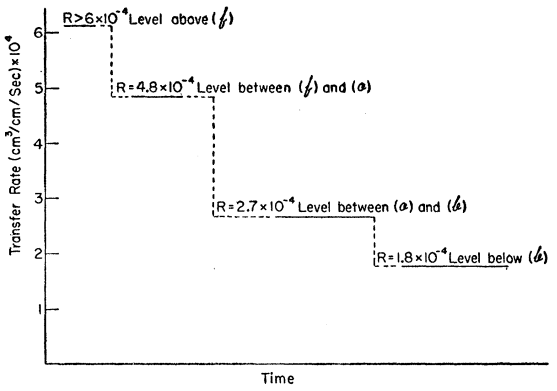

FIG. 3. Flow rates for liquid levels above the Pyrex capillaryl At the point (0) there was a constriction in the stainless stee. tube.

In order to insure that the flow was indeed being constricted at the 211-micron Pyrex capillary, enough helium was admitted to bring the liquid level up into the valve. The transfer rate was then measured as a function of time (Fig. 3). Each step corresponds to liquid levels between known constrictions, and the length of each step corresponds to the mass of liquid removed. The latter fact confirms the validity of the method for measuring the rate of vapor efflux, since known amounts of liquid flowed out in times corresponding to the transfer rates as measured. To support the observations below 1°K it was also necessary to demonstrate that the flow was not then being constricted at a point whose temperature was controlled by the bath. This was done by raising the bath from 0.95 to 1.7°K while the reservoir was well below 1°K. No significant change in the transfer rate was observed.

A calculation based upon the extrapolated thermal conductivity of glass,[9] upon the specific heat of liquid helium[10] below 1°K, and upon the quality of thermal contact between salt and copper[11] indicates that thermal equilibrium between the salt and the liquid in reservoir (*a*) should have been reached within a few minutes after demagnetization. Further, the approximate rate of flow of vapor through the stainless steel tube could be determined, with the reservoir (*a*) in thermal contact with the helium bath, by noting the difference between the observed transfer rates with the valve open and those with it closed. This was on the order of one percent for bath pressure of 80 microns. From this one may conclude that the reverse flow occurring with the salt below 1°K was too small to carry an appreciable amount of heat into the reservoir, and thus disturb the temperature equilibrium there.

DISCUSSION

Experiments on the rate of thermal film flow above 1°K fall into two classes. The class represented in the present work includes those in which the film creeps up to a region where it evaporates, the resulting mass rate of flow of vapor being determined and converted to volume rate of flow of liquid. The second class, the isolated beaker experiments, consists of measurements of the volume rate of flow between baths at different temperatures or with different heat inputs and the results cannot be compared with those being reported here.

In addition to the present experiment three others of the first type have been described,[5,12,13] and they all yielded thermal rates lower than those reported here. However, each appears to be open to one or both of the following criticisms. First, in the cases of references 5 and the first experiment reported in reference 13, one would be inclined to question whether all the helium evaporating from the film actually arrived at a point where it could be observed. Second, in the work reported in reference 13 the constricting periphery was not necessarily isothermal throughout its length, and the film flow rates quoted depend upon the assumption that this will have no effect.

On the basis of the evidence so far accumulated it does not appear impossible that a real difference exists between the film flow rates under, respectively, gravitational and thermal impetus.

ACKNOWLEDGMENTS

I should like to express my gratitude to Professor C. T. Lane who suggested this experiment and under whose guidance it was carried out. I am also indebted to Dr. E. Ambler of the National Bureau of Standards for kindly allowing me to examine his Oxford dissertation.

[9] R. Berman, Advances in Physics **2**, 103 (1953).
[10] Hull, Wilkinson, and Wilks, Proc. Phys. Soc. (London) **A64**, 379 (1951).
[11] E. Mendoza (private communication).
[12] B. V. Rollin and F. Simon, Physica **6**, 219 (1939).
[13] E. Ambler and N. Kürti, Proceedings of the International Conference on Low Temperature Physics, Oxford, 1951 (unpublished), p. 70.