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STATIC HEAT TRANSFER TO LIQUID HELIUM IN OPEN POOLS AND NARROW CHANNELS*

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Abstract—The transfer of heat to boiling liquid helium has been measured in open pools and narrow channels. In open pools a marked dependence of heat transfer on the orientation of the heated surface is observed. The maximum heat flux for nucleate boiling varies from 1 W/cm² with the heated surface horizontal facing upwards to about 0·1 W/cm² with the surface horizontal facing downwards. In a narrow vertical channel the maximum heat flux is reduced to about 0·15 W/cm² for a rectangular channel 10 mm × 1 mm (50 cm length), and appears to decrease linearly with the channel dimension. The heat transfer is considerably increased in the narrow channel when the fluid is pressurized.

NOMENCLATURE

A, heated area [cm^2];
C_{pl}, specific heat of liquid [J/g °K];
f, function;
g, gravitational acceleration [cm/s^2];
K, numerical constant of the order $\sqrt{(\pi/128\sqrt{3})} < K < \sqrt{\pi/128}$;
k_l, thermal conductivity of the liquid [W/cm°K];
L, length of the heated surface [cm];
n, exponent;
p, pressure of the boiling system [dynes/cm^2];
q, heat flux density [W/cm^2];
ΔT, temperature difference [°K];
β, volumetric coefficient of expansion of liquid [°K^{-1}];
φ_l, φ_v, liquid and vapour densities [g/cm^3];
λ, latent heat [J/g];
μ, dynamic viscosity [poise];
σ, surface tension between liquid and vapour [dynes/cm].

Subscripts
l, liquid;
v, vapour;
max, maximum.

1. INTRODUCTION

THE GROWTH in the use of superconducting devices, particularly large superconducting solenoids, has caused a subsidiary interest in the use of liquid helium as a heat transfer agent. The stability characteristics of a high field superconductor are directly dependent of the efficacy of heat transfer, and an improvement in heat transfer can lead to a considerable improvement of performance of a device using such materials. In this paper we will present the results of experimental studies on heat transfer with liquid helium carried out as part of a program of magnet design and construction.

Relatively little is known about the heat transfer characteristics of liquid helium, except in open pools. Useful reviews of existing knowledge have been given by Brentari and Smith [1], Lyon [2] and Smith [3]. The dependence of the heat transfer as a function of the surface orientation in pool boiling has been studied by

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Dorey [4] and Lyon [5]. They obtained very contradictory results. Dorey did not find any noticeable change in heat transfer coefficient for both vertical and horizontal positions. Lyon observed a very marked orientation dependence of the heat transfer for horizontal upwards, downwards, and vertical positions. The effect of hysteresis as a very marked phenomena in pool boiling at atmospheric pressure has been shown by Lyon [5], Thibault *et al.* [6], and Cummings and Smith [7]. Other experiments of interest to this work have been made by Keilin *et al* [8], Efferson [9], and Butler *et al.* [10]. Studies of static heat transfer in narrow channels at atmospheric pressure have been made by Wilson [11], Lehongre *et al.* [12], and Ogata *et al.* [13], for channel thicknesses of 1·0 mm and more. We have already reported on the effect of forced circulation of liquid helium in narrow channels on the improving of the heat transfer [14, 15]. An extensive evaluation and compilation of data concerning general heat transfer problems has been made by Hartnett *et al.* [16].

In the present work we will describe experiments on boiling heat transfer with liquid helium in open pools with particular attention to the effect of surface orientation on the heat transfer. Then we will present results indicating how the heat transfer and its hysteresis is affected when the heated surface is in a narrow channel with the channel thickness of 1·0 mm and less at the atmospheric pressure and under over pressure.

2. EXPERIMENTAL PROCEDURE

The heater element used in these experiments is shown in Fig. 1. It consisted of a cylindrical plug of copper 15 mm o. d. and 10 mm in length with a shoulder around which was wound a heating coil of manganin wire. The manganin keeps a constant electrical resistance in the region of temperature used here. A hole was drilled almost to the polished face of the copper, and in this hole was inserted an accurately calibrated Texas Instruments germanium resistance thermometer. The sensitivity of thermometer for the range of 4·2–5·0°K is stated by the manufacturer to be better than 5 m°K. The platinum leads of the thermometer were placed in the best possible thermal contact with the region whose temperature was measured. Very fine Cu wire, temperature anchored in liquid helium, was used for connections of germanium thermometer to the outside measuring circuits. For given dimensions of the wire and maximum value of maximum nucleate boiling heat flux of 1·142 W/cm^2 used at experiments, the error from heat conduction through these leads was estimated to be less than 10 m°K. The temperature gradient inside the heater element should be less than 5 m°K for given dimensions of element, germanium thermometer, and maximum value of maximum nucleate boiling heat flux.

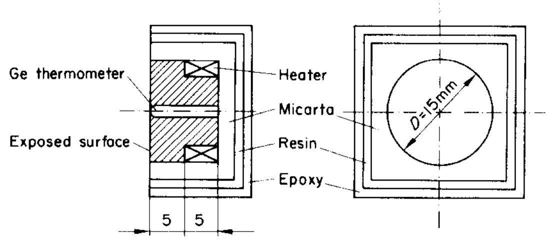

FIG. 1. Schematic diagram of the heater element. The hatched material is copper with a polished face.

Then the maximum temperature shift from all temperature gradients and uncertainties is less than about 20 m°K; that is, for the maximum experimental value of ΔT_{max} this should be less than 4 per cent and for the minimum experimental value it should be less than 10 per cent of the observed value.

The assembly was carefully insulated, except for the polished face with area of heat transfer equal 1·766 cm^2, and placed in liquid helium. Then by measuring the heater power and the temperature indicated by the thermometer, it was possible to deduce the heat flux q/A into the liquid helium as a function of the temperature difference ΔT between the heated surface and the liquid. One run took about one hour; there was sufficient time for proper temperature balance. If repeated immediately, the characteristics obtained were indistinguishable from each other for open pool boiling but the reproducibility decreased for narrow channels. The surface conditions, and the characteristics then too, were slightly changed if measuring apparatus was taken out of liquid helium for a couple of days.

Much experiment was needed to obtain results which were considered to be reliable. The insulation of the heater block must be such that only insignificant heat flows are obtained in regions other than the polished face. Also the shape and size of the block must be such that the temperature measurement is substantially uniform. Otherwise the temperature measurement is misleading, and the curve of q/A against ΔT takes uncharacteristic shapes. The thermometer must be, of course, in good thermal contact with the heater block. The particular heater configuration of Fig. 1 gave satisfactory results, which agreed well with the results of other experiments such as those of Lyon [5]. The face of the heater was highly polished; no measurements of heat transfer as a function of surface roughness were made. (Roughness effects have been studied by Cumming and Smith [7], Butler *et al.* [10] and Boissin *et al.* [17].)

For studies of the dependence of heat transfer on the orientation of the surface the heating element was mounted on a support (with the heater face horizontally up, horizontally down, and sideways in different experiments) and immersed in a pool of liquid helium at atmospheric pressure. The heater power was obtained by a potentiometer measurement of current and voltage, and the temperature by a potentiometer measurement of the voltage across the thermometer with a fixed current. The liquid temperature was deduced from a measurement of atmospheric pressure.

For the experiments on heat transfer in narrow channels a special cryostat was used. This cryostat had two vertical cylindrical containers for liquid helium each having a capacity of about 2·5 l. The two containers were interconnected by a vertical cooling channel which was 50 cm in length. The cooling channel was rectangular in cross-section and accurately machined from a brass flat. The width of the channel was 10 mm in all cases and its thicknesses were 0·3, 0·6 and 1·0 mm. The same heater element used before was inserted in the wall of the channel, in the lower container about 1 in. from the mouth of the channel.

3. DEPENDENCE OF HEAT TRANSFER ON SURFACE ORIENTATION

In Fig. 2 are shown data for heat transfer in an open pool of liquid helium at 1 atm. Curve 1 is for the heated surface horizontal facing upwards, curve 2 for the surface vertical facing sideways, and curve 3 for the surface horizontal facing downwards. Curve 4, inserted for the purpose of comparison, is for the heater element in a vertical cooling channel of thickness 1·0 mm The data of Fig. 2 are quite reproducible points from various tests falling along the appropriate line.

Examining curve 1 we can see the characteristic features of heat transfer to a liquid. The flat portion from $\Delta T = 0$ to about 200 m°K corresponds to heat transfer with natural convection of the liquid. The steeper part of the curve above 200 m°K is the region of nucleate boiling. In this region bubbles form on the surface, detach themselves, and move away in the liquid. As ΔT increases, the heat flux increases to a maximum at which point there is a sudden transition to the film boiling region (not shown on Fig. 2) at a much larger ΔT but with about the same heat flux.

Figure 2 shows a marked dependence on the surface orientation. The upwards surface gives a maximum heat flux about 1·5 times better than the sideways surface, and about 7·5 times better than the downwards surface. It is obvious that such a dependence must exist; a downwards surface and the gravitational acceleration will considerably hinder the process of bubble

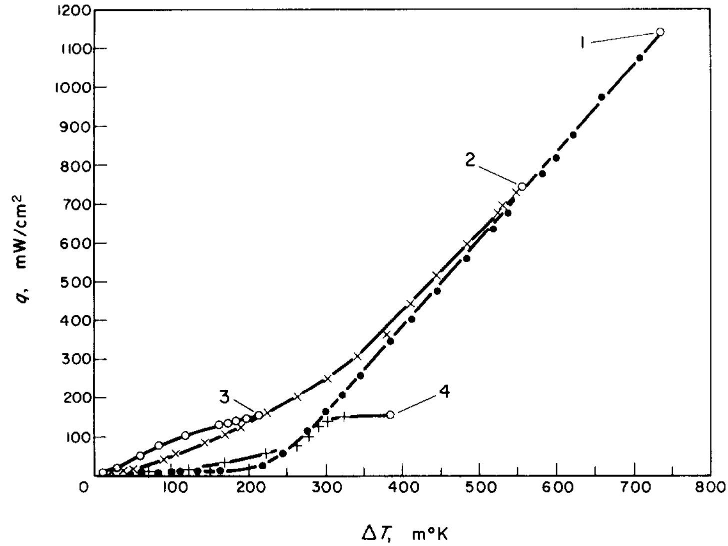

FIG. 2. Nucleate boiling to liquid helium at 1 atm in an open pool for different orientations of the heater surface. Curves 1, 2 and 3 are for the surface upwards, sideways, and downwards. Curve 4 is for a rectangular channel.

detachment, and bubble collection will hasten the transition to film boiling. The orientation dependence is also dependent on the relative size of bubble and heated surface. If the two are about the same size the orientation dependence is less important, Bernath [22] and Carne [25].

4. HEAT TRANSFER IN NARROW CHANNELS WITHOUT AND WITH AN OVERPRESSURE

In Fig. 3 are shown data for static heat transfer (at 1 atm) in vertical channels (50 cm in length) of three different thicknesses 0·3, 0·6 and 1·0 mm. The data for the 1·0 mm channel are also plotted on Fig. 2 for comparison. The results are of qualitative importance in that they indicate the degradation of heat transfer caused by bubble entrapment. The reproducibility of the maximum q and ΔT decreases as the channel size decreases. For the 1·0 mm channel the maximum q is reproducible to perhaps 5 per cent, but for the 0·3 channel the maximum q varied between 40–70 mW/cm^2. Such a large variation from run to run is consistent with the trapping of bubbles.

Other results on heat transfer with liquid helium in narrow channels have been given by Wilson [11], who demonstrated the relationship of Sydoriak and Roberts [18] indicating a variation of maximum heat flux with $w/z^{\frac{1}{4}}$ where z is the channel height and w the channel width.

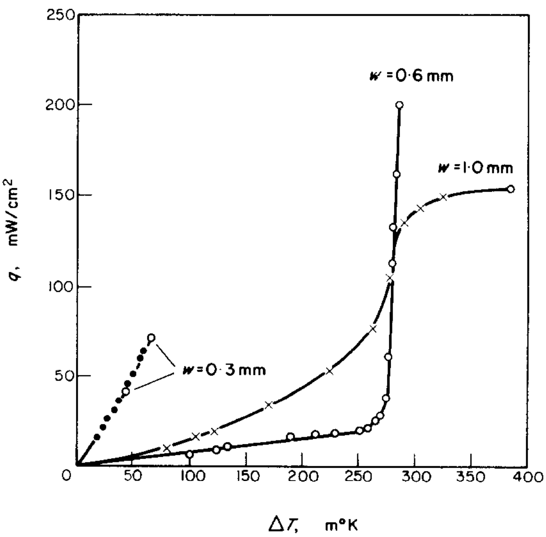

FIG. 3. Heat transfer with no forced circulation to liquid helium in rectangular channels of 1 cm width, 50 cm length, and thicknesses of 1·0, 0·6 and 0·3 mm.

Our results appear to be in rough agreement with Wilson's, but it is not quite useful to compare the two sets since his were taken for channels heated over their whole length.

The effect of pressure on the heat transfer is shown in Fig. 4, which gives data for static heat transfer in the vertical channel of 1·0 mm thickness at various pressures above atmospheric. Data exist for pressure effects on open pool heat transfer, see Smith [3], but apparently none exist for channels. From Fig. 4 it can be seen that the convection region is not greatly affected, nor apparently is the maximum ΔT. However the nucleate boiling region and the maximum heat flux for nucleate boiling is considerably affected. The important parameter here is the relative size of bubble and channel. Although the temperature of the liquid rises with pressure, the bubble size decreases. Then the heat transfer is not much affected until the bubbles become smaller than the channel and can detach themselves easily, at which point the heat transfer might be expected to increase. This hypothesis is made somewhat plausible by a comparison of the data of Figs. 4 and 2. In Fig. 4 an overpressure of 60 torr has relatively little effect on the heat transfer, whereas an overpressure of 175 torr increases the maximum nucleate heat flux to about 500 mW/cm^2. This value is comparable to the 730 mW/cm^2 maximum shown on Fig. 2 for the vertical heating surface in an open pool.

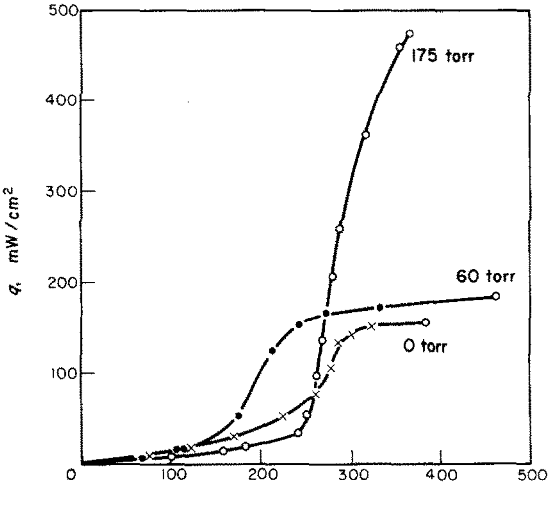

FIG. 4. The effect of pressure on heat transfer in the 1·0 mm channel.

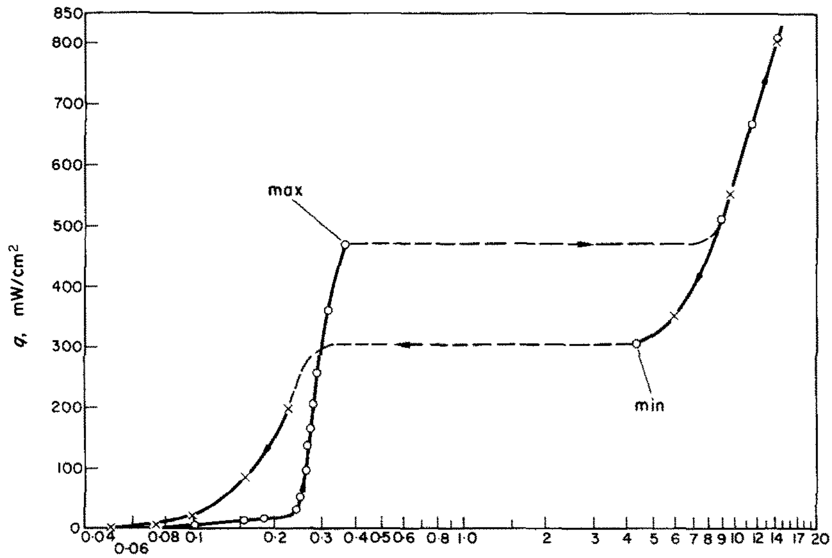

FIG. 5. The transition to the film boiling region, and hysteresis in the recovery of nucleate boiling with an overpressure of 175 torr.

5. HYSTERESIS OF HEAT TRANSFER IN NARROW CHANNELS WITH AN OVERPRESSURE

In Fig. 5 is shown the static heat transfer characteristic in a channel of width 1·0 mm with an overpressure of 175 torr. For ΔT increasing from zero the convective region is found up to $\Delta T \cong 0{\cdot}2°K$. Then there is the steeper nucleate boiling region between $\Delta T = 0{\cdot}25$–$0{\cdot}35°K$. A maximum nucleate boiling heat flux is observed of about 500 mW/cm^2 (for this particular case). Then there is a sudden transition to the film boiling region at a ΔT of about 8°K with a slightly higher heat flux. The film boiling region is reversible in the sense that the heat flux is the same for ΔT's increasing and decreasing. At a minimum ΔT of about 5°K there is a sudden transition back to nucleate boiling, but along a different line than for ΔT increasing.

Similar hysteresis effects in the nucleate boiling region for open pool boiling helium have been observed elsewhere; Lyon [5], Thibault *et al.* [6] and Cummings and Smith [7].

6. COMPARISON OF PRESENT EXPERIMENTS TO EXISTING THEORIES

It is of interest to compare these data with equations developed on a theoretical basis. According to Kutateladze [19] the maximum nucleate boiling heat transfer in a liquid is given by

$$q_{\max} = K\lambda\left[g\varphi_v\left(1 + \frac{\varphi_v}{\varphi_1}\right)\right]^{\frac{1}{2}}[\sigma(\varphi_1 - \varphi_v)]^{\frac{1}{4}} \quad (1)$$

where K is a numerical constant obtained by Zuber [20]. Using data for liquid helium at 4·2°K, this equation gives $0{\cdot}575 < q_{\max} < 0{\cdot}760$ W/cm^2. This is of the same magnitude as the results shown in Fig. 2 for the heater surface vertical or horizontal facing upwards in the open pool. The equation does not give a good comparison with experiment when the heater surface is horizontal facing downward, but this is only to be expected as in that case the process of bubble detachment must be different.

The shape of the heat transfer curve is in the form $q = f(\Delta T^n)$. For free convection with laminar flow Jakob [21] gives

$$q = 0{\cdot}61\left[\frac{k_l^3\varphi_l^2 g\beta C_{pl}}{L\mu}\right]^{\frac{1}{4}}\Delta T^{\frac{5}{4}} \quad (2)$$

and for free convection with turbulent flow

$$q = 0{\cdot}16\left[\frac{k_l^2\varphi_1^2 g\beta C_{pl}}{\mu}\right]^{\frac{1}{3}}\Delta T^{\frac{4}{3}}. \quad (3)$$

In the region of nucleate boiling

$$q = 4{\cdot}87 \times 10^{-11}\left(\frac{C_{pl}}{\lambda\varphi_v}\right)^{\frac{3}{2}}\left(\frac{k_l\,\varphi_l^{1{\cdot}282}\,p^{1{\cdot}750}}{\sigma^{0{\cdot}906}\,\mu^{0{\cdot}626}}\right)\Delta T^{2{\cdot}5}. \quad (4)$$

The experimental results for the exponent n in ΔT^n and for the maximum heat flux in nucleate boiling are shown in Table 1. As was mentioned previously $q_{\max}$ calculated from (1) is in reasonable agreement with experiment for

Table 1. Comparison of experimental data with theoretical correlations for boiling heat transfer

The arrangement of the measuring apparatus		ΔT^n: n free convection	ΔT^n: n nucleate boiling	$q_{\max}$ (mW/cm^2)
Surface orientation	facing upwards	1·27	3·0	1140
	facing downwards	2·15	no visible transition	150
	facing sideways	1·25	2·25	740
Channels without liquid helium transfer	channel 1·0 mm width	1·73	5·5	155
	0·6	1·53	19·5	200
	0·3	1·12	12·5	50–70
Effect of pressure in 1 mm channel	0 torr	1·73	5·5	155
	60 torr	2·09	4·2	160
	175 torr	1·73	14·2	470

two of the open pool boiling cases. Similarly the exponents $n = 1{\cdot}25$ for laminar free convection and $n = 2{\cdot}5$ for nucleate boiling are found when the heater is vertical or horizontal upwards in the open pool. The existing theories thus give a good representation of experiment for the simple cases of open pool boiling. By evaluating data of other authors for liquids other than liquid helium, Bernath [22] came to the conclusion that the value of vertical maximum nucleate boiling heat flux should be about three quarters of that for a horizontal position of the heater. Our results agree also with this conclusion which indicates that liquid helium (at about 4·2°K) may be regarded as an ordinary liquid as far as boiling heat transfer properties are concerned.

For the more complicated cases of boiling, with the heater element facing downwards or in a channel, the comparison of our results with the above mentioned equations does not give satisfactory results. For the downwards position, vapor patches are created if the area of heat transfer is large enough, thus lowering efficiency of cooling. As was found by Ivey and Morris [23], Costello and Frea [24], and Carne [25], there is an apparent geometry influence of the heater diameter for diameters less than about 5 mm. In our case for a flat heater this would mean that with decreasing diameter, the orientation dependence would decrease also. In the free convection region for heat transfer in the channels, the exponent n seems to be about 1·75 as compared to 1·25 in (2). In the nucleate boiling region n varies from about 5 to about 20, and obviously (4) does not apply. It is interesting therefore to compare the data for different channels as shown in Table 1 and Fig. 3. First it can be noticed that there is not much difference between the 0·6 and 1·0 mm channels. The maximum heat fluxes are about the same, as are the temperature differences, and the transition to nucleate boiling occurs at the same temperature. However the results are quite different for the 0·3 mm channel. In the open pool, as a consequence of the departure of bubbles from the heated surface, so-called "natural" bubble velocities exist and bubble trajectories are unhindered. In narrow channels the decreasing hydraulic diameter has a blocking effect on bubble motion. In our case this situation occurs for channel thicknesses between 0·3 and 0·6 mm. Thus the thinner channel becomes choked with bubbles, which causes a considerable deterioration of the heat transfer. The increasing of pressure in the case of heat transfer in narrow channels means effectively the enlarging of the hydraulic diameter and therefore the lowering of the bubble blocking effect.

7. APPLICATION TO MAGNET DESIGN

The main use of heat transfer with liquid helium is for the cooling of superconductive devices, and it is of interest to discuss the results in that light. We can see that the magnet can be operated only in the nucleate boiling region, from 4·2°K to about 5°K with the liquid at atmospheric pressure. An increase in heat flux above what is available from nucleate boiling in this region, causes a transition to a film boiling state at about 15°K; at this temperature a magnet will most probably be normal.

The maximum heat flux varies from about 1 W/cm^2 under the best conditions to about 0·1 W/cm^2 in a small channel. Edge cooling of horizontal pancakes is an ineffective way of cooling a magnet, giving a maximum heat flux of 0·1–0·3 W/cm^2 at most. In an edge cooled system care should be taken to avoid the trapping of gas pockets. For vertical channels the heat transfer can be considerably improved by operating the liquid above atmospheric pressure; this improvement is caused by a reduction in bubble size leading to better bubble clearance from the channel.

REFERENCES

1. E. G. Brentari and R. V. Smith, Nucleate and film pool boiling design correlations for O_2, N_2, H_2 and He, *Int. Adv. Cryogen. Engng* **10**, Part 2, 325–341 (1965).
2. D. N. Lyon, Pool boiling of cryogenic liquids, *Chem. Engng Prog. Symp. Ser. No.* 87, **64**, 82–92 (1968).

3. R. V. SMITH, Review of heat transfer to helium I, *Cryogenics* **9**, 11–19 (1969).
4. A. P. DOREY, Heat transfer at low temperature, *Cryogenics* **5**, 146–151 (1965).
5. D. N. LYON, Boiling heat transfer and peak nucleate boiling fluxes in saturated liquid helium between the λ and critical temperatures, *Adv. Cryogen. Engng* **10**, Part 2, 371–379 (1965).
6. J. J. THIBAULT, J. ROUSSEL et E. FADDI, Echange thermique avec ébullition dans l'hélium liquide, Bull. IIR, Meeting of Comm. I, Grenoble, pp. 249–258 (1965).
7. D. R. CUMMINGS and J. L. SMITH, Boiling heat transfer to liquid helium, Bull. IIR, Meeting of Comm. I, Boulder, Colorado, pp. 85–94 (1966).
8. V. E. KEILIN, E. YU. KLIMENKO and I. A. KOVALEV, Device for measuring pressure drop and heat transfer in two-phase helium flow, *Cryogenics* **9**, 36–38 (1969).
9. K. R. EFFERSON, Heat transfer from cylindrical surfaces to liquid helium I, *J. Appl. Phys.* **40**, 1995–2000 (1969).
10. A. P. BUTLER, G. B. JAMES, B. J. MADDOCK and W. T. NORRIS, Improved pool boiling heat transfer to helium from treated surfaces and its application to superconducting magnets, *Int. J. Heat Mass Transfer* **13**, 105–115 (1970).
11. M. N. WILSON. Heat transfer to boiling liquid helium in narrow vertical channels, Bul. IIR, Meeting of Comm. I, Boulder, Colorado, p. 109 (1966).
12. S. LEHONGRE, J. C. BOISSIN C. JOHANNÈS and A. DE LA HARPE, Critical nucleate boiling of liquid helium in narrow tubes and annuli, Proc. of Second Int. Cryogenic Eng. Conf., Brighton, pp. 274–275 (1968).
13. H. OGATA, M. KENMOCHI, S. SATO and H. KIMURA, Boiling heat transfer to liquid helium in long narrow channels, *Cryogenic Engng (in Japanese)* **4**, 219–225 (1969).
14. M. JERGEL and R. STEVENSON, Heat transfer to liquid helium in narrow channels with laminar and turbulent flow, *Appl. Phys. Letters* **17**, 125 (1970).
15. M. JERGEL, R. STEVENSON and K. HECHLER, Heat transfer to liquid helium in narrow channels with forced flow of liquid, Paper presented at the IIR Comm. I Meeting, Tokyo 11–12 Sept. (1970).
16. J. P. HARTNETT, E. R. G. ECKERT, H. S. MICKLEY and R. L. PIGFORD, *Recent Advances in Heat and Mass Transfer*. McGraw-Hill, New York (1961).
17. J. C. BOISSIN, J. J. THIBAULT, J. ROUSSEL and E. FADDI, Boiling heat transfer and peak nucleate boiling flux in liquid helium, *Adv. Cryogen. Engng* **13**, 607–616 (1968).
18. S. G. SYDORIAK and T. R. ROBERTS, Study of the boiling in short narrow channels and its application to design of magnets cooled by liquid H_2 and N_2, *J. Appl. Phys.* **28**, 143–148 (1957).
19. S. S. KUTATELADZE, *Fundamentals of Heat Transfer*. Edward Arnold, London (1963).
20. N. ZUBER, Hydrodynamic aspects of boiling heat transfer, AECU 4439 (1959).
21. M. JAKOB, *Heat Transfer*, Vol. 1. John Wiley, New York (1959).
22. L. BERNATH, A theory of local-boiling burnout and its application to existing data, *Chem. Engng Prog. Symp. Ser. No.* 30, **56**, 95–116 (1960).
23. H. J. IVEY and D. J. MORRIS, Paper presented at the A.I.Ch.E. Annual Meeting, Chicago (December 1962).
24. C. P. COSTELLO and W. S. FREA, A salient nonhydrodynamic effect on pool boiling burnout of semicylindrical heaters, *Chem. Engng Prog. Symp. Ser. No.* 57, **56**, 258–268 (1965).
25. M. CARNE, Some effects of test section geometry in saturated pool boiling on the critical heat flux for some organic liquids and liquid mixtures, *Chem. Engng Prog. Symp. Ser. No.* 59, **61**, 281–289 (1965).

TRANSFERT THERMIQUE PERMANENT À L'HÉLIUM LIQUIDE DANS DES RÉSERVOIRS OUVERTS ET DES CANAUX ÉTROITS

Résumé—Le transfert de chaleur à l'hélium liquide bouillant a été mesuré dans des réservoirs ouverts et des canaux étroits. Dans les réservoirs ouverts on observe une dépendance marquée du transfert thermique à l'orientation de la surface chauffée. Le flux maximal pour l'ébullition nucléée varie de 1 W/cm^2 pour la surface horizontale tournée vers le haut, à environ 0,1 W/cm^2 pour la surface horizontale tournée vers le bas. Dans un canal étroit et vertical le flux maximal est réduit à 0,15 W/cm^2 environ pour un canal rectangulaire 10 mm $\times$ 1 mm (50 cm de longueur) et il apparait décroître linéairement avec la dimension du canal. L'aptitude au transfert thermique du canal étroit est considérablement accrue quand le fluide est pressurisé.

STATIONÄRER WÄRMEÜBERGANG AN FLÜSSIGES HELIUM IN OFFENEN BEHÄLTERN UND ENGEN KANÄLEN

Zusammenfassung—Es wurde der Wärmeübergang an siedendes Flüssighelium in offenen Behältern und engen Kanälen gemessen. In offenen Behältern wurde eine auffallende Abhängigkeit des Wärmeüberganges von der Orientierung der Heizfläche beobachtet.

Die maximale Wärmestromdichte ändert sich von 1 W/cm^2, für die horizontal nach oben gerichtete Heizfläche auf 0·1 W/cm^2, für die horizontal nach abwärts gerichtete Heizfläche. In einem engen vertikalen Rechteckkanal 10 mm $\times$ 1 mm (50 cm Länge) vermindert sich die maximale Wärmestromdichte auf etwa 0·15 W/cm^2 und nimmt anscheinend linear ab mit den Kanalabmessungen. Der Wärmeübergang lässt sich bei einem engen Kanal beträchtlich steigern durch Erhöhen des Flüssigkeitsdrucks.

СТАТИЧЕСКИЙ ПЕРЕНОС ТЕПЛА К ЖИДКОМУ ГЕЛИЮ В БОЛЬШОМ ОТКРЫТОМ ОБЪЕМЕ И УЗКИХ КАНАЛАХ

Аннотация—Измерялся перенос тепла к кипящему жидкому гелию в больших открытых объёмах и узких каналах. В больших открытых объёмах наблюдается значительная зависимость переноса тепла от расположения поверхности нагрева. Максимальный тепловой поток при пузырьковом кипении изменяется от I ватт/см^2 (на нагреваемой горизонтальной поверхности, обращённой вверх), до приблизительно 0,1 ватт/см^2 (на горизонтальной поверхности, обращённой вниз). В узком вертикальном канале максимальный тепловой поток уменьшается до примерно 0,15 ватт/см^2 для прямоугольного канала размером $10 \times 1{,}0$ мм (50 см длиной), и оказывается, что он линейно уменьшается с уменьшением размера канала. Способность узкого канала к переносу тепла знаuительно увеличивается, если жидкость находится под давлением.