Peak Nucleate Boiling Fluxes for Liquid Oxygen on a Flat Horizontal Platinum Surface at Buoyancies Corresponding to Accelerations Between -0.03 and $1g_E$

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Peak nucleate boiling fluxes for liquid oxygen near 1 atm. have been measured on a 0.75-in.–diameter flat polished horizontal platinum surface located in a known, variable magnetic-field gradient that produced steady accelerations (which could be maintained indefinitely) on the oxygen acting in opposition to the earth's gravitation, g_E. Measurements were made under conditions ranging from net negative (directed away from the heated surface) accelerations of $-0.03g_E$ acting on the *bulk liquid* to the normal accelerations, $1.0g_E$. The results indicate that at zero *g* conditions for the bulk liquid, the peak nucleate boiling flux is ~0.55 of the value at $1.0g_E$. For bulk-liquid accelerations ranging from ~0.25 to $1g_E$, the experimental results confirm the ¼ power dependence of peak flux on acceleration as predicted by various correlations. However, below $0.25g_E$ the peak flux becomes insensitive to the acceleration, varying approximately in proportion to the 1/14 power of the net acceleration. At bulk-liquid conditions of zero *g* ($\pm 0.005g_E$) the peak flux breaks sharply and falls by a factor of 10 between zero *g* and $-0.03g_E$ (for this apparatus).

Interest in the effect of acceleration upon boiling heat transfer stems not only from the test it affords for the theories advanced to explain the boiling process, but from the practical need for reliable rules for heat transfer design purposes in orbiting vehicles, superconducting magnets, and other equipment where the boiling fluid experiences an acceleration markedly different from the earth's gravitational acceleration, in particular where acceleration is essentially zero.

Various investigators (*1* to *3*) have reported upon the effects of multiple g_E accelerations in boiling heat transfer. Usiskin and Siegel (*4*) measured peak nucleate boiling fluxes (burnout) for distilled water on horizontal 0.0453-in.–diameter platinum wires at various accelerations between zero and g_E, obtained from controlled drop rates of the apparatus. For free fall (zero g) they observed peak fluxes ranging from 0.3 to 0.45 of the peak flux in normal gravity. For accelerations between 0.06 and $0.28g_E$, their peak fluxes fell consistently above a curve corresponding to a $g^{1/4}$ dependence. Since the duration of fall was about 1 sec., Usiskin and Siegel concluded that the uncertainty due to transient effects would not allow the conclusion of a definite disagreement with the $g^{1/4}$ dependence predicted by the correlations of Kutateladze (*5*), Zuber and Tribus (*6*), and others.

Merte and Clark (*7*) reported transient heat transfer measurements between boiling nitrogen and a 1-in.–diameter copper sphere in free fall (zero g) and at normal gravity. The time of free fall was ~1.4 sec., during which, they report, accelerometer readings were less than $0.01g_E$. The measured P.N.B.F. (peak nucleate boiling flux) in free fall was 0.35 to 0.45 of that at normal gravity.

Sherley (*8*) reported heat transfer data for liquid hydrogen at standard and zero gravity. The reduced accelerations were obtained in a free-fall apparatus (1-sec. duration) and in apparatus borne in a KC135 jet aircraft in parabolic flight path (15-sec. duration). The free-fall drop tower tests indicated a P.N.B.F. of 0.5 to 0.7 of that for standard gravity. Peak fluxes for the longer aircraft-borne tests were reported only for the heater facing downward. No tests were reported for this orientation in standard gravity.

The results of all three investigations indicate a finite P.N.B.F. at zero acceleration and roughly agree as to its magnitude relative to that in normal gravity; all are subject to uncertainty stemming from the transient nature of the tests and from doubt over the actual value of acceleration attained in free fall.

For some time it has been planned to use the magnet facilities of the Low Temperature Laboratory of the University of California to investigate boiling heat transfer at very low net accelerations, as these could be maintained indefinitely so as to eliminate the uncertainty introduced by the transient nature of drop-tower experiments.

If a material of magnetic susceptibility χ, per unit mass, is situated in a region of magnetic field of strength H and gradient (dH/dx) along the earth's gravitation vector, the net acceleration α acting upon a unit mass of material in the vertical direction will be

$$\alpha_{net} = g_E + \frac{\chi}{2} (dH^2/dx) \qquad (1)$$

With a suitable magnetic field, it is possible to vary the net acceleration on a given fluid from negative to multiple g_E values.

Two requirements of such an experiment merit comment. To achieve a magnetic acceleration equal to or greater than g_E over a significant volume with available diamagnetic fluids will require fields of 100,000 oersteds, or greater. The characteristics of the existing vertical 5-in.–bore, 94.5-kg.–air-core solenoid LTL-III [similar to the 4 in., 100-kg. solenoid LTL-II described by Giauque and

Lyon (9)] are such that net accelerations of approximately $0.18g_E$ with methane, $0.24g_E$ with hydrogen, and $0.47g_E$ with ethylene are the lowest currently attainable with diamagnetic fluids. The test at very small net accelerations for diamagnetic fluids will require the construction of a solenoid with a greater field or field gradient or both than LTL-II and LTL-III have. For a given air-core solenoid magnet (dH^2/dx) will be proportional to H^2, so that for a material of constant susceptibility

$$\alpha = g_E + CH^2 \qquad (2)$$

from which one calculates that the necessary stability in magnetic field (dH/H), corresponding to an acceptable fluctuation in acceleration $d\alpha$, is given by

$$(dH/H) = d\alpha/2\,(\alpha - g_E) \qquad (3)$$

If one wishes to operate at $\alpha = 0.01g_E$ with fluctuations of less than $0.001g_E$ (10%), the necessary stability in magnetic field corresponds to a few parts in 10^4. This is easily attainable with the recently completed current-control system (*10*) for the Low Temperature Laboratory magnet power supply.

Preferably, the susceptibility of the boiling fluid should be independent of temperature and be identical in both liquid and vapor phases. In general, this will be true for diamagnetic materials but not paramagnetic. This paper gives the results of measurements with liquid oxygen made to investigate the feasibility of the method. The large paramagnetic susceptibility of oxygen makes it easy to produce a magnetic acceleration equal to or greater than g_E with existing equipment; however, the mass susceptibilities differ in the liquid and vapor phases, and both are temperature dependent.

If one considers a material with liquid density ρ_l, vapor density ρ_v, and a liquid mass susceptibility $\chi_l = \chi_v + \Delta\chi$, where χ_v is the mass susceptibility of the vapor, the net acceleration acting upon the vapor will be given by

$$\alpha = -\left(\frac{\rho_l - \rho_v}{\rho_v}\right)\left[g_E + \frac{\chi_l}{2}\,(dH^2/dx) + \frac{\rho_v}{(\rho_l - \rho_v)}\,\frac{\Delta\chi}{2}\,(dH^2/dx)\right] \qquad (4)$$

as opposed to

$$\alpha = -\left(\frac{\rho_l - \rho_v}{\rho_v}\right)\left[g_E + \frac{\chi_l}{2}\left(\frac{dH^2}{dx}\right)\right] \qquad (5)$$

for the case of constant mass susceptibility. (Accelerations directed *toward* the heated surface are considered *positive.*) For oxygen at its normal boiling point,

$\rho_l = 1.14$ g./cc.; $\rho_v = 0.00446$ g./cc.;
$\chi_l = 241 \times 10^{-6}$ erg/(gauss^2) g.
$\chi_v = 350 \times 10^{-6}$ erg/(gauss^2) g. or
$\Delta\chi = -109 \times 10^{-6}$ erg/(gauss^2) g.

so that the *vapor* acceleration will be 0.0018 of its value in normal gravity conditions when the net acceleration acting upon the liquid phase is zero, and will become zero when the acceleration on the liquid is $-0.0018g_E$, as opposed to the case of equal liquid and vapor mass susceptibility, for which liquid and vapor accelerations become zero simultaneously.

The temperature dependence of the susceptibilities is considerably more serious. Onnes and Perrier (*11*) give for the specific susceptibility of liquid oxygen

$$\chi_l = 2284 \times 10^{-6}\,(T)^{-1/2}\ \text{erg/(gauss}^2\text{) g.} \qquad (6)$$

The data of Woltjer et al. (*12*) for oxygen at a density of 0.0045 g./cc. give

$$\chi_v = 315 \times 10^{-4}\,(T)^{-1}\ \text{erg/(gauss}^2\text{) g.} \qquad (7)$$

Since at peak flux, even at small net accelerations, the surface temperature might well be about 100°K. for a bulk liquid temperature of 90°K., χ_l could range from 228×10^{-6} electromagnetic units at the surface to 241 in the bulk liquid, or from a net acceleration of zero in the bulk liquid to $0.054g_E$ in immediate contact with the platinum surface. It is quite improbable that the liquid temperature even approaches the surface temperature for any distance into the liquid at all comparable with the dimensions of a detaching bubble, so that liquid accelerations corresponding to the platinum surface temperature would be an unrealistic upper limit.

It is also necessary to establish the effect, if any, of a homogeneous magnetic field upon the P.N.B.F.

EXPERIMENTAL APPARATUS

The apparatus consisted of a 0.750-in.-diameter circular, flat thermometer-and heater-equipped platinum surface in contact with a bath of liquid oxygen, so positioned in the magnet that (dH^2/dx) was constant to ± 1% over a vertical distance of 4 cm.

The heated test element was installed in the bottom of a cylindrical brass container for the liquid oxygen. Liquid nitrogen was circulated through a condensing coil located in the vapor space of the condenser so that the buildup of impurities on the heated test surface (with their effect on its heat transfer characteristics), which accompanies open-loop operation (*13*) with liquid oxygen, was avoided. Bulk-liquid temperature was monitored with copper-constantan thermocouples, and auxiliary heaters maintained constant bulk-liquid temperature. The experimental vessel was suspended in an evacuated container for thermal insulation. The schematic arrangement is shown in Figure 1.

The test element proper (*A*), shown in Figure 2, consisted of two 0.750-in.–diameter electrolytic tough-pitch copper cylinders 1¾ and 1⅜ in. long, silver soldered end to end with a ⅛-in.–thick wafer of silicon bronze (*B*) between them to increase the effective "thermal" length between heater and surface and thus the temperature uniformity. The lower (1¾-in.) copper cylinder was drilled axially to a depth of 1½ in. to accept a Chromalox nominal 50-w. cartridge heater (*C*), which was soldered in place with pure tin. Three thermocouple wells (*D*) were drilled radially (at an angle of 15 deg. to the horizontal plane) so as to position thermocouples nominally at 0.08, 0.45, and 0.86 in. from the metal–liquid-oxygen interface along the axis of the cylinder. Because of the finite diameter of the wells and the uncertainty of the exact location of the junction along the length of the couples, the distance between any given junction and the surface is estimated to be uncertain by ± 0.04 in.

To minimize heat loss from the test element to the body of the brass vessel by direct conduction, the test element was

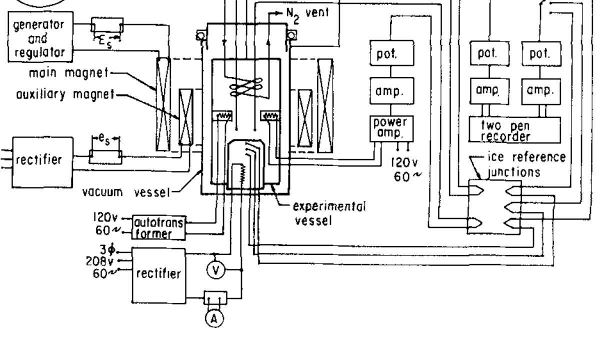

Fig. 1. Schematic arrangement of experimental apparatus.

soft-soldered into an insulated reentrant silicon bronze [$k \approx 0.15$w./(cm.)(°K.)] cylinder (E) of 1⅛ in. O.D., 0.025-in. wall, and 1¾-in. length. The joint between the test element and bronze cylinder was located 1/16 in. below the oxygen–test-surface interface. The annular volume between the wall of the container and the supporting bronze cylinder and test element was filled with blocks machined from silicone-resin-bonded fiberglass (F) [$k \sim 0.006$w./(cm.)(°K.)]. (Tests indicated that it was necessary to heat the resin-bonded fiberglass above 700°C. to obtain combustion when it was dropped into liquid oxygen.)

The fiberglass-insulated copper-constantan wires of the thermocouples were wrapped around the test element for ~ 3 turns immediately before entering their respective wells to provide tempering. They were insulated from contact with the heated end of the test element as much as possible.

The condensing coil (G) of 4.5 ft. of ¼-in. O.D. × 0.31-in. wall copper tubing wound in two concentric helices was located in the upper (vapor) space of the container in a region where net acceleration was never less than $0.5g_E$. A tapering conical baffle below the condenser deflected condensate to the wall to prevent its falling directly into the liquid just above the test surface.

Two nominal 50-w. Chromalox cartridge heaters (H) were soldered into copper wells that protruded into the liquid space 1¾ in. above the test surface. They were used to maintain constant bulk-liquid temperature in spite of fluctuations in refrigerant flow through the condensing coil and varying heat input to the test surface.

Two copper-constantan thermocouples (J) were positioned in a plane ¾ in. above the test surface. Their junctions were embedded in solder plugs that sealed the ends of ⅛-in. O.D. copper tubes that served as conduits for removing the thermocouple leads from the apparatus. The final 6-in. length of the conduits was wound into a horizontal spiral in the plane at the elevation of the thermocouple junction to provide tempering. One thermocouple was used to provide the primary record of bulk-liquid temperature for the determination of ΔT's between test surface and liquid; the second thermocouple was used together with a reference potentiometer to provide error signal for a power-amplifier system that fed one of the auxiliary Chromalox heaters for bulk-liquid temperature control.

A central ½-in. O.D. brass tube (K) served to suspend the experimental vessel from a brass cover plate and to provide connection to a manifold which included a safety valve, pressure gauge, and connections for evacuating or charging the experimental vessel (Figure 1).

A tubular flange on the cover plate slides in an O-ring seal on the flange of the vacuum jacket to provide for vertical motion of the experimental vessel so that the test surface can be optimally positioned in the magnetic-field gradient or located at the midplane of the magnet (zero gradient) to measure the effect of a static magnetic field upon the peak flux.

The geometrical characteristics of solenoid LTL-III are such that the maximum value of (dH^2/dx) occurs roughly 18 cm. below the midplane of the coil and is constant to ± 1% over an axial distance of roughly 1 cm. In order to increase the volume over which essentially uniform magnetic acceleration pertained, an auxiliary solenoid was constructed, the wall of the insulating case for the experimental vessel being used as a mandrel, whose maximum $d(H^2)/dx$ was displaced from that of LTL-III. Thus, for the two coils combined, magnetic acceleration was constant to ± 1% over the region from ~ 13 to 17 cm. below the midplane of LTL-III for a situation in which the auxiliary coil was contributing roughly 2% of the total magnetic field. The details of construction of the auxiliary magnet are given by Jones (*14*).

The magnetic acceleration was determined in two independent ways.

The magnetic field was measured as a function of vertical position for the principal and for the auxiliary magnet by measuring (with a Dymec 201-A integrating digital voltmeter of 0.01% accuracy) $\int$Edt (volt-sec.) generated in a search coil of accurately known turn area corresponding to a given change in potential drop (E_s or e_s, Figure 1) across the shunt which measured magnet current for the respective coils. The results for $(H_{total}/E_s)^2$ as a function of axial position were differentiated (to an estimated accuracy of 1%) and combined with the magnetic susceptibility results of Onnes and Perrier to give the magnetic acceleration in the space above the test surface occupied by liquid. (The current in the auxiliary solenoid as measured by e_s was at all times maintained at a fixed ratio to that in the main solenoid, so that the magnetic acceleration could be expressed in terms of the potential drop, E_s volts, across the reference shunt for the main solenoid.) The result for liquid 16.2 cm. below the midplane of the main magnet at T°K. was

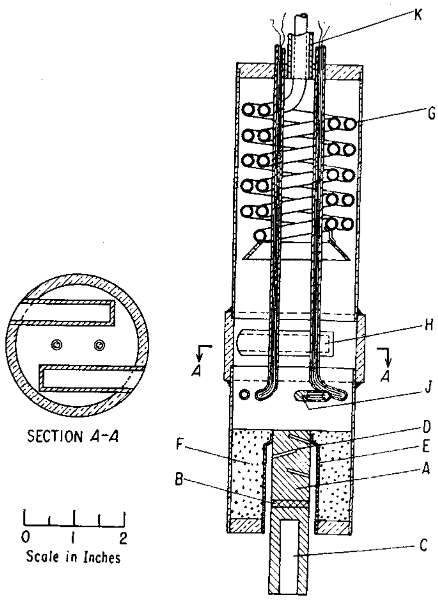

Fig. 2. Details of experimental vessel.

$$g_{\text{magnetic}} = -386 \times 10^3 (E_s)^2/(T)^{1/2} \text{ cm./sec.}^2 \qquad (8)$$

Details concerning magnetic field mapping are given by Ritter (*15*).

The magnetic acceleration on the liquid oxygen can also be determined from the weights of a test body located in a vacuum (w_{vacuo}) and suspended in liquid oxygen (w_{O_2}) at the magnetic field in question and in zero field. The magnetic acceleration for the liquid will be given by

$$g_{\text{magnetic}} = g_E x \frac{[w_{\text{vacuo}} - w_{O_2}]_H - [w_{\text{vacuo}} - w_{O_2}]_{H=0}}{[w_{\text{vacuo}} - w_{O_2}]_{H=0}} \qquad (9)$$

An oblate spheroidal test body with a diameter of 1.9 cm. and a height of 0.5 cm. was machined from OFHC copper. It was suspended from the beam of a chemical balance (built of completely nonferromagnetic materials throughout to facilitate its use in magnetic fields) by a No. 40 B. and S. gauge copper wire. The *vacuo* weights of the test piece were obtained from its observed weights in nitrogen gas at 25°C. at various positions along the axis of the magnet in various fields. The observed weights in liquid oxygen were corrected for buoyancy forces on that portion of the suspension wire that was submerged in liquid. The magnetic acceleration was found to be quite accurately proportional to the square of the magnet currents (magnetic field), indicating, as Onnes and Perrier found, that the susceptibility of oxygen is independent of magnetic field over the ranges used here. Results obtained with the test weight centered at 16.5 cm. below the midplane of the magnet are given in Table 1.

Weighings in the immediate vicinity of $g_{\text{magnetic}} = -g_E$ were inaccurate. This appeared to be due to the growth of large bubbles that rose very slowly through the liquid, creating disturbances so that the beam position and apparent weight were highly uncertain.

The results for liquid acceleration as a function of vertical position with respect to the midplane of the main magnet are

TABLE 1. MAGNETIC ACCELERATIONS FOR LIQUID OXYGEN AT 90.10°K. AT 16.5 CM. BELOW MIDPLANE OF MAIN MAGNET

$g_E = 979.97$ cm./sec.^{2}

Main magnet shunt voltage, E_s, volts	$\dfrac{-g_{(\mathrm{magnetic})}}{g_E}$	$\dfrac{-g_{\mathrm{mag}}}{\text{dynes/(volt}^2\text{) g.}}$
0.05000	0.1033	40.49×10^3
0.08000	0.2660	40.73
0.10000	0.4158	40.75
0.12000	0.5988	40.75
0.135000	0.7581	40.76
0.145000	0.8743	40.75

shown in Figure 3. The interpolated value of $40.9 \times 10^3(E_s)^2$ dynes/g. at the test surface position (—16.2 cm.) agrees with that calculated from Equation (8) ($40.7 \times 10^3 E_s^2$) to within 0.5%. This is satisfactory agreement in view of the possible 1% uncertainty in determining dH^2/dx from the search coil measurements and the 0.5% uncertainty that Onnes and Perrier ascribe to their values for the susceptibility of oxygen. The more precise weight results for the copper test body were used to calculate the magnetic acceleration acting upon the liquid by assuming that the acceleration varied as $(T)^{-1/2}$ as predicted by Perrier and Onnes. The resulting expression for the magnetic acceleration acting on the liquid of temperature T°K. at —16.2 cm. becomes

$$(g_{\mathrm{magnetic}})_{\mathrm{liq}} = -387.9 \times 10^3\, E_s^2 (T)^{-1/2} \text{ dynes} \qquad (10)$$

and the ratio of the net acceleration α to the acceleration experienced in normal gravity α_0

$$(\alpha/\alpha_0)_{\mathrm{liq}} = 1 - 395.8\,(E_s)^2 (T)^{-1/2} \qquad (11)$$

The expression for the ratio of the net acceleration experienced by vapor to its acceleration in normal gravity becomes

$$(\alpha/\alpha_0)_{\mathrm{vap}} = 1 + \left\{ 1 + \frac{\rho_v}{(\rho - \rho_v)} \frac{(\chi_l - \chi_v)}{(\chi_l)} \right\} \frac{(g_{\mathrm{magnetic}})_{\mathrm{liq}}}{g_E} \qquad (12)$$

The correction term $(\rho_v/\rho_l - \rho_v)\ (\chi_l - \chi_v/\chi_l)$ is equal to —0.0018 for oxygen over the range of conditions covered in this experiment so that Equation (12) becomes

$$(\alpha/\alpha_0)_{\mathrm{vap}} = 1 - 395.1 (E_s)^2 (T)^{-1/2} \qquad (13)$$

and the relative accelerations for liquid and vapor are essentially equal for any case in which $|g_{\mathrm{magnetic}}| < 0.995 g_E$.

EXPERIMENTAL PROCEDURE

The copper-constantan thermocouples selected were from a spool of material from which other samples have been calibrated over an extended range of temperature. The five thermocouples used here were checked at the boiling points for pure oxygen and pure nitrogen, and their deviations from a smooth representative table of emf at these two temperatures were linearly extrapolated over the range used here. Absolute temperatures should be accurate to 0.1°K. Two potentiometers with d.c. amplifiers were used with a two-pen strip-chart recorder for null detection so that the temperature indicated by the bulk-liquid (bath) thermocouple and any selected thermocouple from the test element could be displayed simultaneously (Figure 1).

Power for the test-element heater was derived from a 3-phase bridge rectifier fed from a 60-cycle variable autotransformer. The rectifier output was filtered to a ripple of less than 0.5%. Potential drop across the element and the heating current were measured on a model 45 Weston voltmeter and on a shunt and model 45 Weston millivoltmeter that were calibrated prior to the experiments.

The container for the oxygen sample was exacuated to a pressure of less than 10μ, while the test surface was heated to and maintained at or above 80°C. for roughly 20 min. The container was then flushed with pure oxygen (>99.8%) derived from liquid oxygen that had been filtered through a bed of silica gel maintained at 77°K. to strip out any organic material or other high-boiling trace contaminants. Liquid nitrogen was then circulated through the condenser to cool the apparatus and to condense a charge of 370 g. of oxygen in the experimental vessel. The valves were then closed and power input to the auxiliary heaters and liquid nitrogen flow through the condenser were adjusted to maintain the desired bulk liquid temperature. There was a sufficient power input to the auxiliary heater so that as power input to the test element was increased, power input to the auxiliary was decreased and it was not necessary to adjust coolant flow to the condenser.

Measurements of test-element temperature and bulk-liquid temperatures were made for power dissipations in the test-element heater that were increased step by step from zero. A given power input would be established and bath and test element temperatures monitored until it was certain that equilibrium had been attained. As the peak flux was approached, power increments of 2 to 4% were used and maintained for about 3 min. after equilibrium to be sure the flux could be sustained indefinitely without transition to film boiling. As soon as the peak flux was exceeded, power to the test element was turned off and the element allowed to cool so that liquid rewet it. A power input a few percent below the indicated P.N.B.F. was then reestablished, and the P.N.B.F. again approached by steps. Several such determinations of P.N.B.F. were made at each acceleration. The magnetizing currents were then changed to correspond to some preselected magnetic acceleration and a new set of measurements and determinations was made for this acceleration. Whenever the apparatus stood at 77°K. for several hours (overnight or mealtimes), the P.N.B.F. at 1g_E was rechecked before other accelerations were examined. After exploration of the full range of accelerations, 200 g. of oxygen was allowed to boil out of the vessel, and determinations at zero g and 0.01g_E were repeated to check for any large effect of liquid depth above the surface at small accelerations. Conditions corresponding to zero g were then reestablished, refrigerant flow to the condenser was interrupted, the vessel was opened to the atmosphere, and the P.N.B.F. was determined without any condensate returning from the condenser. These variations produced no significant change in P.N.B.F.

At the conclusion of a series of preliminary measurements that covered the entire range of accelerations, the apparatus was hoisted so that the test surface was located at the midplane of the main magnet in a region of zero field gradient. The P.N.B.F.'s were measured in zero field and in a field equal to that corresponding to — 0.03g_E.

TREATMENT OF DATA AND RESULTS

In an extended series of observations made during the preliminary measurements, the temperature difference between the top thermocouple and the surface as a function of power input was determined by linear extrapolation of the three thermocouple temperatures to the surface posi-

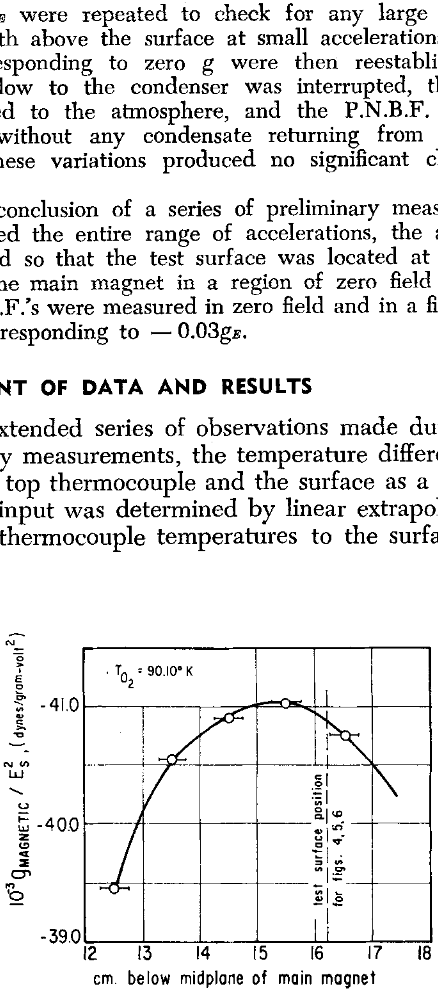

Fig. 3. Vertical magnetic force on liquid oxygen vs. vertical position in magnet.

tion. For most subsequent measurements, and for all in the vicinity of the peak flux, only the top thermocouple was monitored. The smoothed temperature correction for that power dissipation was applied to obtain surface temperature with only occasional checks of the two lower thermocouples. The correction to the top thermocouple temperature to give the surface temperature ranged from −1.25°K. at $1g_E$ to −0.7°K. at zero *g*. The thermal conductivity of the copper test piece as calculated from these measurements was 3.9 w./(cm.) (°K.) compared to the literature value of 4.4 w./(cm.) (°K.). The agreement is within the uncertainties in path length between couples, the effective cross section for heat flow, and copper purity. However, because of these same ambiguities, the difference between surface and top thermocouple temperatures is uncertain by a few tenths and possibly as much as 0.5°K.

Bulk-liquid temperature was taken to be that read by the bath thermocouple. During an equilibrium period, bath-temperature fluctuations, due to overshoot of the regulator, of 4 μv. (0.25°K.) peak-to-peak ($\sim$ 15-sec. period) were representative. The mean temperature was characteristically constant to ± 1 μv. (0.06°K.) or changed only slowly during an equilibrium period. The corresponding uncertainty in bulk-liquid acceleration amounts to $\sim 0.001 g_E$ at zero *g* for the peak-to-peak fluctuation in temperature.

The heat flux through the test surface was obtained from the total heat input to the test-element heater by subtracting the calculated heat loss through the reentrant silicon bronze support surrounded by the resin-bonded fiberglass insulation. The thermal conductivity of the fiberglass was assumed to be 0.006 w./(cm.) (°K.) and that of the silicon bronze to be 0.15 w./(cm.) (°K.). The bottom end of the silicon bronze cylinder and the outer boundary of the fiberglass were assumed to be isothermal at the bulk-liquid temperature, and any thermal resistance at the interfaces between the fiberglass and the bronze support and the outer shell were ignored. This parasitic-heat-leak correction at peak flux ranged from $\sim$ 1.5% of total input at normal acceleration to $\sim$ 2.5% at zero *g* and $\sim$ 6% at $-0.02 g_E$. The correction could easily be in error by 50% or more, but this would not alter any conclusions reached from the results.

The peak-flux values in normal gravity ($1g_E$) were quite reproducible *for a given charge of oxygen*. During the preliminary measurements (March 2 to 4, 1964) there was an apparently discontinuous shift in the $1g_E$ P.N.B.F.'s, and the vessel was warmed, outgassed, and recharged with oxygen. Before the recharging, the average peak flux at $1g_E$ was 21.9 ± 0.1 w./ sq. cm. (average deviation) for eight determinations. After the recharging, four determinations gave 22.6 ± 0.1 (average deviation) w./sq. cm. Likewise, in the measurements of November 24 and 25, 1964, the experimental vessel was vented, warmed, outgassed, and recharged approximately midway through the measurements. Peak flux for the initial charge was 23.3 ± 0.2 w./sq. cm.; after recharging it was 22.9 ± 0.2 w./sq. cm. These values compare with the 23.2 ± 0.7 w./sq. cm. reported by Lyon, Kosky, and Harman (*16*) for oxygen on a 2-mm.-wide flat, horizontal platinum ribbon at 1 atm.

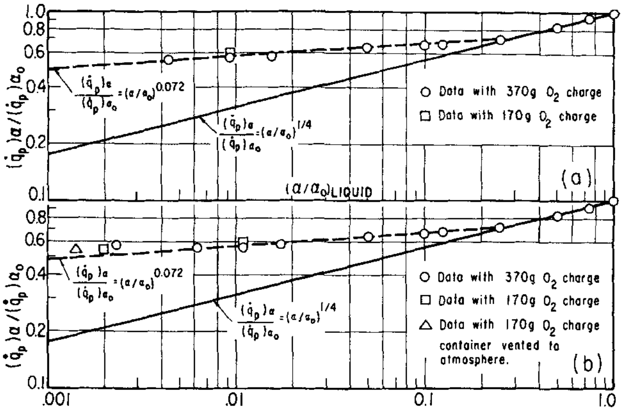

Fig. 4. (*a*) Normalized peak fluxes vs. relative liquid accelerations (based on bulk-liquid temperature). (*b*) Normalized peak fluxes vs. relative vapor accelerations (based on bulk-liquid temperature).

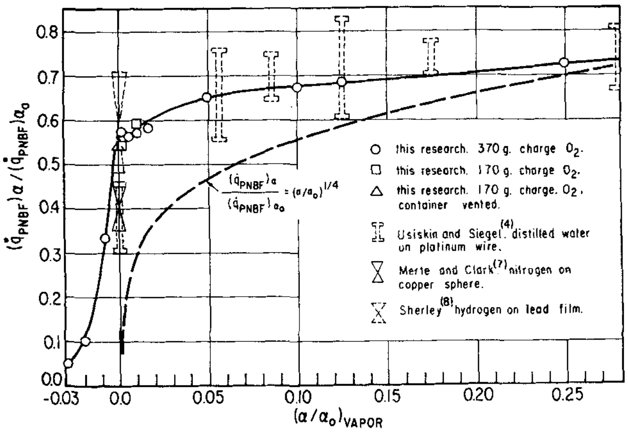

Fig. 5. Normalized peak fluxes at small relative vapor accelerations (calculated from bulk-liquid temperatures).

In the determination of the shift in P.N.B.F. with a uniform magnetic field corresponding to $(a/a_0) = -0.03$ (8,600 gausses), the initial zero field P.N.B.F. was 22.7 w./sq. cm. Two determinations at 8,600 gausses were 23.6 w./sq. cm. and 23.7 w./sq. cm., followed by a final determination in zero field of 22.6 w./sq. cm.

The P.N.B.F.'s measured for a given (a/a_0) were normalized by dividing by the P.N.B.F. that pertained for that charge of oxygen at normal gravity, corrected by a linear interpolation of the shift in P.N.B.F. with magnetic field.

These normalized peak fluxes are plotted against positive relative liquid accelerations in Figure 4*a* (calculated from bulk-liquid temperatures) and against the relative vapor accelerations in Figure 4*b*. Data points for the container charged with 370 g. of oxygen, with 170 g. of oxygen, and initially with 170 g. of oxygen but venting to the atmosphere during the determination are included in the plots. It is only at relative liquid accelerations below 0.01 that there is a significant difference between the two sets of data, and that difference will alter no conclusions which may be drawn here.

In Figure 5 the results for relative vapor accelerations below 0.28 are plotted, together with the results of Usiskin and Siegel in this region for water, as well as the zero *g* drop-tower results of Merte and Clark for nitrogen and those of Sherley for hydrogen.

Since an extreme (unrealistic) upper limit to the relative accelerations is that obtained for liquid with a temperature of the test surface, the reduced P.N.B.F.'s are plotted vs. relative vapor accelerations in liquid at test-surface temperature in Figure 6.

In preliminary experiments, the test surface was inadvertently positioned at −17.4 cm., so that in the region above the test surface the magnetic force increased to approximately 1.025 times its value at the test surface. (In these experiments the relative positions of the main and auxiliary magnets were slightly different from the position for Figure 3, with the result that the magnetic-force–vs.–

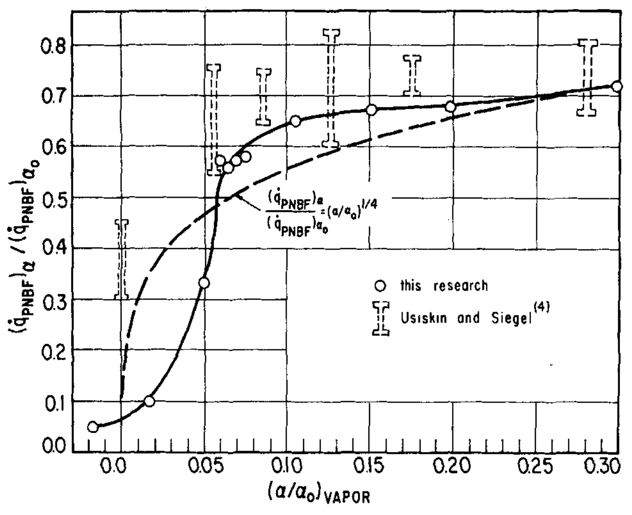

Fig. 6. Normalized peak fluxes at small relative vapor accelerations (calculated from test-element surface temperatures).

position curve had a slightly sharper peak.) The normalized fluxes for this arrangement are plotted against relative vapor accelerations in Figures 7 and 8, together with the data for the −16.2-cm. test-surface position. Accelerations for the −17.4-cm. position are calculated both from the magnetic force at the test-surface elevation and from the maximum value of the magnetic force in the region vertically above the test surface.

DISCUSSION

The 4% increase in P.N.B.F. with uniform magnetic field at normal gravity introduces a small, but unimportant uncertainty in the values for the normalized P.N.B.F.'s. The origin of the shift is not clear. The correlation of Noyes (*17*) for peak flux contains more physical-property parameters than most.

$$(\dot{q})_{g_E} = a\,\lambda\,\rho_v\,[(\rho_l - \rho_v)/\rho_v]^{1/2}\,(g_E\sigma/\rho_l)^{1/4}\,(N_{Pr})_l^{-0.245} \tag{14}$$

The changes in heat of vaporization, heat capacity, and density with magnetic field at constant temperature are readily calculated and are completely trivial for these fields. It is not evident how to correct quantitatively for the effect of magnetic field upon interfacial tensions or upon liquid viscosity and thermal conductivity. The effect of the field correction to $\dot{q}_{a_0}$ as applied served to reduce the normalized P.N.B.F.'s by 2, 3, and 3.5% at relative accelerations of 0.75, 0.5, and 0.25, respectively. This shift in normalized flux amounts to less than the radius of plotting symbols used in Figure 4. For relative accelerations between 1.0 and ~ 0.3, the normalized P.N.B.F.'s are proportional to $(\alpha/\alpha_0)^{1/4}$ to well within the uncertainty in the P.N.B.F.'s. For relative accelerations between 0.25 and 0.0005, the normalized P.N.B.F. is proportional to $(\alpha/\alpha_0)^{0.072\pm.01}$. In this region the field correction to $\dot{q}_{a_0}$ is virtually constant and introduces no uncertainty into the slope of $(\dot{q}/\dot{q}_0)$ vs. (α/α_0); the reproducibility of the peak fluxes is 2 to 4% in this region.

In Figure 5 the agreement between these results and those of Usiskin and Siegel for relative accelerations less than 0.3 is complete, considering the scatter inherent in their much more difficult drop-tower measurements. For the results reported here, there is no question of transient effects, for heat fluxes 2% below the indicated P.N.B.F. often were sustained for 5 min. or more and could undoubtedly have been sustained indefinitely. Subject to the remote possibility that effects due to vibrations from pumps, fans, and mechanical equipment happen to be the same in this experiment as the effect of parasitic accelerations in Usiskin and Siegel's drop-tower experiments, the deviation from the commonly predicted ¼ power dependence on acceleration in this region is definite and complete.

The work of Merte and Clark (*18*) on nitrogen at fractional g_E accelerations came to our attention in the last stages of preparation of this paper. They verify the ¼ power dependence of P.N.B.F. upon relative acceleration between 0.2 and 1.0. They report no values between accelerations of $0.2g_E$ and free fall, which they state corresponds to between 0.01 and $0.03g_E$. As plotted in their Figure 12, the free fall P.N.B.F.'s agree with the ¼ power dependence if ascribed to an acceleration of 0.03 g_E and are significantly high if ascribed to $0.01g_E$. However, in view of the absence of any measurements by them between $0.2g_E$ and free fall and in view of the scatter in their free-fall P.N.B.F. data (their Figure 8), we do not believe that disagreement between their results and those reported here has been established.

The agreement between these results and drop-tower experiments at zero relative acceleration is only modest, but each of the four investigations reported so far has been for a different solid-liquid system and the effect of this cannot be evaluated at present.

The peak fluxes measured at negative accelerations were sharp, well defined, and reproducible.

No effects representing unique apparatus characteristics were recognized. The results with charges of 370 and 170 g. of liquid, and with the container vented (condenser inoperative) all agreed to within normal scatter. The concurrent power level to the auxiliary heaters was varied tenfold at accelerations of −0.024 (based on maximum magnetic force) *in the preliminary experiments* without affecting the peak flux. Thus any kinetic energy effects or subcooling due to the condenser condensate was either absent or insensitive to the quantity of condensate.

The temperature coefficient of magnetic susceptibility introduces by far the largest uncertainties in the net effective accelerations for such a test with paramagnetic liquids. The plot of normalized fluxes vs. relative accelerations calculated from test-surface temperatures in Figure 6 represents an extremely unrealistic limit to system behavior. Not only is it difficult to believe that there is not very good mixing and temperature uniformity in liquid above a surface from which 7.5 cc. of vapor/sec. is being generated [(α/α_0) = 0.05 datum, Figure 6], but the (inadvertent) results with the test surface located at −17.4 cm. lend weight to the assumption that it is the acceleration in the bulk liquid above the surface that governs here.

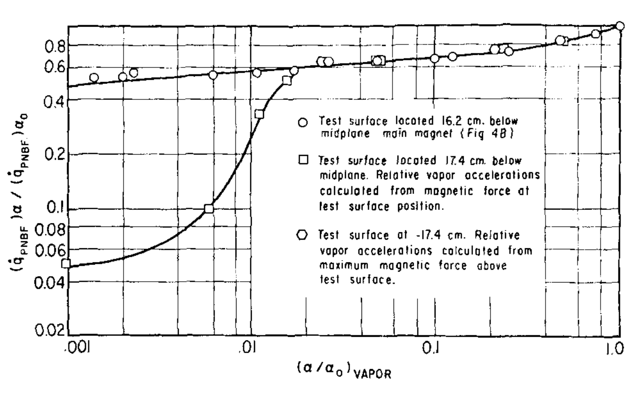

Fig. 7. Comparison of normalized peak fluxes vs. positive relative vapor accelerations for surface located at −16.2 and −17.4 cm.

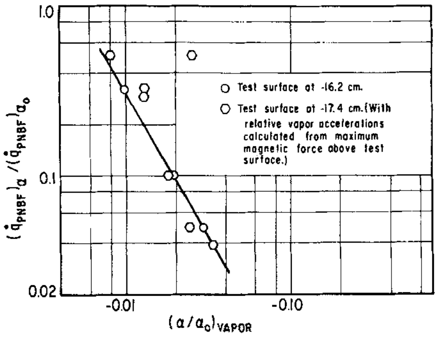

Fig. 8. Comparison of normalized peak fluxes vs. negative relative vapor accelerations for surface located at —16.2 and —17.4 cm.

In Figure 7 the normalized flux values with the test surface at −17.4 cm. break and drop precipitately when the relative accelerations based upon bulk-liquid temperatures and the magnetic force *at the test surface* (square symbols) fall below 0.025. However, for these conditions the relative accelerations some 2 cm. above the test surface have reached *negative* values. If one compares the normalized fluxes with relative accelerations calculated from bulk-liquid temperatures and the *maximum magnetic force* (hexagonal symbols) there is complete agreement over the full experimental range (Figures 7 and 8), with the exception of a single datum point from the preliminary measurements at $(\alpha/\alpha_0) = -0.025$ (Figure 8). For an experiment of extended duration, with the liquid above the heated surface subject to negative accelerations in some region between the surface and the liquid source, it is reasonable that this zone of negative acceleration would govern behavior of the system, even though acceleration in the immediate vicinity of the surface might be positive. As heating continued, liquid below the negative acceleration zone would become exhausted, leaving a vapor bubble trapped below the zone of negative liquid acceleration. Vapor removal could occur only as some surface-film flow mechanism fed liquid to the heated surface to be vaporized, or as the vapor was heated directly by the surface. Portions of the vapor bubble would be discharged, then, as it expanded from one cause or the other and moved the liquid-vapor interface into a region of positive acceleration.

For a system of cylindrical symmetry such as the air-core solenoids used here, an axial variation in magnetic field is inevitably accompanied by a radial variation in magnetic field and therefore by a radial component of acceleration on any material of nonzero susceptibility placed in it. For the solenoids used here, the radial component of magnetic field was calculated as a function of radius from first principles by machine computation (and verified at 3-cm, radius from the search-coil measurements). The resulting radial magnetic force increases linearly with radius from zero at the axis to, for zero relative vertical acceleration conditions, 31 dynes ($0.03g_E$) at the perimeter of the heated test surface, with an average value of 19 dynes ($0.02g_E$) over the surface. At a relative vertical acceleration of 0.25, the radial accelerations were $0.02g_E$ at the perimeter, and $0.014g_E$ averaged over the surface of the test piece. Since the radial magnetic force acting on a volume element of oxygen is directed outward, there will be a radial *buoyancy* arising from the difference in liquid and vapor densities that causes vapor to be displaced to the axis of the solenoids and to collect *above* the heated test surface. One would expect this vapor binding mechanism to *diminish* the effectiveness of heat transfer, and it is therefore difficult to visualize how the small radial acceleration could account for the much *larger* heat transfer observed than is predicted by the correlations of Kutateladze, Zuber and Tribus, and others.

CONCLUSIONS

The use of a magnetic field of sufficient gradient is eminently suitable for investigating boiling heat transfer at small net accelerations. It is desirable that the fluid exhibit a specific susceptibility that is the same for both vapor and liquid phases and is not temperature dependent; however, even measurements with a paramagnetic fluid yield significant results.

These measurements confirm the ¼ power dependence of peak nucleate boiling flux upon accelerations predicted by the correlations of Kutateladze, Zuber and Tribus, and others, based upon vapor-liquid dynamics, for accelerations corresponding to from 0.3 to $1.0g_E$.

For accelerations less than $0.25g_E$, they are in quantitative agreement with the measurements of Usiskin and Siegel and indicate a significant departure from a ¼ power dependence of P.N.B.F. on acceleration. This agreement suggests that although transient effects may contribute to the scatter of data for the inherently difficult drop-tower experiments, there is a relatively large P.N.B.F. that pertains to zero g conditions. Although the temperature coefficient of susceptibility introduces some uncertainty as to the correct or effective acceleration that pertains for these measurements, the measurements with the test surface located well below the region of maximum magnetic acceleration clearly indicate that it is the bulk-liquid accelerations which govern here. We believe the uncertainties in these bulk-liquid accelerations to be less than $0.005g_E$, so that the P.N.B.F. at zero relative acceleration cannot be ascribed to this uncertainty.

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NOTATION

a = constant
G. = gauss (kG = kilogauss)
g = local acceleration, cm./sec.^{2}
g = mass, g.
g_E = earth's gravitational acceleration, 979.97 dynes/g. (this location)
E,e = potential difference, v.
H = magnetic field strength, gausses
k = thermal conductivity, w./(cm.) (°K.)
N_{Pr} = Prandtl number
P.N.B.F. = peak nucleate boiling flux, w./sq. cm.
$\dot{q}$ = peak nucleate boiling flux, w./sq. cm.
T = absolute temperature, °K.
x = distance from heated surface, cm.
w = weight, dynes
W = power dissipation, w.

Greek Letters

α = net vertical acceleration, cm./sec.^{2}
α_0 = vertical acceleration in earth's gravitational field only, cm./sec.^{2}

λ = heat of vaporization, joules/g.
ρ = density, g./cc.
σ = surface tension, dynes/cm.
μ = pressure, microns of mercury
χ = magnetic susceptibility, ergs/(gauss^2) (g.)

Subscripts

l = liquid
o = under reference conditions
v = vapor

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Thermodynamic Consistency Tests for Solid-Liquid Equilibria

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The technique of testing the validity of phase equilibria by applying thermodynamic consistency tests is highly developed for vapor-liquid equilibria. The application to solid-liquid equilibria, however, has been developed very little. The problems associated with thermodynamic consistency tests are discussed and a new technique for evaluating the validity of experimental data has been developed. Several possible test equations are presented and are applied to test the consistency of three sets of solid-liquid equilibrium data.

The use of thermodynamic consistency tests to evaluate the validity of experimental vapor-liquid equilibrium data is widespread. However, such tests are rarely, if ever, used for testing solid-liquid equilibria. The *need* for consistency tests is even greater for the solid-liquid case, because of the inherent difficulty in obtaining an equilibrium solid phase solution. Annealing times of months at or near the solidus temperature are sometimes required for equilibration of solid solutions.

The specific need for a thermodynamic consistency test arises in data taken by McNeely (3). There is substantial disagreement between data obtained by McNeely and those reported in the literature in the location of the solidus curve for the InSb-GaSb system. When such discrepancies arise in vapor-liquid equilibria, the usual procedure is to resolve the disagreement by testing the data for consistency with one of the forms of the Gibbs-Duhem equation. Usually one set of data will be thermodynamically inconsistent and the conclusion drawn that the data do not represent an equilibrium situation.

A search of the literature revealed no equivalent test of practical applicability for solid-liquid equilibria. The prime difficulty is in the fact that in vapor-liquid equilibria the nature of the vapor phase is sufficiently known that corresponding activities in the liquid phase can be calculated. For solid-liquid equilibria, however, neither phase is known to behave as an ideal solution in advance; thus, the activities of the two phases are not readily calculated. The purpose of this paper is to present a test for thermodynamic consistency in solid-liquid equilibria that surmounts this difficulty.

THEORY

The thermodynamic consistency tests for phase equilibria are generally based on the equation relating an infinitesimal change in free energy as

$$dF = -S_T dT + V_T dp + \Sigma \mu_i dn_i \qquad (1)$$

combined with a recognition that the total free energy of a system is given by $F = \Sigma \mu_i n_i$; thus

$$dF = \Sigma \mu_i dn_i + \Sigma n_i d\mu_i \qquad (2)$$