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A STUDY OF THE RATES OF HEAT TRANSFER AND BUBBLE SITE DENSITY FOR NUCLEATE BOILING ON AN INCLINED HEATING SURFACE

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ABSTRACT

Nucleate pool boiling of distilled water from an electrically heated surface at atmospheric pressure is studied for varying heating surface inclinations. The constants of the accepted boiling equation $\phi = K\ T^B$ and the Rohsenow Correlation Coefficient are found to be dependent on surface orientation. Convection cooling is observed to play a major role in pool boiling phenomena and causes large changes in the heat transfer rates for a given excess of temperature of the heated surface. Active nucleation site density is studied and found to be independent of surface inclination. Empirical relations are presented to provide an understanding of the effects of inclination on other boiling parameters.

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INTRODUCTION

Nucleate boiling has long been of interest to the engineer because of the exceptionally high heat fluxes associated with it. It has been used for many years in steam, refrigeration and air conditioning plant and more recently in nuclear reactors and rocket nozzles.

However the phenomena is not yet completely understood, since in any study of boiling heat transfer an extremely large number of variables is involved. These include the liquid properties of temperature, viscosity, density, thermal conductivity, expansivity, specific heat, surface tension, latent heat of evaporation, pressure and velocity, along with the heating surface properties of temperature, roughness, ageing, specific heat, thermal conductivity and wettability. The large number of variables has prevented a complete theoretical analysis from being developed to predict the rates of heat transfer, but considerable progress has been made in the development of empirical relations to correlate experimental data.

The present investigation concerns the effects of yet another variable on boiling heat transfer, viz the angular inclination of the heating surface. This has been rarely mentioned in the literature, particularly for the nucleate regime.

NOMENCLATURE

A	Area of heated surface exposed to water.
B	Slope of boiling curve, equation (2)
C	Specific Heat
C_{sf}	Empirical Constant, equation (5)
D	Constant of proportionality, equation (7)

F	Exponent of equation (7)
g_c	Conversion factor
g	Gravitational acceleration
h_{fg}	Latent heat of vaporisation
k	Thermal conductivity
K	Constant of proportionality of equation (2)
N	Number of active nucleation sites
n	Active nucleation site density = $\frac{N}{A}$, (cm^{-2})
Pr	Prandtl Number
t	Thickness of the heating strip
T	Excess temperature = $T_s - T_o$ (^{o}C)
T_I	Temperature of the insulated face of the heating strip
T_s	Temperature of the boiling surface
T_o	Bulk liquid temperature
β	Contact angle for the vapour-liquid interface at the boiling surface
θ	Surface inclination (degrees)
μ	Viscosity
ρ	Density
σ	Surface Tension
ϕ	Heat Flux (Watts / cm^2)

Subscripts

ℓ	Saturated liquid
v	Saturated vapour

EXPERIMENTAL INVESTIGATION

The Apparatus

The pool boiling equipment, Fig. 1, comprises a 40 cm x 40 cm x 15 cm brass tank with hardened glass windows on the front and rear. The test surface material is nichrome V (Ref. 1), providing high resistivity, low temperature coefficient of resistance, and a maximum operating temperature of 1200°C.

The nichrome was cast in high temperature araldite to provide thermal insulation for the back of the strip while the two ends were clamped to brass electrodes. This arrangement provided a single heating surface of 5.08 cm x 0.635 cm exposed to the distilled water, Fig. 2.

A copper-constantan thermocouple was spot welded to the back of the test strip and connected to a potentiometer. Heat loss from the test surface by conduction along the thermocouple (Ref. 2) was reduced by using fine wires, (30 gauge) covered with enamel, glass and a compound which is resistant to both moisture and heat.

The test strip was heated by direct current supplied from 6 and 12 volt, 200 amp - hr lead - acid batteries. This eliminated temperature fluctuations and thermocouple pickup as has been experienced with alternating current heating (Ref. 3). Fine control of current was achieved using a resistance panel consisting of a carbon plate rheostat in series with a bank of fixed and variable resistances, Fig. 3. Such an arrangement allowed the current to be varied continuously from 0 to 100 amps. Power delivered to the test surface was measured using a voltmeter and shunted ammeter.

A two pole switch enabled reversal of the current through the strip. This was necessary because a voltage drop from electric heating occurs across the finite thermocouple junction, introducing an error in the thermocouple reading. The mean of two readings, one for each polarity of the test surface, eliminates this error.

Since the thermocouple readings represented the temperature on the insulated side of the test strip, the temperature on the boiling surface was determined assuming one dimensional heat flow with internal heat generation. Thus the temperature of the boiling surface is given by

$$T_s = T_I - \frac{\phi t}{2k} \qquad \ldots (1)$$

The test blocks and electrodes are mounted on an annulus graduated in degrees to allow the inclination of the test surface to be varied through 360°. This may be varied without altering the heat flux, and the centre of the heated surface is maintained at a constant distance below the surface of the liquid. The inclination, designated θ, is measured in an anticlockwise direction from the horizontal.

The bulk temperature of the water is measured with a precision mercury-in-glass thermometer and controlled by a variac connected to two 900 watt immersion heaters. Distilled water is used in all tests and the liquid bath is maintained at 100°C at atmospheric pressure.

Preparation and Procedure for Tests

For all experiments, the test surface was prepared by finishing with a minimum of 300 strokes of either 240 or 600 grit emery paper applied parallel to the axis of the strip. The surface was examined carefully to make sure all scratches were parallel. It was then cleaned with distilled water prior to placing it in the tank. This procedure was repeated between each test run to reproduce the surface finish as closely as possible. No attempt was made to measure the R.M.S. roughness of the test surface because of its limited applicability.

Before conducting each series of tests, the distilled water in the tank was boiled vigorously for one hour to degass the system, and after adjusting the required heat flux, it was allowed thirty minutes to stabilise. A further ten minutes was allowed between test readings after adjustment of the controlling parameters.

The tests were divided into three main sections : the first to examine the relationship between heat flux, surface inclination and temperature excess of surface over bulk temperature of liquid, the second to examine the influence of the immersion heaters on convection cooling of the test surface, and the third to study the effects of surface inclination on nucleation site density.

To examine the former effect, two series of tests were conducted. In the first series, the heat flux was maintained constant and the surface temperature excess determined for surface inclinations varying from upward-facing horizontal (0^o) to downward-facing horizontal (180^o) in increments of 30^o. This was repeated for several heat fluxes, the results being plotted in Fig. 4. In the second series, the heat flux was varied for fixed surface inclinations and its variation with surface temperature excess recorded. This was repeated for the full range of inclinations in 30^o steps. A first order least squares line of best fit was calculated on a log-log basis for each inclination and the mean deviation and slope calculated. The slopes of these curves are plotted against surface inclination in Fig. 5.

To examine the influence of the immersion heaters on convection cooling of the test surface, a perspex cover, 4 cm x 5.5 cm x 11 cm was placed around the araldite test block. Small holes were drilled in the cover to allow vapour to escape into the tank. Convection currents from the immersion heaters were thus shielded completely leaving only those convection currents caused by the heating surface itself. A series of constant heat flux tests were then conducted from which surface temperature excess versus surface inclination curves were obtained. These are shown in Fig. 5.

To determine the active nucleation site density, the number of bubbles were counted visually from each side of the tank. The data was only accepted when the two countings did not vary by more than one nucleation site. Heat flux was not increased beyond a condition where the sites could no longer be counted accurately. Thus site density data could not be collected for inclinations greater than 90° because of the released bubbles moving along the strip tended to interfere with other sites making visual counting difficult.

A test surface was prepared with 600 grit emery paper, and for a constant heat flux a series of tests was conducted in which the nucleation site density and surface temperature excess was obtained at various angular inclinations. The results of this series are plotted in Fig. 7. Other test surfaces were then prepared with 240 grit paper and tests were run in which the variation in bubble site density with varying heat flux was observed at fixed angular inclinations. The resulting curves are shown in Fig. 8.

DISCUSSIONS AND ANALYSIS OF EXPERIMENTAL RESULTS

Heat Flux

The first series of tests, Fig. 4, indicate that for constant heat flux, the heated surface temperature decreases steadily as the surface inclination is changed from the upward facing position (0°) to the downward facing (180°). Similar effects were observed by Price (Ref. 4) in a study of film boiling of nitrogen at surface inclinations of 0°, 30° 60° and 90°, and by Class (Ref. 5) for film-boiling of hydrogen at inclinations of 0°, 45° and 90°. These similar variations for both nucleate and film boiling indicate that the same mechanism is effecting the heat transfer rates in both regimes.

Also from Fig. 4, the rate of surface temperature variation with increased surface inclination is greater at the lower heat flux rates. Thus for a constant surface inclination, the rate of change of temperature excess with heat flux becomes greater as the angle is increased. This effect can best be observed from the series of tests with fixed surface inclinations and varying heat fluxes. These enable the slopes of the boiling curves, B, to be determined as plotted in Fig. 5 for use in the empirical equation

$$\phi = K\ T^{B} \qquad \ldots (2)$$

After consideration of numerous other forms, equation (2) was found the most satisfactory for relating flux and surface temperature excess for the various angular inclinations.

A second order curve of best fit for the boiling curve slopes yields

$$B = 5.71 + 0.000548\theta - 0.000114\theta^{2} \qquad \ldots (3)$$

This relation provides a mean deviation of 5% which is within the accuracy of the experimental data.

The experimental results illustrate that for a given excess temperature, the rate of heat transfer increases as the heating surface is inclined from the horizontal position facing up, through the vertical, to the horizontal position facing down. To obtain a given increase in the heat flux, larger temperature differentials are required for larger values of θ. In previous works concerning the effects of surface inclination on the rate of heat transfer, no explanation has been given for the variations either in surface temperature or boiling curve slopes, although Elrod (Ref. 6), in a study of nucleate boiling of water from vertical and horizontal tubes, noted a steeper sloped boiling curve for the horizontal case in both natural and for· ⁴ convection.

The constant of proportionality in equation (2) is dependent on many factors including the heating surface roughness, inclination, wettability and depth of the heating surface below the free liquid surface.

In the boiling curve tests conducted for constant θ, the test surface had to be prepared for each test run. The unavoidable variations in surface roughness tended to shift the curves bodily, along the temperature axis. Subsequent errors reduce the accuracy of any empirical relation predicting the effect of incline on the constant of proportionality, K. A more satisfactory result is obtained by consideration of the constant heat flux tests in which the same surface roughness is used for each heat flux, and the convection cover is added to avoid convection currents from the immersion heaters.

Thus from an interpretation of the results plotted in Fig. 6, for the calculation from a second order plot on a semi-log basis gives

$$K = \mathrm{EXP}\ (-10.68 + 0.0173\theta + 0.000198\theta^2) \qquad \ldots (4)$$

with a mean deviation of 11%.

The combination of equations (2), (3) and (4), Fig. 9, are intended only to provide an understanding of the effects of surface inclination on pool boiling of water for a 240 grit polished nichrome V surface at atmospheric pressure.

The accepted Rohsenow correlation equation for pool boiling (Ref. 7)

$$\frac{C_\ell\ T}{h_{fg}\ Pr_\ell^{\ 1\cdot 7}} = C_{sf}\left[\frac{\phi}{\mu_\ell\ h_{fg}}\left(\frac{g_c\ \sigma}{g(\rho_\ell-\rho_v)}\right)^{0\cdot 5}\right]^{0\cdot 33} \qquad \ldots (5)$$

was considered also from the data of Fig. 6 to determine whether it could be used to predict the effects of surface inclination. This revealed a mean deviation of 4.3% for the linear relation

$$C_{sf} = 0.0101 - 0.000022\theta \qquad \ldots (6)$$

The coefficients from equation (6) lie within the range 0.0101 for $\theta = 0^\circ$ to 0.00614 for $\theta = 180^\circ$, and are comparable with those obtained for water-platinum, 0.013 and water-brass, 0.006 by Rohsenow (Ref. 7). Vachon (Ref. 8) reported values of C_{sf} within the range 0.0106 to 0.0155 for his studies of water on stainless steel.

Convection Cooling Effects

Although the same trends were present from tests with or without the surrounding perspex convection shield in position, it did have the effect of reducing the rate of change of surface temperature excess with angular inclination by approximately one half.

To examine further the influence of convection currents from the immersion heaters, a series of thermocouples were used to measure the temperature profile of the bulk liquid, while the test surface was maintained at 108.3°C, for inclines of 0°, 90° and 180°. The convection cover was used throughout the test so that any currents remaining were those caused by the heating surface only. The results, plotted in Fig. 10, illustrate a more favourable temperature profile for surface cooling as the inclination is increased. The cooler liquid close to the heating surface provides a higher rate of heat transfer at a given excess temperature for the larger values of θ. The rate of heat transfer had to be increased for the 90° and 180° tests to maintain the surface temperature at 108.3°C. This tended to reduce any variation in the profiles between the three inclines, so that the difference in temperature profiles is more pronounced than it appears in Fig. 10.

Nucleation

The tests conducted at a constant flux density for a 600 grit surface finish reveal, Fig. 7, that nucleation site density is independent of angular inclination of the surface. This is apparent also from Fig. 8 for the 240 grit surface, since the site density verses flux curves for the three inclinations used are almost coincident. From the results plotted in Fig. 8, a least squares computer programme was used to obtain the proportionality constant, D, and exponent, F, in the empirical equation

$$\phi = D\, n^{F} \qquad \ldots (7)$$

for comparison with the work by others. This gave values of $D = 0.154$ and $F = 1.61$ with a mean deviation of 4.3%. Jacob (Ref. 9), Gaertner (Ref.10) and others have presented empirical relations of this form, with values of the exponent, F, varying between 0.49 and 1.0 for a 4/0 polished surface. To compare the results more closely, further tests were conducted using 600 grit emery to produce a smoother finish. This gave $D = 0.26$ and $F = 1.54$ with a mean deviation of 4.8% which compares favourably with the previous result.

However, a log-log plot of heat flux versus site density, Fig. 11, reveals a curve which is concave upwards for both series of tests. A plot of log ϕ versus n for each series, Fig. 12, gives straight lines with mean deviations of 2.8% and 2.6% respectively. The relations thus obtained were

$\phi = 1.22 \text{ EXP } (0.161n)$ for a 240 grit surface finish . . . (8)

$\phi = 1.8 \text{ EXP } (0.154n)$ for a 600 grit surface finish . . . (9)

This modified form of the equation provides a much better correlation for the data than the previously accepted form, equation (7), and is valid for inclines in the range $0^{\circ} < \theta < 75^{\circ}$.

CONCLUDING REMARKS

Convection cooling plays a major role in the heat transfer mechanism associated with pool boiling. A horizontal heating surface facing upwards tends to be sheltered from convection currents as they move around a test block. As the inclination of the surface with the horizontal is increased, it becomes exposed to convection currents resulting in cooler bulk liquid moving closer to the heated surface. This more favourable temperature profile provides a higher convective heat transfer coefficient.

Also, as the angular inclination is increased, the vapour bubbles move along the heating surface rather than away from it. For inclinations above 90°, the vapour is trapped under the surface and slides along it providing an insulating effect from the cooler bulk liquid.

As the heat flux is increased, larger quantities of vapour are present near the heating surface and the thermal resistance becomes more apparent. The more efficient convection cooling still predominates for large angles of inclination, but its effect is diminished by the insulation of the surface with water vapour. The net result is a closer grouping of the boiling curves at higher rates of heat transfer which reduces the boiling curve slopes as indicated by equation (3).

The insulation of the surface by vapour becomes apparent since it is found that the burnout for the test surface is considerably lower for larger angular inclinations. Burnout was found to occur at inclinations near 180° for heat fluxes and excess temperatures which were considerably lower than those which could be maintained at lower angles of inclination.

The heat flux delivered to the boiling liquid is dependent on the number of active nucleation sites on the heating surface as given by equations (8) and (9). The nucleating site density is not affected by varying the inclination at constant heat flux within the range $0 < \theta < 75^{\circ}$, even though the temperature of the surface is affected.

ACKNOWLEDGEMENT

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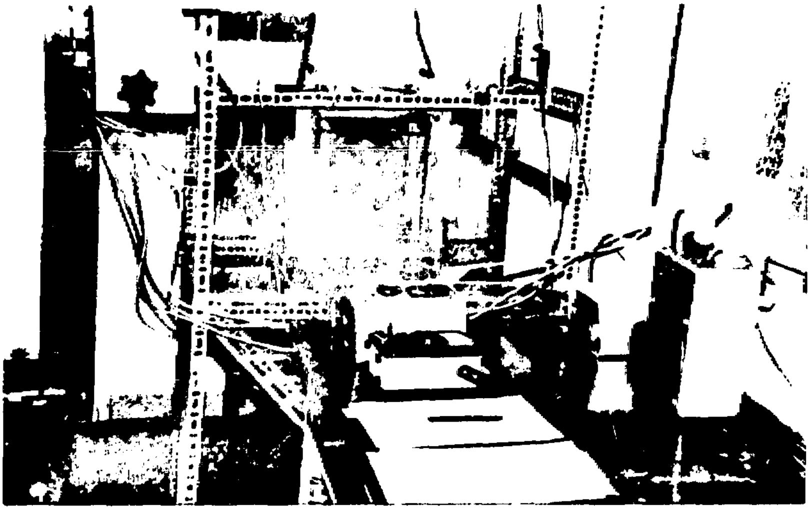

FIG 1 Experimental Equipment.

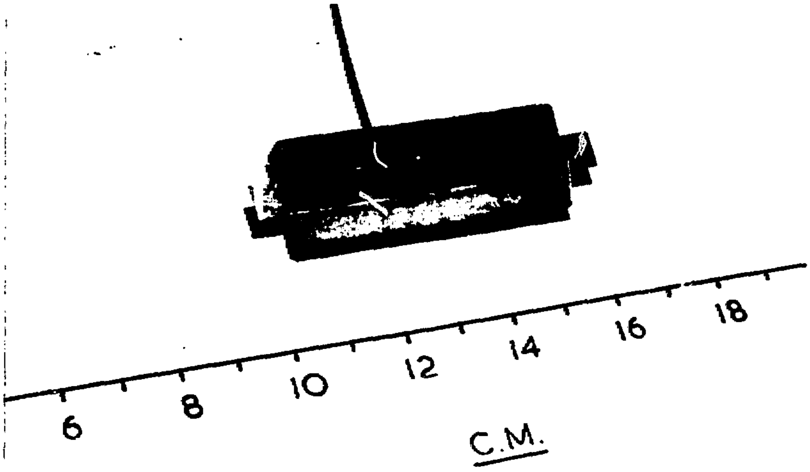

FIG 2 Experimental Test Block with Thermocouple.

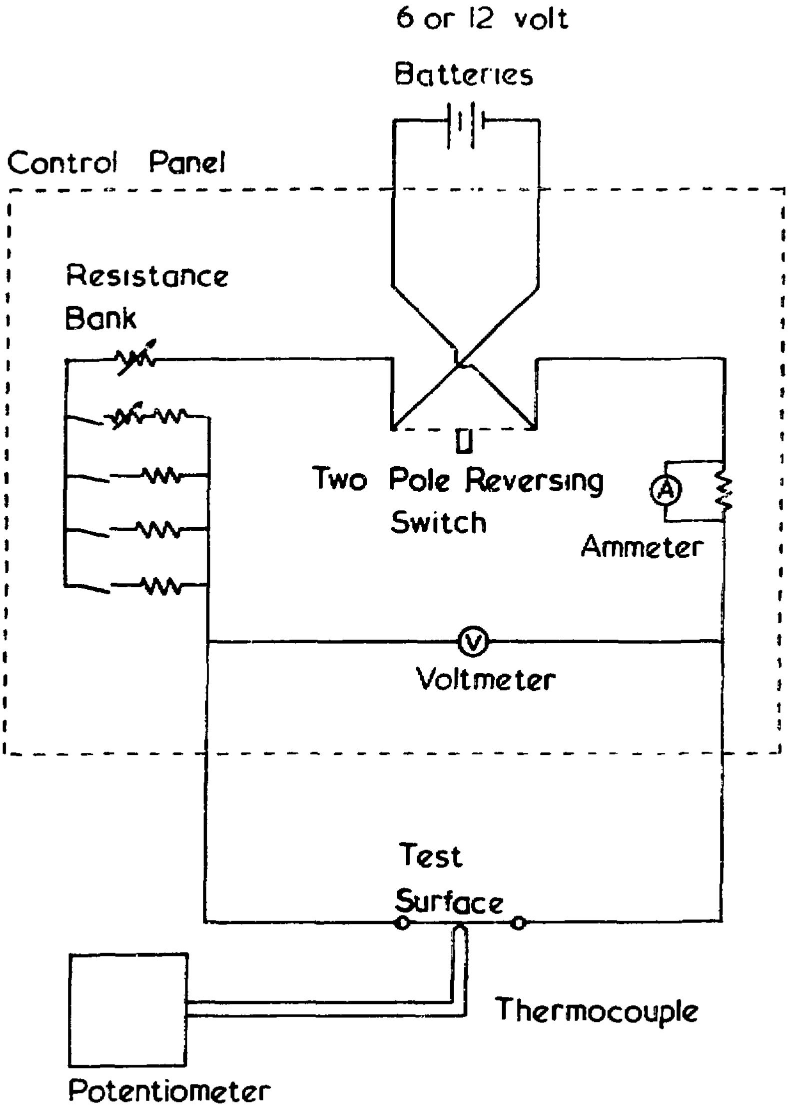

Fig 3 Schematic Layout of Test Equipment.

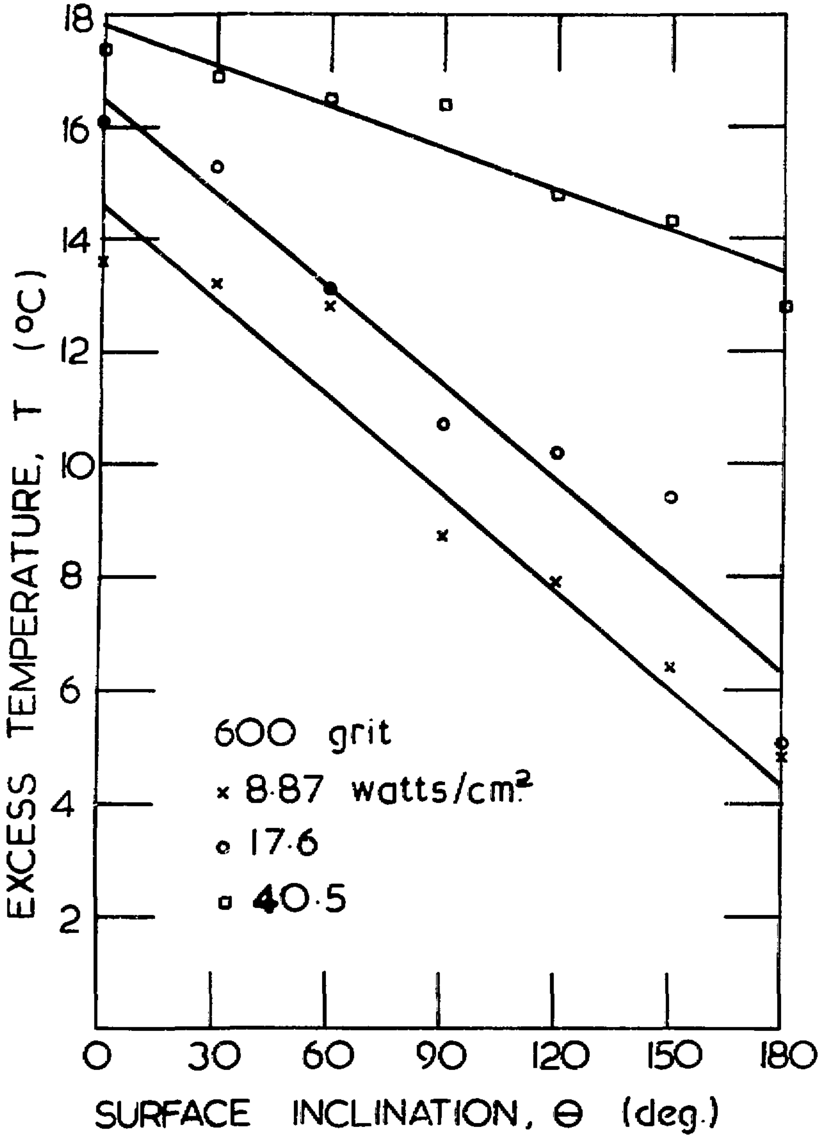

FIG 4 Variation of Excess Temperature with Surface Inclination for a Constant Heat Flux.

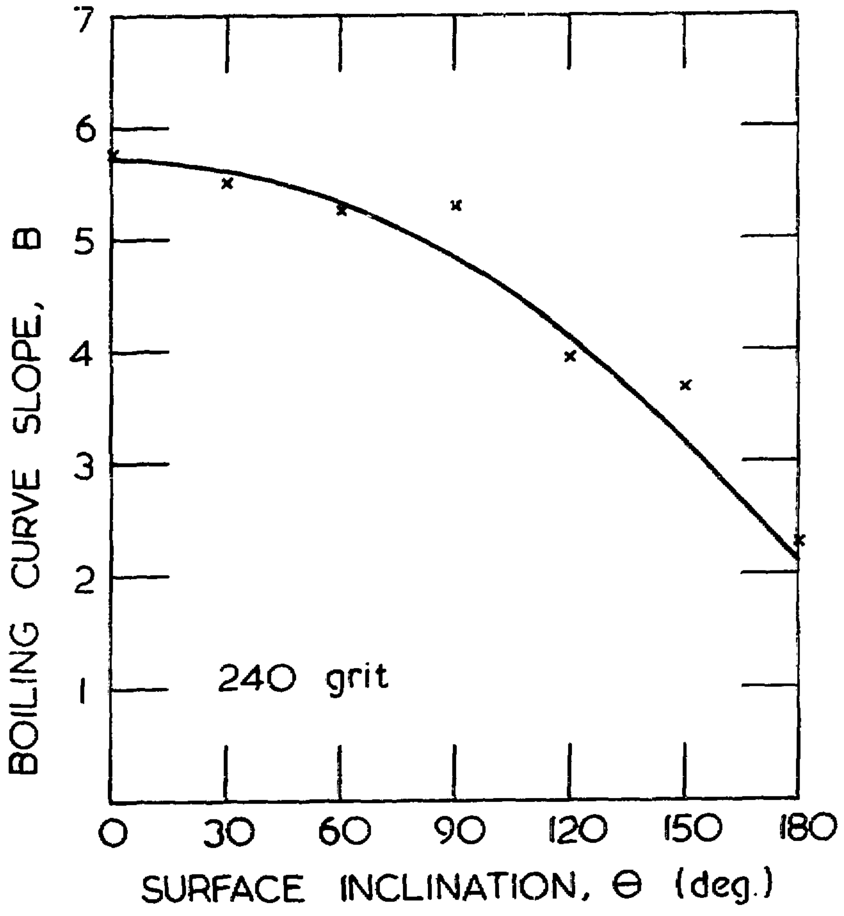

FIG 5 Effect of Surface Inclination on Boiling Curve Slope B, equation (1).

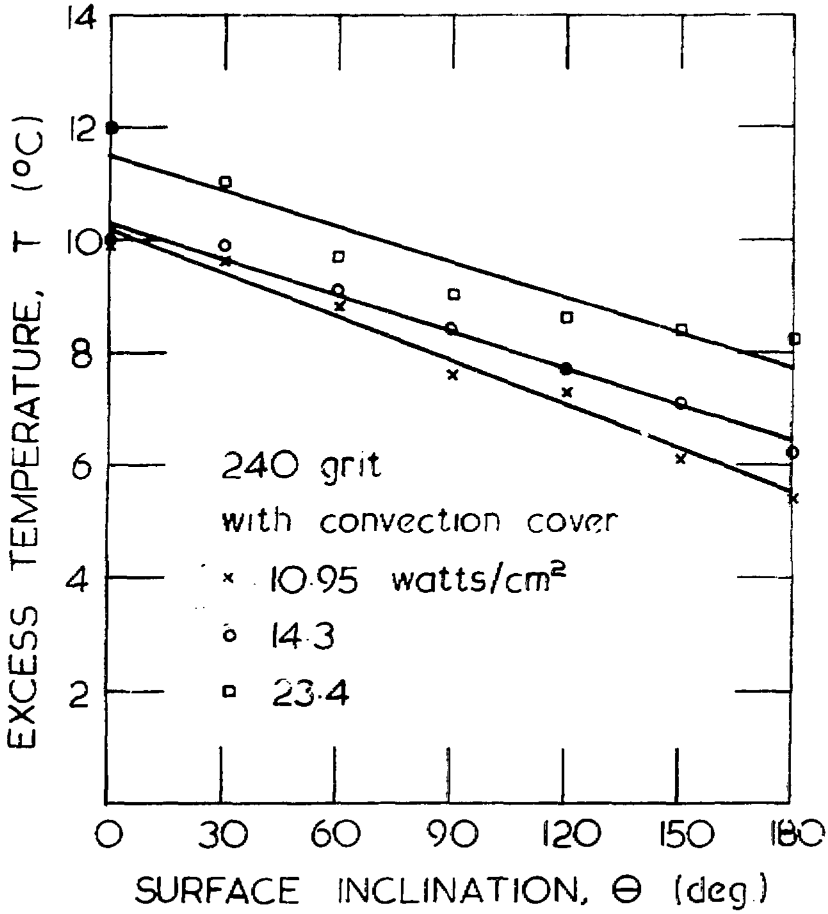

FIG. 6 The Influence of Immersion Heaters on the Rates of Heat Transfer.

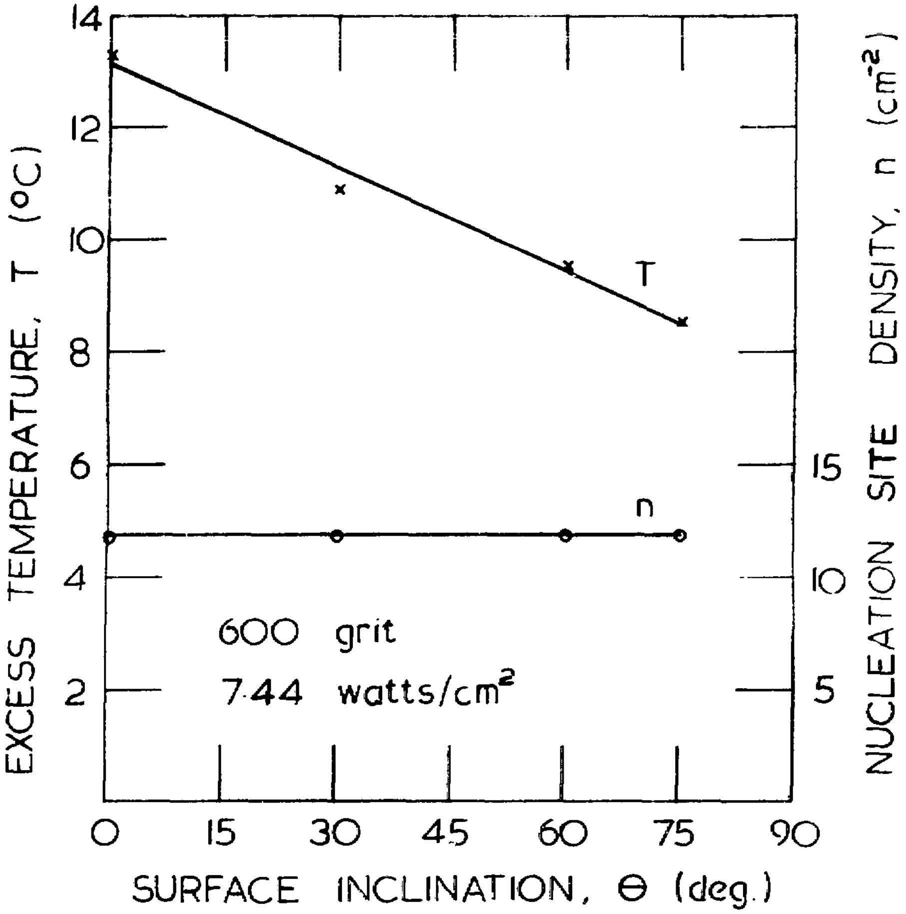

FIG 7 Variation of Nucleation Site Density with Surface Inclination at a Constant Heat Flux.

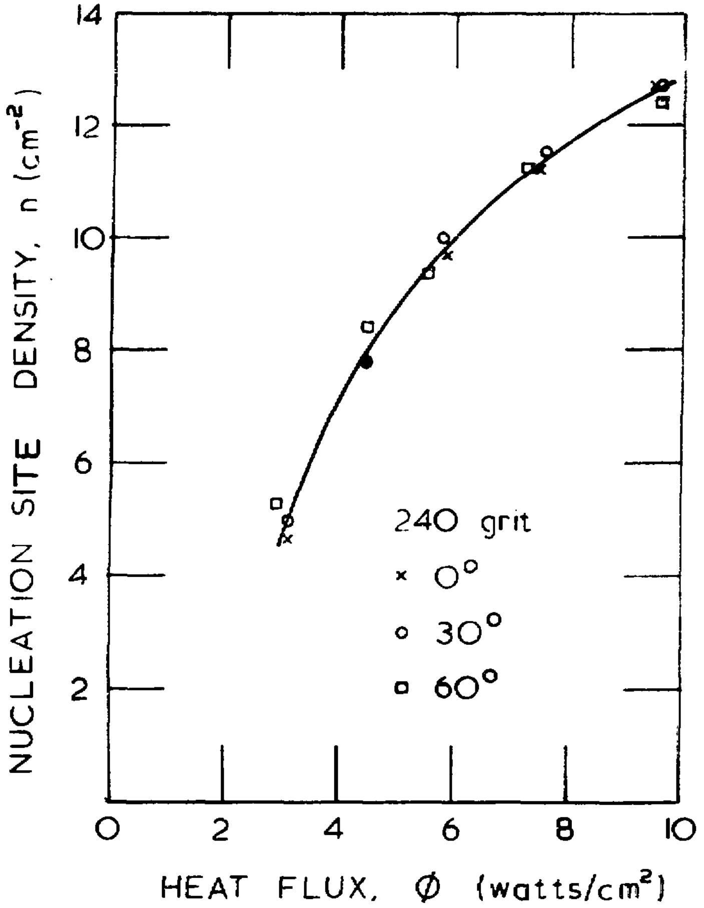

FIG 8 The Effect of Heat Flux on Nucleation Site Density.

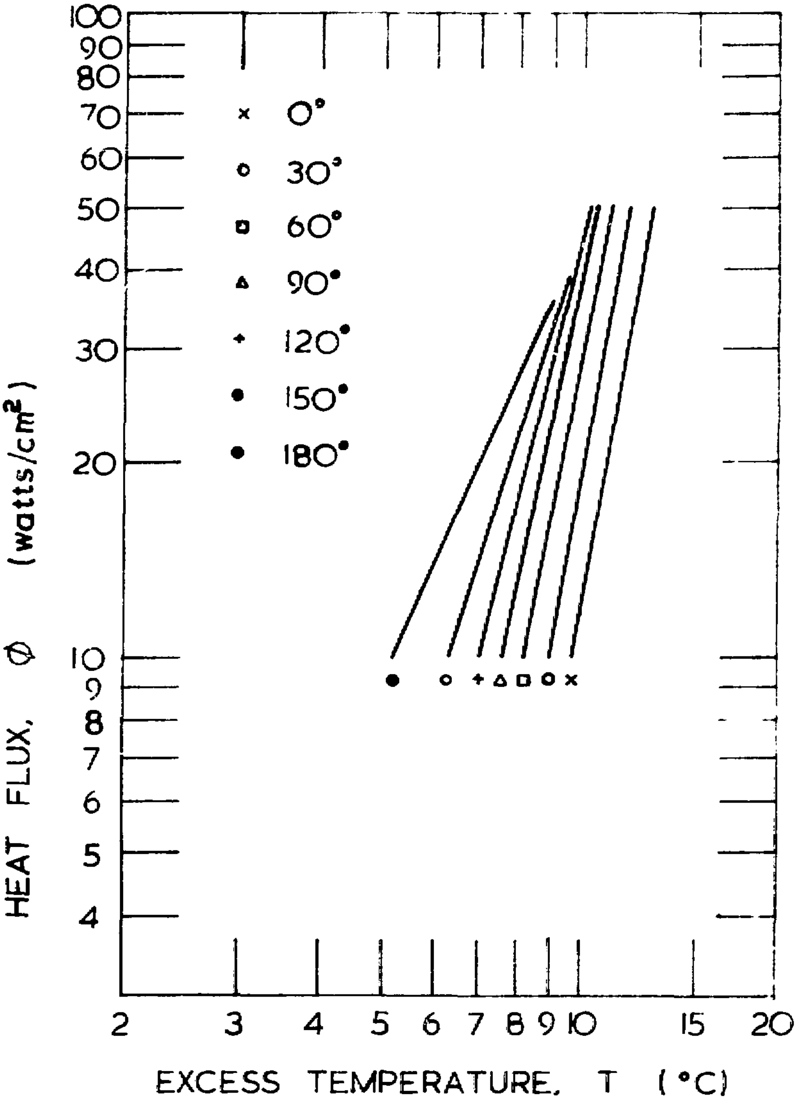

FIG 9 Boiling Curves Predicted from Equations (2),(3) & (4).

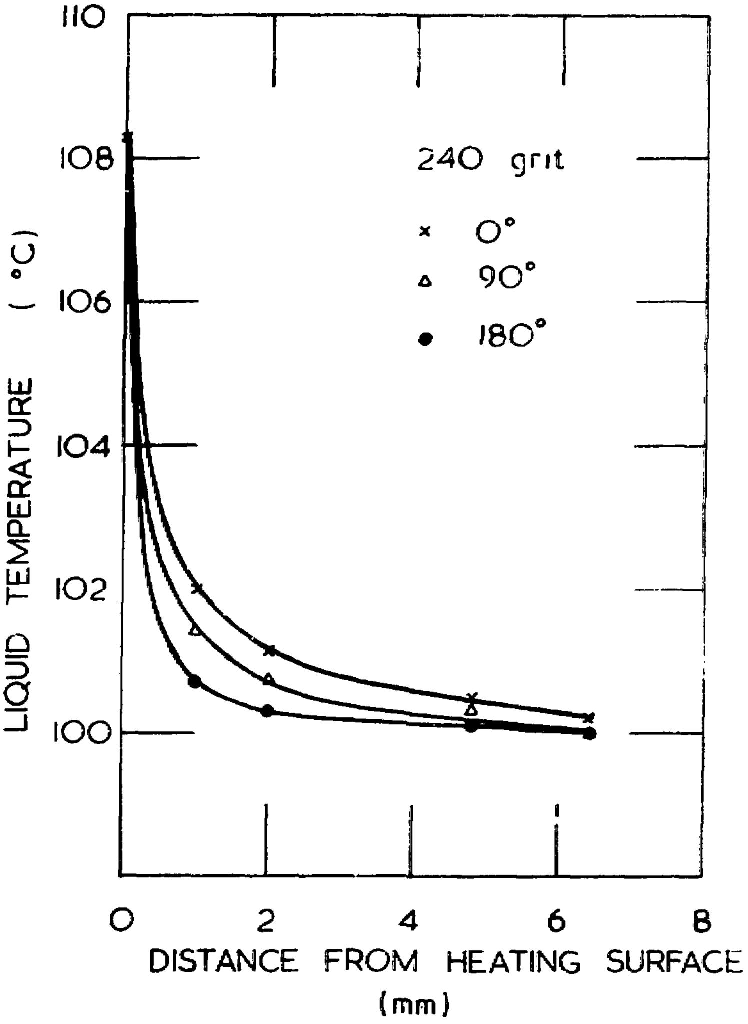

FIG 10 Temperature Profiles as Effected by Surface Inclination.

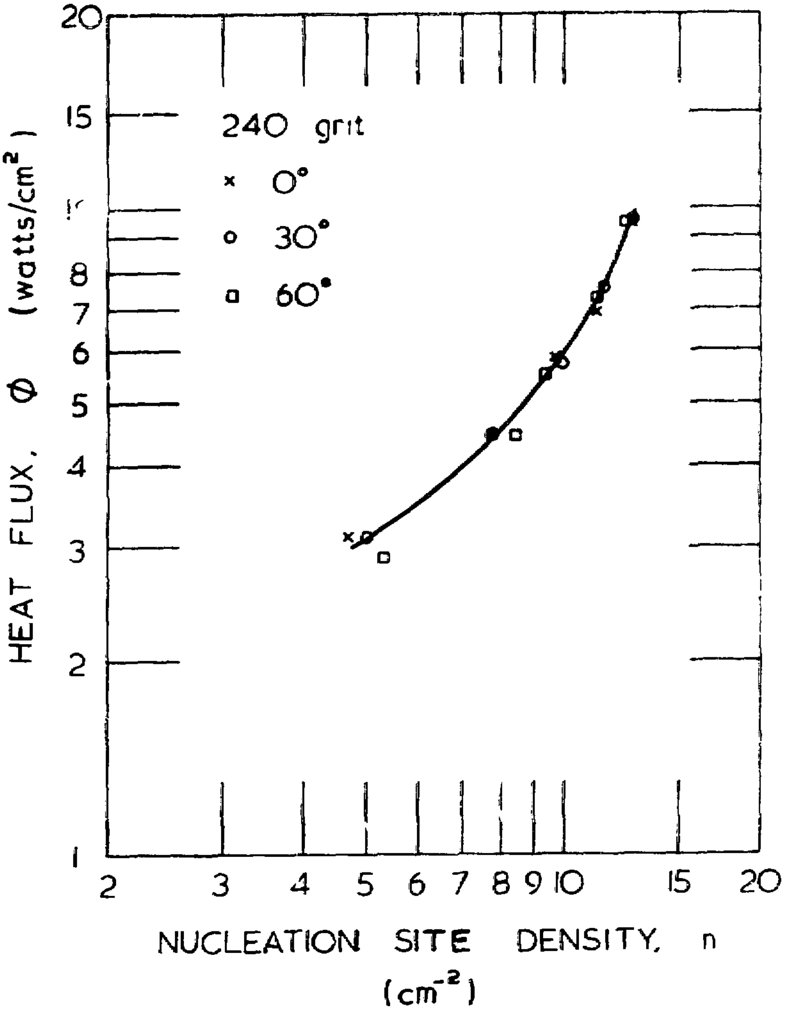

FIG II Heat Flux verses Nucleation Site Density on log-log axes.

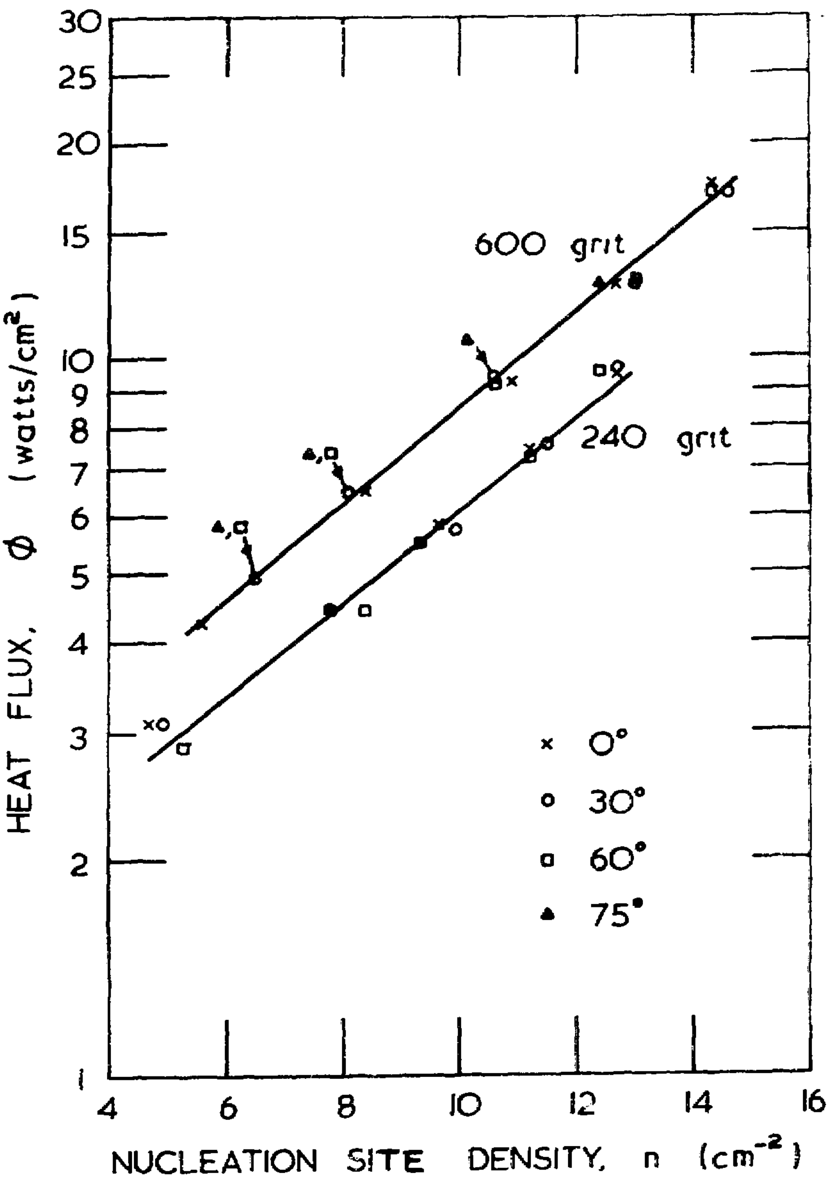

FIG 12 Heat Flux verses Nucleation Site Density on log-linear axes.