*Int. J. Heat Mass Transfer.* Vol. 9, pp. 365–377. Pergamon Press 1966. Printed in Great Britain

# THE CRITICAL HEAT FLUX FOR ELECTRICALLY HEATED WIRES IN SATURATED POOL BOILING

C. C. PITTS* and G. LEPPERT
Department of Mechanical Engineering, Stanford University, Stanford, California

(*Received* 15 *January* 1965 *and in revised form* 13 *August* 1965)

**Abstract**—An experimental and analytical investigation of the variation of critical heat flux with wire diameter and wire material in saturated pool boiling of water and mixtures of water–methyl ethyl ketone is presented and compared with the results of other investigators.

Water data are presented for electrically heated wires of tungsten, Tophet A, copper and constantan with diameters ranging from 0·0005 to 0·051 inch. Measurements are also presented for 0·0035, 0·010 and 0·051 inch Tophet A wires in mixtures of water–methyl ethyl ketone with concentrations of 0–17 per cent by weight of the ketone.

A simplified model is proposed for the critical flux phenomenon with small wires. An analysis based on this model agrees qualitatively with the experimental results. There is little variation of the critical flux with wire properties over the entire range of diameters tested, although the thermal coefficient of resistivity appears to have some effect, especially for very small wires.

## NOMENCLATURE

| | |
|---|---|
| $c$, | specific heat; |
| $D$, | wire diameter; |
| $g$, | acceleration of gravity; |
| $g_c$, | dimensional constant relating force and mass in Newton's law of motion; |
| $h$, | average heat-transfer coefficient; |
| $k$, | thermal conductivity; |
| $N_{Bi}$, | Biot number, $hr_o/k$; |
| $N_{Fo}$, | Fourier number, $\alpha\tau/r_o^2$; |
| $N_{Pr}$, | Prandtl number, $\mu c/k$; |
| $q'''$, | volumetric energy generation rate; |
| $q''$, | heat flux; |
| $q''_c$, | critical heat flux; |
| $r$, | radial wire dimension; |
| $r_b$, | bubble radius; |
| $r_o$, | wire radius; |
| $t$, | temperature; |
| $t_c$, | critical temperature; |
| $t_l$, | liquid temperature; |
| $\Delta t_c$, | critical temperature difference, $t_c - t_l$. |

Greek symbols

| | |
|---|---|
| $\alpha$, | thermal diffusivity; |
| $\beta$, | contact angle; |
| $\theta$, | angular wire dimension; |
| $\theta_h$, | half angle subtended by idealized bubble on a wire surface; |
| $\lambda$, | latent heat of vaporization; |
| $\mu$, | viscosity; |
| $\rho_l$, | liquid density; |
| $\rho_v$, | vapor density; |
| $\sigma$, | surface tension; |
| $\tau$, | time. |

## INTRODUCTION

APPARENTLY the first determinations of the critical heat flux on an electrically heated wire were made by Moscicki and Broder [1] using platinum wires both in subcooled and in saturated water. They suggested that there is a critical heater temperature, independent of liquid temperature, above which the surface cannot remain in nucleate boiling. Nukiyama [2] measured the critical heat flux in saturated pool boiling of water using platinum, nickel and nichrome wires. He observed that the critical heat flux decreases significantly with wire diameter.

Critical flux data for platinum wires of various diameters in saturated water have been presented by Marcy [3], Boscov [4], Rinaldo [5], Day [6], Addoms [7], and Rao, Desai and Gogate [8].

---

* Present address: Pomona Division of General Dynamics, Pomona, California.

Farber and Scorah [9] published results for wires of Chromel C, Chromel A, nickel and tungsten. Castles [10] measured the critical flux in pool boiling using wires of platinum, aluminium, nickel, Chromel A and Chromel C. He suggested that with small diameter, electrically heated wires it is possible to have a localized "pseudo" vapor binding at a much lower flux than the value required for a cylinder heated with pressurized steam. He called the latter value the "true" maximum heat flux.

McAdams, Addoms, Rinaldo and Day [11] noted the increase in critical flux with diameter and concluded from the data of Rinaldo [5] and Day [6] that the critical heat flux for water at atmospheric pressure increases with wire diameter up to about 0·012 inch and then becomes constant at 380 000 Btu/h ft$^2$. Bernath [12] summarized prior data and presented a best-fit correlation which indicates that the critical flux increases with diameter up to about 0·06 inch, but is independent of diameter for larger wires.

An extensive experimental investigation of the effects of heater geometry and composition has been made by Ivey and Morris [13]. Their work includes experiments in saturated water with platinum wires ranging in diameter from 0·00075 to 0·030 inch and with nickel, chromel, silver, stainless steel and aluminum wires of various sizes. They point out that it is doubtful if the term "critical heat flux" as a vapor bubble packing phenomenon could be applied to small wires where the diameter of the bubble is many times the wire diameter.

The critical heat flux in aqueous mixtures of aliphatic organic compounds was first investigated by Bonilla and Perry [14] using a flat plate. Their data show that the critical flux for the mixtures is higher than the value for either pure component. Extensive experiments have been conducted by Vos, van Wijk and von Stralen [15–23] to determine the critical flux in aqueous binary mixtures using small wires. In each case their data show a maximum in the curve of critical heat flux versus concentration. They observed that the bubbles in the binary mixtures are considerably smaller than in either pure component, and the bubble size is a minimum at the concentration where the maximum critical flux occurs. Similar findings were reported by Fastovskii and Artym [24]. Carne [25] found that the magnitude of the maxima in critical heat flux for binary mixtures were reduced and in many cases eliminated for a $\frac{1}{8}$ inch rod. Owens [26] has reported that the addition of organic fluids to water decreases the critical flux approximately 30 per cent for a $\frac{3}{16}$ inch tube.

## EXPERIMENTAL APPARATUS AND PROCEDURE

The pool boiling apparatus used in these experiments consists of a covered stainless steel tank 6 in wide, 8 in long and 14 in deep, with front and back walls fitted with pyrex glass windows for visual and photographic observations. The tank is wrapped with a flexible tape guard heater and is insulated. The liquid surface is maintained approximately $5\frac{1}{2}$ in above the heated wire, and the vapor space is vented to the atmosphere through a reflux condenser in the lid.

Two stainless steel electrodes are suspended in the pool through insulators in the lid and the test wires are held at each end between copper inserts which are in turn bolted between stainless steel blocks attached to the bottom of the electrodes. One of the electrodes and the tank are grounded, and the polarity is adjusted so that the test wires are positive with respect to ground [10, 27]. The voltmeter, ammeter and shunts used to measure d.c. heating are accurate to 0·5 per cent.

An immersion heater near the bottom of the tank serves to maintain the liquid at saturation temperature during an experiment. Two layers of stainless steel screen and a perforated stainless steel plate placed over the immersion heater prevent bubbles which rise from the heater from collecting in columns or impinging on the test element.

A series of preliminary experiments were conducted with water to determine what variables significantly affect the critical flux and to establish a standard experimental procedure. Mineral content was found to have the greatest effect of the variables examined. In cases where the mineral content was high, the flux was as much as 100 per cent higher than the maximum values found for demineralized water. In the final experiments the water was demineralized so that resistivity was maintained at a value greater than $5 \times 10^5\ \Omega$ cm.

The wires in the final experiments were used in the "as received" state after washing with detergent and rinsing, first with tap water, then with distilled water. Several preliminary tests were made with wires which had been annealed in film boiling. The critical flux for these wires was only a few per cent higher than values found for wires in the "as received" state. Furthermore, annealing did not reduce the experimental scatter [9].

Vliet and Leppert [28] have reported that for forced convection, subcooled boiling aging the test section in nucleate boiling tends to increase the critical flux. Similar results were found in the present experiments, although the effect was less pronounced. The rate of power increase also has a significant effect on reproducibility of the results. This is particularly true for 0·051 inch Tophet A wires over a range of heat fluxes from 80 000 to 120 000 Btu/h ft$^2$. In this range large power fluctuations were observed, indicating that the resistance of the wire was fluctuating because of large temperature oscillations. The cause of these oscillations is not known, since there is no detectable change in the boiling pattern. If the heat flux is increased rapidly in this range, the element often goes into film boiling. The aging time was standardized by boiling the water from the immersion heater for 5 min before turning on power to each new test section. This process also reduced the air content of the water to less than 2·5 ml/l. The power to the test section was next increased to about 60 per cent of the expected critical flux and maintained at this level for 5 min to permit nucleation sites to become active. The power was then increased slowly at 2 min intervals in steps of 5–7 per cent of the expected maximum flux until the critical condition was reached.

The concentration of methyl ethyl ketone in the binary mixture experiments was determined by measuring the density of the mixture [29].

## ANALYSIS

When the bubble diameters approach the wire diameter in magnitude, the heated wire can become blanketed locally by a few coalescing bubbles. Hence film boiling can occur, at least locally, at a lower heat flux than would be required with a large rod or a flat plate [10, 12]. When a bubble forms at a typical nucleation site, the heat-transfer process to the vapor will be much less effective than to the liquid, and the surface temperature will rise. When the bubble breaks off and that part of the surface is once again in contact with liquid, the heat transfer will improve and the site will cool. The magnitude of these temperature oscillations will increase as the heat flux is increased.

Suppose that during the time a bubble or a patch of coalescing bubbles is attached to the surface the temperature under the bubble rises to a level such that the liquid can no longer return to contact the surface [1]. Instead of breaking away, the bubble patch will spread and blanket the perimeter of the wire, causing local film boiling. An attempt will now be made to predict variations of the critical heat flux with wire diameter by analysing an idealized model to find the wire temperature under a vapor patch and to determine the energy-generation rate necessary to give the critical surface temperature.

Suppose that bubbles from adjacent nucleation sites along the wire coalesce to form a vapor patch of sufficient length that conduction along the wire is negligible. Let this patch be idealized as a cylinder of radius $r_b$, with a contact angle $\beta$, as in Fig. 1. The half angle subtended by the

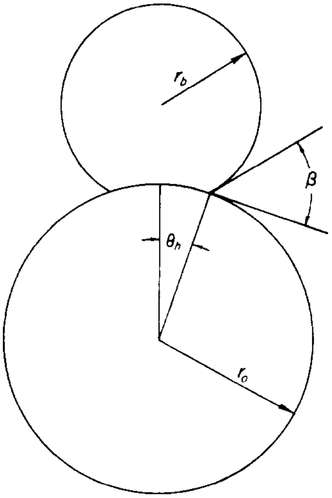


FIG. 1. Idealized analytical model of vapor patch on the surface of a wire.

cylindrical patch on the surface of a wire of radius $r_o$ is given by

$$\tan\theta_h = \frac{\sin\beta}{\cos\beta + r_o/r_b} \qquad (1)$$

Assume that there is an average heat-transfer coefficient from the wire to the liquid and that the heat transferred directly to the vapor is negligible. It is recognized that this is in opposition to the model proposed by Moore and Mesler [30], who hypothesize that a liquid film remains on the surface when a bubble forms. They suggest that evaporation of this microlayer into the bubble cools the surface more effectively than does the convection away from the bubble. However, since experimental observations show that film boiling on small wires is initiated under a bubble, it seems that, if this film does exist, it must evaporate completely while the bubble is on the surface, leaving a section of the wire partially insulated. Otherwise the effective cooling of the evaporating liquid layer would tend to prevent the onset of film boiling.

Although the thermal conductivity and the electrical resistivity of the wire are functions of temperature, it will be assumed that they are constant to simplify the solution. The differential equation and boundary conditions which describe the steady-state temperature distribution in a wire which has a constant volumetric heat generation and which meets the restrictions of the proposed model are:

$$\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r} + \frac{1}{r^2}\frac{\partial^2 t}{\partial \theta^2} + \frac{q'''}{k} = 0 \qquad (2)$$

$$\frac{\partial t}{\partial r} = 0, \quad \text{for} \quad r = r_o \quad \text{and} \quad |\theta| \leqslant \theta_h \qquad (2a)$$

$$-\frac{\partial t}{\partial r} = \frac{h}{k}(t - t_l),$$

$$\text{for} \quad r = r_o \quad \text{and} \quad \theta_h \leqslant |\theta| \leqslant \pi \qquad (2b)$$

$$t \text{ is everywhere finite} \qquad (2c)$$

$$t(\theta) = t(-\theta) \qquad (2d)$$

$$t(\theta) = t(\theta + 2\pi) \qquad (2e)$$

This set of equations can be solved by the method of separation of variables to give

$$\frac{(t - t_l)k}{q'''r_o^2} = \frac{1 - (r/r_o)^2}{4} + \frac{1}{2N_{Bi}} + a_o + \sum_{n=1}^{\infty} a_n \left(\frac{r}{r_o}\right)^n \cos n\theta \qquad (3)$$

$$a_o\,[2N_{Bi}(\pi - \theta_h)] - \sum_{n=1}^{\infty} a_n \left[2N_{Bi}\frac{\sin n\theta_h}{n}\right] = \theta_h \qquad (3a)$$

$$\left.\begin{aligned} & -a_o\left[2N_{Bi}\frac{\sin m\theta_h}{m}\right] + a_m \\ & \left[m\pi + N_{Bi}\left(\pi - \theta_h - \frac{\sin 2m\theta_h}{2m}\right)\right] \\ & -\sum_{\substack{n=1\\ n\neq m}}^{\infty} a_n\left[N_{Bi}\left(\frac{\sin(n-m)\theta_h}{(n-m)}\right.\right. \\ & \left.\left. + \frac{\sin(n+m)\theta_h}{(n+m)}\right)\right] = \frac{\sin m\theta_h}{m} \end{aligned}\right\} \qquad (3b)$$

for each $m = 1, 2, 3, \ldots\ldots$

Equations 3(a), (b) represent an infinite set of linear algebraic equations which, if they could be solved, would give the values of $a_n$. The solution of an infinite number of equations is, of course, not possible. However, it has been found that when the Biot number is less than one, the values of $a_n$ in equations 3(a) and 3(b) are weak functions of each other and it is possible to obtain an approximate solution for the first few values of $a_n$ by solving a relatively small number of truncated equations. The LINEAR-SYSTEM code by McKeeman [31] for the IBM 7090 computer was used to calculate for the first eighty Fourier coefficients.

The average heat flux based on the total surface area of the wire is given by

$$q'' = \frac{q'''r_o}{2}$$

Thus the temperature distribution can be written as

$$\frac{(t - t_l)h}{q''} = 1 + \left[\frac{1 - (r/r_o)^2}{2}\right] N_{Bi} + 2N_{Bi}\left\{a_o + \sum_{n=1}^{\infty} a_n \left(\frac{r}{r_o}\right)^n \cos n\theta\right\} \qquad (4)$$

We are interested in what average flux will give the critical temperature under the bubble, where $r = r_o$ and $\theta = 0$. This flux is found from equation (4):

$$\frac{q_c''}{h\Delta t_c} = \frac{1}{1 + 2N_{Bi}\sum\limits_{n=0}^{\infty} a_n}$$

For values of $\theta_h$ greater than 0·1 radians the summation of the Fourier coefficients converges so rapidly that

$$\sum_{m=0}^{\infty} a_n = \sum_{m=0}^{79} a_n$$

The calculated values of the dimensionless group, $q_c''/h\Delta t_c$, are plotted in Fig. 2 as a function of the Biot number for various values of $\theta_h$.

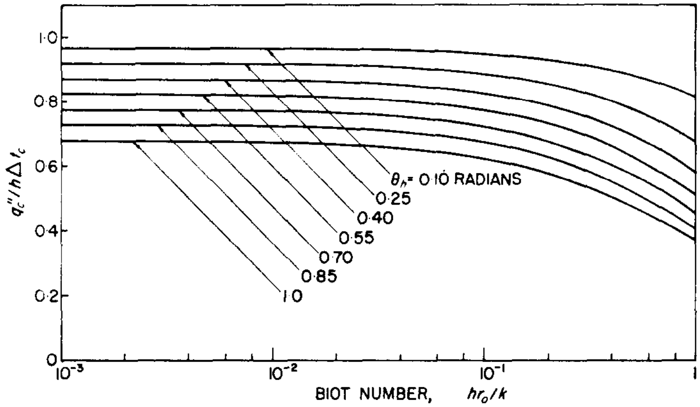


FIG. 2. Variation of $q_c''/h\Delta t_c$ with $N_{Bi}$ for various half-angles of insulation.

Rohsenow [32] has shown that for a given liquid–surface combination the variation of the heat-transfer coefficient with heat flux in saturated pool boiling can be expressed by the relation

$$h = \frac{(q'')^{2/3}}{A_f C_{sf}}$$

where

$$A_f = \frac{\lambda}{c}\left[\frac{1}{\mu\lambda}\left(\frac{g_c\sigma}{g(\rho_l - \rho_v)}\right)^{1/2}\right]^{1/3} N_{Pr}^{1{\cdot}7}$$

$C_{sf}$ is a function of the liquid–surface combination and has the value 0·013 for platinum–water and copper–water. For saturated water at atmospheric pressure

$$\frac{1}{C_{sf}A_f} \cong 1{\cdot}3\left[\frac{\text{Btu}}{\text{h ft}^2}\right]^{1/3}(\text{degF})^{-1}$$

for platinum and copper with water. It will be assumed, in absence of other information, that this relation also holds for the other combinations of interest here.

The shapes of the analytical curves are unaffected by the choice of critical temperature difference and are not significantly affected by the choice of contact angle. However, the vertical position of these curves depends on the values selected for these two parameters. Cole [33] has measured contact angles between 35 and 75 degrees for steam bubbles forming on a heated strip near the critical flux while Staniszewski [34] reports a contact angle approximately 43 degrees for water. Staniszewski's value will be used for calculating the analytical curves presented in this paper. With this choice of contact angle, a critical temperature difference of 67 degF was found to give the best agreement with the experimental data. This value is somewhat higher than the critical temperature differences reported in the literature (between 40 and 60 degF). However, the reported values are average temperature differences over an entire wire or tube at the critical flux before the element makes the transition to film boiling. Therefore, it would be expected that the temperature which initiates the critical condition under a bubble would be somewhat higher.

An examination of photographs of boiling from various sizes of wire indicates that, although the bubbles from larger wires coalesce after breaking away to form large agglomerates of vapor, the bubbles attached to the wire are approximately the same size independent of wire diameter. A bubble diameter of 0·020 inch gives the best agreement between the analysis and the data and will therefore be used to compare the trends predicted by the analysis with experimental data. A study of boiling from 0·020 inch wires show that most of the bubbles attached to the wire are about the same diameter as the wire, indicating that a 0·020 inch bubble diameter is a reasonable choice.

## EXPERIMENTAL RESULTS

Ivey and Morris [13] observed that with small diameter wires the critical condition is quite different than with large rods. In the present paper, the critical flux is defined as the flux which gives rise to a temperature excursion of such magnitude that a portion of the wire is visually observed to glow, even if the glowing portion is small and the excursion is short-lived. Before discussing the critical condition further, it is useful to describe the boiling patterns for wires of various diameters at the critical flux.

For wires larger than about 0·040 inch, the pattern resembles Zuber's description of boiling from a flat plate near the critical flux [35]. Large patches of vapor coalesce on the surface of the wire, and it is difficult to detect individual bubbles. The vapor appears to rise in almost continuous columns which break up into large bubbles some distance from the wire. However, for smaller wires, the boiling pattern near the critical flux is different. Figure 3 shows photographs of pool boiling from tungsten wires of various sizes at approximately 89–100 per cent of the critical flux. With the 0·020 inch wire, the bubbles coalesce to form vapor agglomerates, but individual bubbles with diameters of the same order of magnitude as that of the wire are plainly visible. The 0·010 inch tungsten wire shows bubbles quite closely spaced but with very few of the large vapor patches which are characteristic of the boiling pattern for larger wires. Finally, the 0·003 inch wire shows a similar pattern to the 0·010 inch wire, except the bubble spacing has increased with decreasing diameter. Several bubbles which are an order of magnitude larger than the wire are also visible on the wire. Bubble spacing near the critical flux continues to increase with decreasing wire diameter until only three or four nucleation sites are active on a $3\frac{1}{2}$ inch length of 0·0005 inch wire at the critical flux.

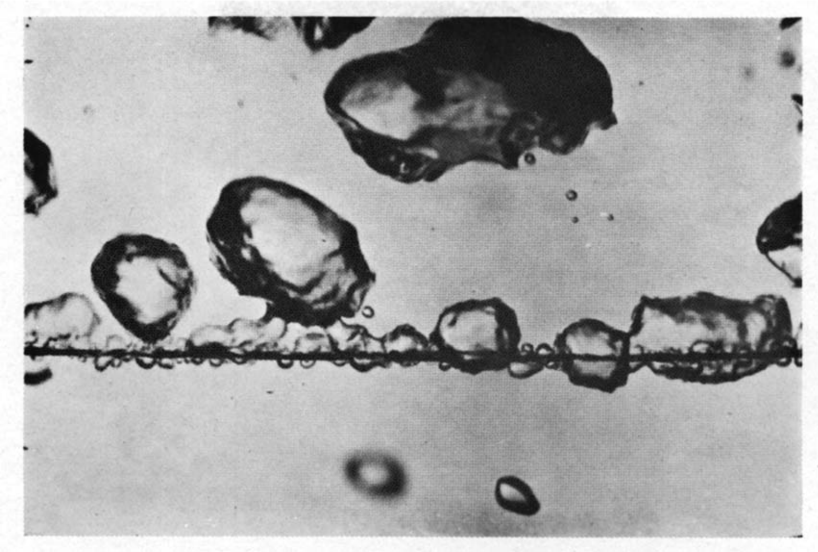
No difficulty arises in detecting the critical flux on wires with diameters of 0·010 inch or greater, since these wires either melt or remain in stable film boiling over at least part of their length. However, the patches of film boiling quite often collapse with the 0·006 inch wires. Localized film boiling on a 0·006 inch tungsten wire is shown in Fig. 4. This film collapsed soon after the photograph was taken and the wire continued in nucleate boiling.

For even smaller wires, the film, which appears to result from coalescing bubbles at two or more adjacent nucleation sites, always collapses. In several cases the heat flux for 0·001 and 0·003 inch tungsten was increased until the wire melted. The heat flux at which the wires melted was from 10 to 20 per cent higher than the flux at which the wires were first observed to glow.

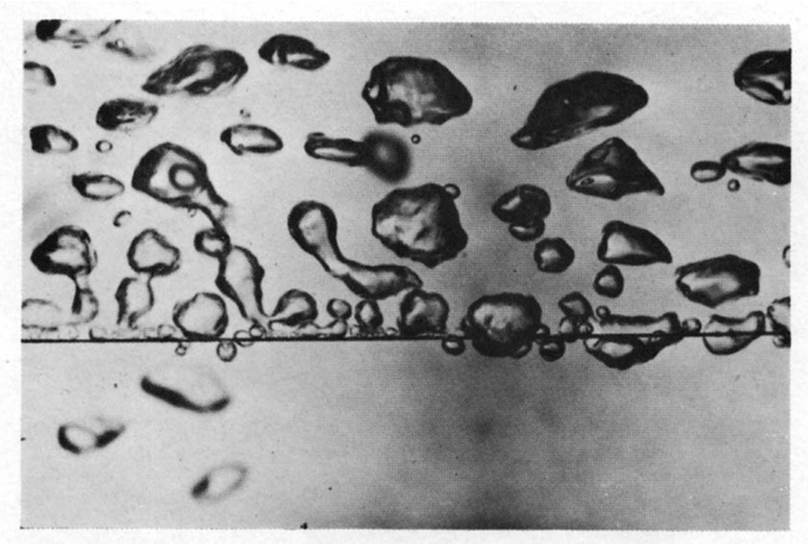
The critical condition on the 0·0005 inch tungsten wires occurred with a single bubble, although not at the heat flux at which the first bubble formed. In a few cases these wires melted at the critical flux, but in general the wire failed at a flux which was 10–20 per cent higher than the critical value.

## COMPARISON WITH THE RESULTS OF OTHER INVESTIGATORS

Figure 5 shows the present results compared to data by Ivey and Morris [13] for platinum wires, which are the only data from a single source which cover a wide range of diameters. The general agreement is good, with both sets of data showing a decrease in the critical flux with decreasing diameter down to about 0·010 inch. For smaller diameter wires the critical heat flux remains nearly constant or increases with decreasing diameter. The relatively large disagreement between the two sets of data for very small diameter wires is believed to be a result of the different methods of detecting the critical condition, since Ivey and Morris used a resistance-bridge burnout detector.

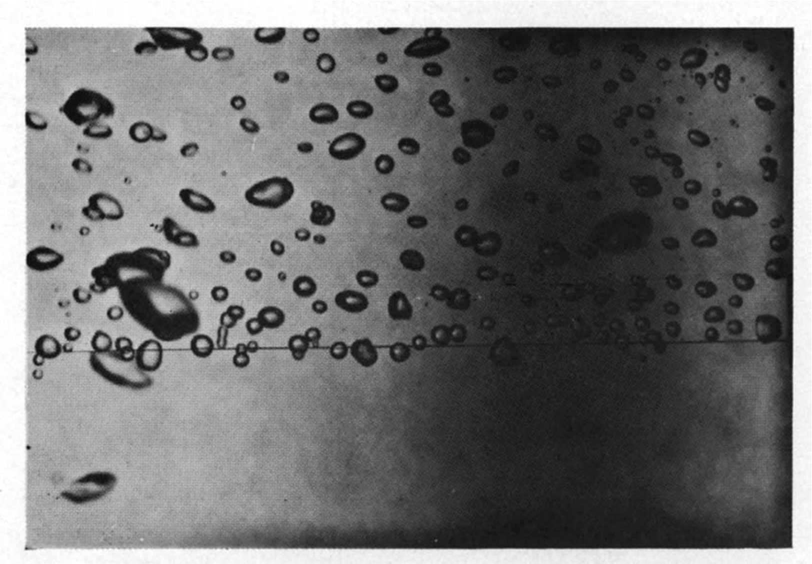


(*a*) $D = 0{\cdot}020$ inch, $q'' = 334\,000$ Btu/h ft$^2$ $= 0{\cdot}89\, q_c''$.



(*b*) $D = 0{\cdot}010$ inch, $q'' = 228\,000$ Btu/h ft$^2$ $= 0{\cdot}94\, q_c''$.

FIG. 3. Saturated pool boiling of water at atmospheric pressure with electrically heated tungsten wires.



(*c*) $D$ = 0·003 inch. $q''$ = 212 000 Btu/h ft$^2$ = $q_c''$.

FIG. 3 (*cont.*)

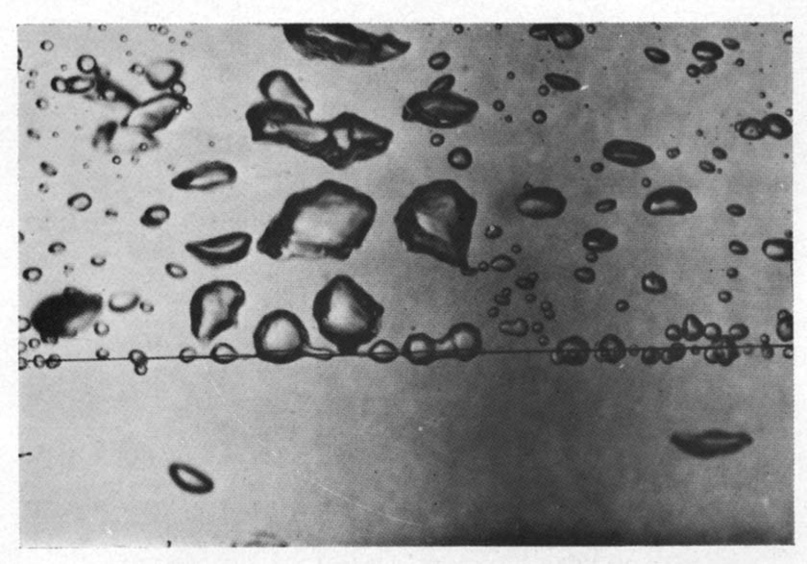


FIG. 4. Localized film boiling on a 0·006 inch tungsten wire in saturated water at atmospheric pressure, $q''$ = 248 000 Btu/h ft$^2$ = $q_c''$.

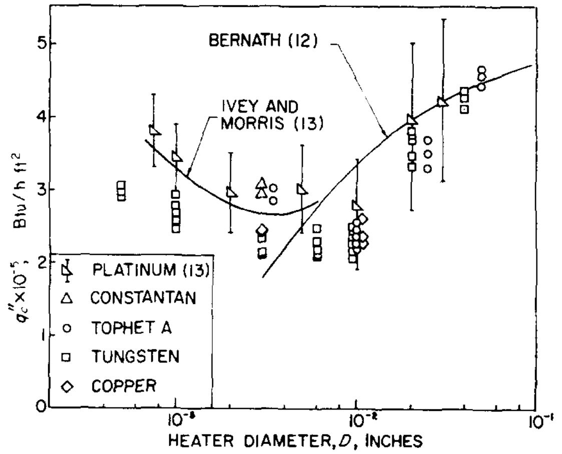


FIG. 5. Comparison of experimental data with results of other investigators.

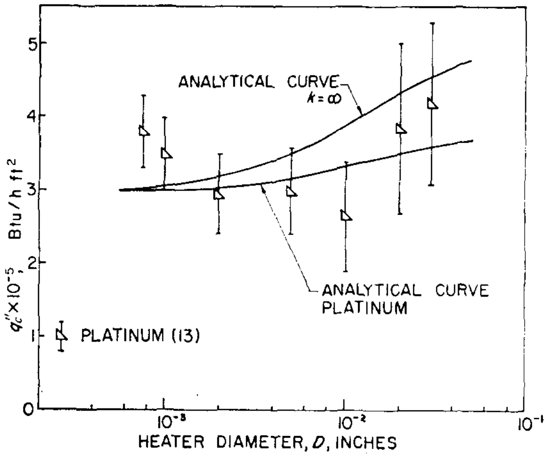


FIG. 7. Comparison of analytical results with experimental data of Ivey and Morris [13].

The correlation given by Bernath [12] is also shown in Fig. 5. Agreement with both sets of data is good for the larger wires, but the Bernath correlation does not show the correct trend below about 0·020 inch.

The variations of the critical flux with diameter predicted by the analysis for tungsten, Tophet A and platinum wires are shown in Figs. 6 and 7, together with the present data and the range of data presented by Ivey and Morris [13]. The theoretical variation has been calculated in each case only up to a Biot number of one, since for larger values the solution for the Fourier coefficients is questionable.

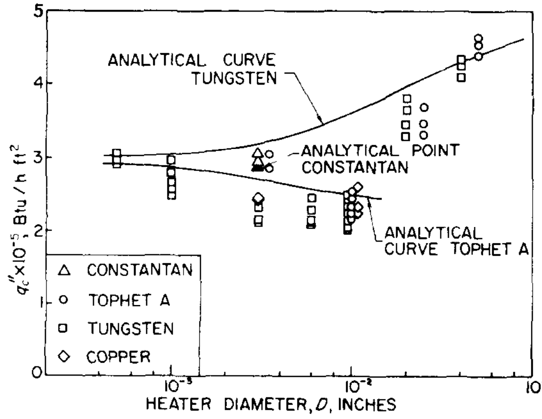


FIG. 6. Comparison of analytical results with experimental data.

Although the data show more pronounced variations than are predicted by the analysis, the same trends are shown. The rather large disagreement between the predicted curve and the data for tungsten wires between 0·001 and 0·010 inch probably results from assuming a constant electrical resistance in the analysis. When a bubble forms on the surface of a wire made of a metal such as tungsten, which has a large temperature coefficient of resistivity, the temperature rise under the bubble will cause the resistance and hence the energy generation to increase in that area. The temperature will rise further due to the increased energy and so on until the critical temperature is reached. This may occur at a lower heat flux than would be necessary for a material whose resistance does not change with temperature. This argument is supported by the fact that the data for the 0·0035 inch Tophet A wires compare quite well with the predicted curve, as do the experimental points for 0·003 inch constantan wires. Both of these alloys have low temperature coefficients of resistivity.

The increase in the critical flux with decreasing diameter for the tungsten and platinum wires with diameters smaller than 0·003 inch is not predicted by the analysis. This increase may be due to vibration of the wires as Ivey and Morris have suggested, although no vibrations were observed in the present experiments. Another possible explanation is that, since the bubble spacing is so large for these wires, it is less likely that two adjacent bubbles will coalesce and the two-dimensional assumption of the analysis would probably not be valid.

The decreasing critical flux with increasing diameter shown by both data and analysis for the small Tophet A wires is an interesting anomaly. The thermal conductivity for this alloy is only about 6·5 Btu/h ft degF, so the Biot number is relatively large even for the small wires. From equation (1) it can be seen that when the bubble diameter is large compared to the wire diameter, the angle $\theta_h$ is not significantly different from $\beta$. Thus, $\theta_h$ remains nearly constant over a fairly wide range of diameters. The surface temperature distributions for two wires of the same material and the same $\theta_h$ but with different diameters can be found from equation (8). The temperature is found to be nearly constant over the entire surface of the smaller wire, and, since convection is proportional to the temperature difference, the heat transfer over the part of the wire not insulated by the bubble is nearly constant. However, for the larger wire the temperature decreases rapidly away from the insulated sector and the heat-transfer rate over most of the wire is relatively low. The average heat flux, based on total surface area, necessary to attain the same critical temperature will therefore be higher for the small wire [27].

For materials with large thermal conductivities and correspondingly small Biot numbers the conduction within the wire is so effective that, even for large wires, the surface temperature is nearly constant. Therefore, the critical flux is nearly the same for different sizes of wires with approximately the same insulated angle. Equation (1) also shows that for wires with diameters of the same order as the bubble diameter, the angle $\theta_h$ decreases with increasing wire size. Therefore, since more of the surface is transferring heat, the average flux necessary to attain the critical temperature increases with wire diameter, as is shown in Figs. 6 and 7 for tungsten and platinum.

An analytical curve for a hypothetical material with infinite thermal conductivity is plotted in Fig. 7 for comparison with the curve for platinum ($k$ = 40 Btu/h ft degF). For small diameters the difference is small, and even with wires as large as 0·040 inch, where the boiling pattern is such that the model probably does not apply, the difference is less than 30 per cent. Furthermore, since the bubbles are attached to the surface for a finite amount of time, it might be expected that for larger diameter wires a transient effect would be important. A measure of how closely the temperature distribution in the wire approaches steady state is given by the Fourier number

$$N_{Fo} = a\tau/r_o^2$$

where $a$ is the thermal diffusivity of the metal and $\tau$ is the time that a bubble or vapor patch is attached to the surface. Since materials with low thermal diffusivities would require a longer time to reach the steady state temperature distribution, a larger heat flux would be required for their surfaces to reach critical temperature. This fact may account for the increase in the critical flux for Tophet A wires between 0·010 inch and 0·051 inch that does not appear to be predicted by the steady state analysis. It would also tend to reduce the differences in the critical flux which are predicted by the steady-state analysis for wires with different conductivities.

## THE CRITICAL HEAT FLUX IN TWO-COMPONENT MIXTURES

The boiling patterns in binary mixtures have been studied visually and with the aid of high speed motion pictures over a range of concentrations from zero to approximately 17 per cent by weight of methyl ethyl ketone in water. In all cases the sizes of the bubbles are considerably smaller in the binary mixtures than in water, and there appears to be a minimum bubble size at concentrations between 4 and 7 per cent.

At concentrations less than 1 per cent the boiling pattern is similar to the patterns observed with water on all wire sizes tested, even though the bubbles are smaller and the nucleation is somewhat more active. However, at higher concentrations the pattern is quite different. The boiling is so vigorous, even with small wires, that it is difficult to see the heater. The bubbles, which appear to be at least an order of magnitude smaller than the bubbles on the same size wire in water, rise in a dense cloud from the top of the wire to the surface of the boiling pool. There is some tendency toward coalescence of the small bubbles, but less in the mixtures than in water.

The boiling patterns on the 0·051 inch diameter wires appear to be about the same in the binary mixtures as in water. An almost continuous film of vapor oscillates on top of the wire, and the vapor leaves the wire in columns. The film of vapor that forms on the very small wires at the critical condition always collapses, and nucleation is not as active at that spot for several minutes thereafter. This tendency of film boiling to make nucleation sites inactive was also observed in water.

At concentrations greater than about 14 per cent the condensate which falls back into the pool appears as oily droplets. Since water will dissolve only about 18 per cent of its weight of methyl ethyl ketone, the condensate, which is rich in the ketone, is not readily dissolved by the liquid in the pool. No data were taken at concentrations greater than 17 per cent, since at higher concentrations two layers of liquid are present, each with a different concentration. The violent mixing of the boiling causes the two phases to emulsify, and it is felt that the data taken with these concentrations would have little or no significance. Fastovskii and Artym [24] and von Stralen *et al.* [15–23] report data in the region of two phase mixtures, with reported concentrations apparently based on a weighed amount of ketone and water placed in the pool at the beginning of an experiment.

Critical heat flux experiments were conducted with Tophet A wires with diameters of 0·0035, 0·010 and 0·051 inch. Figure 8 shows the variation of the critical flux with concentration for the 0·010 inch wires together with data by von Stralen *et al.* and Fastovskii and Artym for wires of approximately the same diameter. The agreement is poor for concentrations less than approximately 10 per cent. However, the agreement for water and for higher concentrations of the ketone is good. The experimental scatter is so large that it is difficult to establish a correlation, particularly in the range of concentrations between 2 and 10 per cent. However, a suggested correlation is shown which appears to follow the trends of the data. The maximum in the present data is less pronounced and occurs at a somewhat higher concentration than the maximum found by the other experimenters.

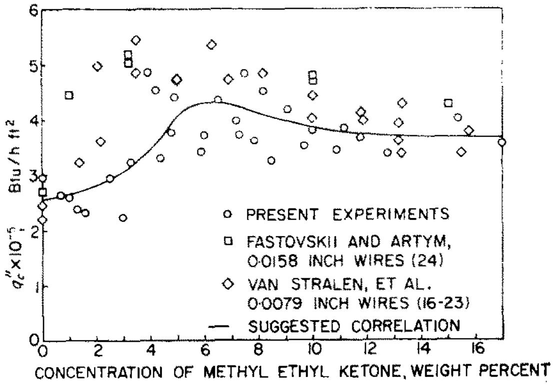


FIG. 8. Variation of the critical heat flux with concentration of methyl ethyl ketone in water for 0·010 inch wires.

Figure 9 shows the experimental data taken with 0·051 inch wires. The critical heat flux for low concentrations of methyl ethyl ketone is slightly below the value for water. For concentrations greater than about 2 per cent, the critical flux increases and reaches a maximum at about 9·5 per cent. This maximum is approximately 30 per cent higher than the critical flux for water. Carne's data [25] for $\frac{1}{8}$ inch rods and Owens' data [26] for $\frac{3}{16}$ inch tubes are also plotted in Fig. 9. Although Carne's data do not show a maximum or minimum the agreement with the present data is within the range of experimental scatter. Owens' data decrease sharply at low concentrations and then remain

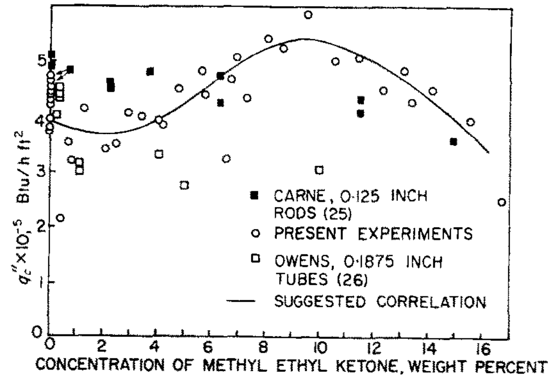


FIG. 9. Variation of the critical heat flux with concentration of methyl ethyl ketone in water for 0·051 inch wires.

nearly constant at a value approximately 30 per cent lower than the critical flux for water. Although Owens' heater elements were larger than the 0·051 inch wires, it would not be expected that diameter would have a significant effect, since it has been shown that the critical flux is nearly independent of diameter for large heaters. This independence is also shown by the excellent agreement between the three sets of data for water.

The decrease in the critical flux at low concentrations is probably the result of the rather large decrease in surface tension which results from the addition of small amounts of methyl ethyl ketone to water [36]. It is difficult to say what causes the increase in the critical flux between 2 and 10 per cent, since there is virtually no information available on the properties of mixtures of water and methyl ethyl ketone at their saturation temperatures. The problem of predicting values of the critical flux for the mixtures is considerably greater than with water, since mass transfer plays a more important role in the mixtures.

In general the reproducibility of the 0·051 inch wire data is quite good. However, it was found that increasing the flux too fast in the range between 80 000 and 120 000 Btu/h ft$^2$ often resulted in premature film boiling. Large oscillations in electrical resistance were observed in this range similar to those already mentioned for 0·051 inch wires in water.

Figure 10 shows the critical heat flux data for 0·0035 inch wires. The experimental scatter of this data was small over the entire range of concentrations. Film boiling generally occurred quite close to the electrodes, possibly because of interference in the flow patterns. However, the critical condition was reached at other spots on the wire at heat fluxes which were only a few per cent higher than the value at which film boiling was first observed near the electrodes.

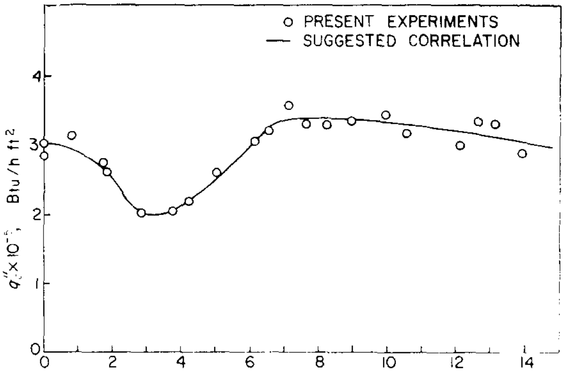


FIG. 10. Variation of the critical heat flux with concentration of methyl ethyl ketone in water for 0·0035 inch wires.

Comparison of the proposed correlations for the three wire sizes tested with the binary mixtures indicates that the effects of the reduced bubble size on the critical flux can be explained qualitatively by the analytical model. Since the bubble diameters are of the same order of magnitude as the wires, the angle subtended by a bubble on the surface of the wire decreases with increasing wire size [equation (1)]. Therefore, a higher heat flux is required to reach the critical temperature as the wire size increases. It should be noted that the critical fluxes for the 0·010 and 0·051 inch wires are nearly the same in the range of concentration between 4 and 6 per cent, for which the bubbles appear to have a minimum size [17].

## CONCLUSIONS

Experimental values of the critical heat flux are significantly affected by experimental conditions and procedure, particularly water purity and rate of power increase.

For pool boiling of water at atmospheric pressure, the critical heat flux is nearly independent of wire diameter for wires larger than about 0·05 inch. However, for wires smaller than 0·05 inch, the critical flux varies with diameter, and this variation has been explained qualitatively by a simple model.

In the range of diameters between 0·01 inch and 0·05 inch, the critical flux increases with diameter because the bubble diameters are of the same order as the wire diameter. Hence, as the wire diameter increases, the sector which can be insulated by a bubble decreases, and it requires a higher heat flux to attain the critical temperature.

For wires between 0·003 and 0·01 inch, the critical flux remains nearly constant or decreases slightly with increasing diameter. Since the bubbles are large compared to the wire in this range, the sector of a wire insulated by a bubble does not change significantly with wire diameter. For wires which have moderate or high thermal conductivity, the critical flux remains nearly constant. However, for wires with a very low thermal conductivity, the heat transfer through the wire is so ineffective that the critical temperature under the bubble can be reached at a lower heat flux for the larger wires, and the critical flux therefore decreases with increasing diameter.

The critical flux increases with decreasing diameter for wires smaller than about 0·003 inch. While this behavior is not predicted by the analysis, it seems likely that, since the bubbles are spaced further apart for the smaller diameter wires, it is more difficult for adjacent bubbles to coalesce and form a vapor patch. Hence, a higher heat flux is required to reach the critical temperature.

The data show only slight differences in the critical flux for wires of the various materials tested over the entire range of diameters. The analysis predicts this behavior for all wires smaller than 0·01 inch and also between 0·01 and 0·05 inch for conductivities greater than about 40 Btu/h ft degF. However, for wires with lower thermal conductivities, the analysis predicts a substantial variation of the critical flux with conductivity. This discrepancy may be caused by the failure of large wires with low thermal conductivities to reach the steady-state condition assumed in the analysis.

The addition of small amounts of methyl ethyl ketone to water significantly reduces the size of boiling bubbles which, in turn, influences the critical heat flux, since the sector of a wire which can be insulated by a bubble is smaller. The critical flux for 0·051 inch wires is reduced by adding small amounts of methyl ethyl ketone to water, probably because of the resulting decrease in surface tension. However, for higher concentrations, the critical flux increases, reaching a maximum at about 9·5 per cent by weight of the ketone. This maximum is approximately 30 per cent higher than the critical flux for water.

## ACKNOWLEDGEMENTS

This paper is based on a dissertation submitted to Stanford University by C. C. Pitts, in partial fulfillment of requirements for the degree of Doctor of Philosophy. Dr. Pitts was the holder of an Atomic Energy Commission Fellowship during part of the investigation, while the major part of the work was supported by a research grant from the U.S. Army Research Office (Durham). The 0·0035 inch Tophet A wires were furnished without charge by the Wilbur B. Driver Company, Los Angeles, California.

## REFERENCES

1. I. Moscicki and J. Broder, Study of the spheroidal state of liquids on hot metal surfaces, *Roszniki Chemie* **6**, 319–354 (1926). (Translation: E. I. duPont de Nemours and Co., Wilmington, Del.).
2. S. Nukiyama, Experiments on the determination of the maximum and minimum values of the heat transferred between a metal surface and boiling water, *Nippon Kikai Gakkai Shi*, **37**, 367–374 (1934). (Translation: *AERE*-Trans-854).
3. W. Marcy, Boiling liquids at high heat flux, S.B. Thesis, Massachusetts Institute of Technology (1937).
4. J. L. Boscov, Heat transfer to boiling water under pressure, SM Thesis, Massachusetts Institute of Technology (1947).
5. P. M. Rinaldo, SM Thesis, Massachusetts Institute of Technology (1947).
6. R. S. Day, SM Thesis, Massachusetts Institute of Technology (1947).
7. J. N. Addoms, Heat transfer at high rates to water boiling outside cylinders, Sc.D. Thesis, Massachusetts Institute of Technology (1948).
8. R. D. Rao, H. S. Desai and D. V. Gogate, A note on heat transfer and film boiling, *Indian J. Phys.* **34**, 456–460 (1960).
9. E. A. Farber and R. L. Scorah, Heat transfer to water boiling under pressure, *Trans. Am. Soc. Mech. Engrs* **70**, 369–384 (1948).
10. J. T. Castles, Effect of liquid–solid adhesion forces on the boiling of liquids, SM Thesis, Massachusetts Institute of Technology (1947).
11. W. H. McAdams, J. N. Addoms, P. M. Rinaldo and R. S. Day, Heat transfer from single horizontal wires to boiling water, *Chem. Engng Progr.* **44**, 639–646 (1948).
12. L. Bernath, A theory of local-boiling burnout and its application to existing data, *Chem. Engng Progr. Symp. Ser.* **56**, 95–116 (1960).
13. H. J. Ivey and D. J. Morris, The effect of test section parameters on saturation pool boiling burnout at atmospheric pressure, Symposium on Boiling Phenomena in Nuclear Heat Transfer, Chicago, 1962, Technical Session No. 42, Paper No. 160, also *AEEW-R*176 (4162).
14. C. F. Bonilla and C. W. Perry, Heat transmission to boiling binary liquid mixtures, *Trans. Am. Inst. Chem. Engrs* **37**, 685–705 (1941).
15. W. R. van Wijk, Heat transfer in boiling binary mixtures, *Dechema-Monogr.* **28**, 63–74 (1956).
16. A. S. Vos and S. J. D. von Stralen, Heat transfer to boiling water–methyl ethyl ketone mixtures, *Chem. Engng Sci.* **5**, 50–56 (1956).
17. W. R. van Wijk, A. S. Vos and S. J. D. von Stralen, Heat transfer to boiling binary liquid mixtures, *Chem. Engng Sci.* **5**, 68–80 (1956).

18. S. J. D. von Stralen, Heat transfer to boiling binary liquid mixtures at atmospheric and subatmospheric pressure, *Chem. Engng Sci.* **5**, 290–296 (1956).
19. A. S. Vos, Heat transfer to boiling binary liquid mixtures, *Ingénieur (Utrecht)* **68** (17), 9–13 (1956).
20. S. J. D. von Stralen, Heat transfer to boiling binary liquid mixtures, *Br. Chem. Engng* **4**, 8–17 and 78–82 (1959).
21. W. R. van Wijk and S. J. D. von Stralen, Heat transfer to binary liquid mixtures boiling under pressures from 0·1 to 50 atmospheres, *Dechema-Monogr.* **32**, 94–106 (1959).
22. W. R. van Wijk and S. J. D. von Stralen, Growth rate of vapour bubbles in water and in a binary mixture at atmospheric pressure, *Physica, 's Grav.* **28**, 150–171 (1962).
23. S. J. D. von Stralen, Heat transfer to boiling binary liquid mixtures, *Meded. LandbHoogesch. Wageningen* **59** (6), 1–78 (1959). Doctoral thesis, Rijksuniversiteit te Groningen.
24. V. G. Fastovskii and R. I. Artym, Experimental investigation of the critical heat flux for boiling binary mixtures, *Teploenergetika* **5** (8), 74–78 (1958).
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, Seventh National Heat Transfer Conference, Cleveland (1964). AIChE Preprint No. 6.
26. W. L. Owens, An analytical and experimental study of pool boiling with particular reference to additives, Ph.D. Thesis, University of Aberdeen (1961).
27. C. C. Pitts, The critical heat flux for electrically heated wires in saturated pool boiling, Ph.D. Thesis in Mechanical Engineering, Stanford University (1963).
28. G. C. Vliet and G. Leppert, Critical heat flux for subcooled water flowing normal to a cylinder, *J. Heat Transfer* **86**, 68–74 (1964).
29. *Methyl Ethyl Ketone*, Shell Chemical Corporation, Technical Publication SC: 50–2, San Francisco (1950).
30. F. D. Moore and R. B. Mesler, The measurement of rapid surface temperature fluctuations during nucleate boiling of water, *A.I.Ch.E. Jl* **7**, 620–624 (1961).
31. W. M. McKeeman, An accurate algorithm for the solution of simultaneous linear algebraic equations, Applied Mathematics and Statistics Laboratories, Stanford University, Technical Report No. 26 (1963).
32. W. M. Rohsenow, A method of correlating heat-transfer data for surface boiling of liquids, *Trans. Am. Soc. Mech. Engrs* **74**, 969–976 (1952).
33. R. Cole, A photographic study of pool boiling in the region of the critical heat flux, *A.I.Ch.E. Jl* **6**, 533–538 (1960).
34. B. E. Staniszewski, Nucleate boiling bubble growth and departure, Massachusetts Institute of Technology Technical Report No. 16 (1959).
35. N. Zuber, Hydrodynamic aspects of boiling heat transfer, *AECU*-4439, (1959). Ph.D. Thesis, University of California, Los Angeles.
36. G. Leppert, C. P. Costello and B. M. Hoglund, Boiling heat transfer to water containing a volatile additive, *Trans. Am. Soc. Mech. Engrs* **80**, 1395–1404 (1958).

**Résumé**—Une étude expérimentale et théorique de la variation du flux de chaleur critique avec le diamètre et le matériau du fil chauffé pendant l'ébullition saturée en réservoir d'eau et de mélanges d'eau et de méthyl-éthylcétone est présentée et comparée avec les résultats d'autres chercheurs.

Les résultats pour l'eau sont donnés pour des fils chauffés électriquement en tungstène, en Tophet A, en cuivre et en constantan avec des diamètres de 12,5 μ et de 1,27 mm. Les résultats des mesures pour des fils en Tophet A de 87 μ, 0,25 mm et 1,27 mm de diamètre dans des mélanges d'eau et de méthyl-éthylcétone avec des concentrations massiques de 0 à 17% de cétone sont également donnés.

Un modèle simple est proposé pour le phénomène du flux critique dans le cas des fils fins. Un calcul théorique basé sur ce modèle est en accord qualitatif avec les résultats experimentaux. Les propriétés du fil ont peu d'influence sur le flux critique dans toute la gamme de diamètres, bien que le coefficient de variation thermique de la résistivité semble avoir un certain effet, spécialement pour des fils très fins.

**Zusammenfassung**—Eine experimentelle und analytische Untersuchung der Änderung der kritischen Wärmestromdichte mit Drahtdurchmesser und Drahtmaterial beim Sieden unter freier Konvektion in Wasser und Gemischen von Wasser und Methyläthylketon im Sättigungszustand wird beschrieben und die Ergebnisse mit jenen anderer Autoren verglichen.

In Wasser ermittelte Werte sind für elektrisch beheizte Drähte aus Wolfram, Tophet A, Kupfer und Konstantan mit Durchmessern von 0,015 mm bis 1,3 mm wiedergegeben. Messungen mit 0,09, 0,25 und 1,3 mm dicken Tophet A Drähten in Gemischen aus Wasser und Methyläthylketon mit Ketonkonzentrationen von 0–17 Gewichtsprozent sind ebenfalls angegeben.

Ein vereinfachtes Modell wird für das Phänomen des kritischen Wärmflusses an dünnen Drähten vorgeschlagen. Eine auf diesem Modell beruhende Analysis stimmt qualitativ mit den Versuchsergibnissen überein. Über den gesamten Bereich der untersuchten Drahtdurchmesser zeigt sich nur eine geringfügige Änderung des kritischen Wärmeflusses bei geänderten Drahteigenschaften, obwohl der Temperaturkoeffizient des Widerstandes, besonders für sehr dünne Drähte einen gewissen Einfluss auszuüben scheint.

**Аннотация**—Описано экспериментальное и аналитическое исследование изменения критического теплового потока в зависимости от диаметра и материала проволочки при насыщенном кипении в большом объеме воды и смесей воды с метил-этил-кетонап. Результаты этого исследования сопоставлены с данными других исследователей. Данные для воды приведены для нагреваемых электрическим током проволочек из вольфрама, Tophet A, меди и константана при изменении диаметра проволочек от 0,0005 до 0,051 дюйма. Представлены также результаты измерений для проволочек из Tophet A (диаметром 0,0035, 0,010 и 0,051 дюйма) для смесей воды метил-этил-кетонап при весовой концентрации последнего от 0 до 17%.

Предложена упрощенная модель явления критического теплового потока от тонких проволочек. Анализ, основанный на этой модели, качественно согласуется с экспериментальными результатами. Критический тепловой поток мало зависит от свойств проволочек во всем исследованном диапазоне их диаметров, хотя оказывается, что термический коэффициент электрического сопротивления имеет некоторое значение в особенности, для очень тонких проволочек.