The Measurement of Rapid Surface Temperature Fluctuations During Nucleate Boiling of Water

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The surface temperature during nucleate boiling was measured with a special thermocouple so designed as to measure the temperature of a small area and to have an extremely rapid response time. The surface temperature was found to drop occasionally 20° to 30°F. in about 2 msec. during the boiling of water. This indicates a rapid extraction of heat during a short time interval. The significance of this observation is that it provides an important new clue to an understanding of nucleate boiling. A hypothesis is advanced to explain these observations.

This investigation was initiated to measure temperature fluctuations of the heating surface during nucleate boiling. Several investigators (*11*, *15*, *16*) have observed surface temperature fluctuations during nucleate boiling, but little study has been made of them. Only one of these investigators designed his apparatus to measure the fluctuations (*11*). Usually the surface temperature has been obtained by extrapolating from measurements made beneath the surface. Since surface temperature fluctuations are rapidly damped away from the surface, their full amplitude would not be observed in the extrapolation method. Where surface temperature have been measured directly either the measuring device was sensitive to such a large area that the temperature fluctuations averaged out, or the device had such a large time constant that the amplitude of the rapid fluctuations was damped out.

APPARATUS

The measurement of the full amplitude of these temperature fluctuations of the heating surface requires a device capable of measuring the temperature of a relatively small area and of responding rapidly to temperature fluctuations. Also it must be associated with auxiliary equipment capable of recording these rapid temperature changes. A thermocouple which comes close to meeting both of these requirements is described by Bendersky (*4*). This thermocouple measures the average temperature around a circle with a diameter of 0.005 in., and it has a microsecond response time. The thermocouple is fabricated from a wire and concentric tube, the tube being insulated from the wire by a thin oxide film. The thermocouple is made by polishing one end of the wire and tube, then applying a thin metal film, making electrical contact between the wire and tube. The temperature sensed by this thermocouple is the average temperature around the annulus between the wire and the tube.

This thermocouple was press fitted into a strip of metal, and the thermocouple was machined flush with the top of the strip. A nickel plating, approximately 0.00005 in. thick, was vacuum deposited over the entire surface of the strip and the ends of the thermocouple. Details of this thermocouple are shown in Figure 1. The thermocouple was an Alumel wire in a Chromel P tube and the metal strip was Nichrome V. Nichrome V was selected because it matched the physical properties of the Chromel P closely. Later in the program the nickel plating was removed, and the entire surface, including the end of the thermocouple, was polished with 150 grit abrasive paper. This polishing action insured a relatively uniform surface over the entire strip. It formed the thermal junction between the Alumel wire and the Chromel tube of the thermocouple by carrying metal slivers over the edges of the insulation layer separating the wire and the tube. No significant differences were observed in the records with the thermocouple junction formed by nickel plating or the metal slivers.

The boiling strip was mounted between two brass electrodes. An epoxy resin (Stycast 2651) was then cast around the strip and electrodes to expose a known area of the strip for heat transfer. An electric current to heat the strip was obtained from six parallel 2-v. cells with an adjustable series resistor. The thermocouple voltage was read on a potentiometer and the temperature fluctuations were viewed on an oscilloscope with a differential preamplifier. A problem during early operation in observing the thermocouple emf on the oscilloscope was the pickup of stray signals. Some of these stray signals were found to originate from a nearby radio station, the fluorescent lights, and from the auxiliary heater. After the stray signals were reduced to a minimum by either removing the source or shielding against them, the temperature fluctuations were recorded by photographing the oscilloscope face.

EXPERIMENT

The fluid boiled in these experiments was water at atmospheric pressure. It was maintained at its saturation temperature by auxiliary heaters. The water was degassed by boiling for 3 hr. Prior to taking data the strip was heated at 100,000 B.t.u./(hr.) (sq. ft.) for at least an hour.

The current flowing through the strip and the voltage across the strip were measured so that the average heat flux could be calculated from the strip area and power input.

RESULTS

During nucleate boiling the surface temperature was observed to fluctuate

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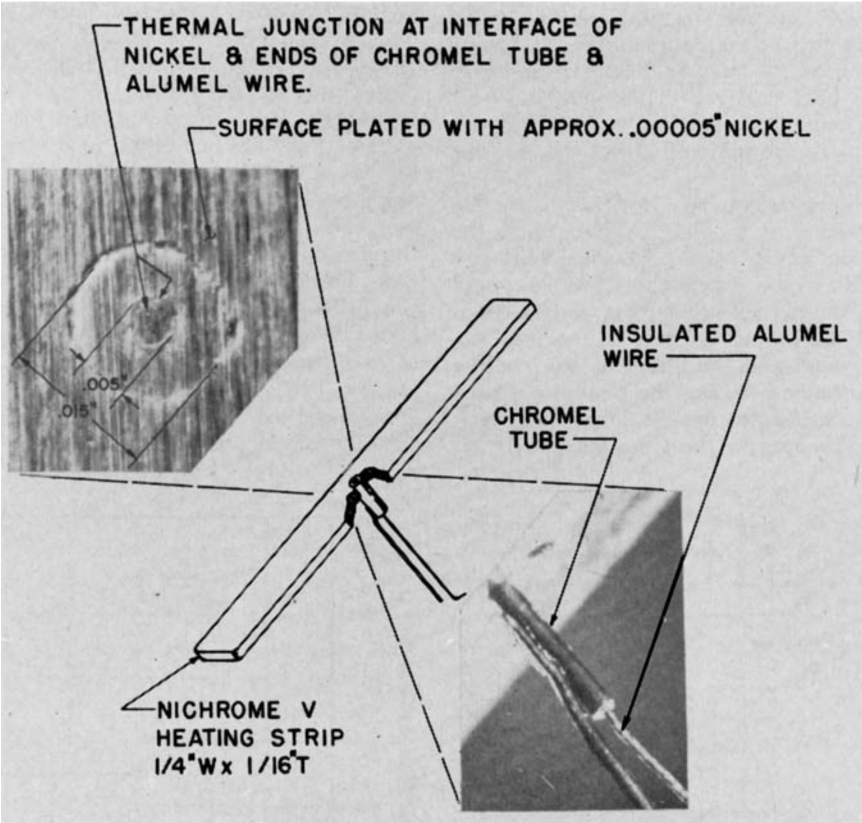

Fig. 1. Miniature surface thermocouple mounted in the nucleate boiling surface.

with time. An interesting characteristic of the fluctuations was that occasionally the surface temperature would drop rapidly and then return to its previous level. At low heat fluxes these dips occurred only infrequently; at higher heat fluxes the dips occurred more often.

The temperature drop was extremely rapid. To examine the details of the temperature drop it was necessary to observe the drops at rapid sweep rates on the oscilloscope. Such rapid sweep rates were required that at the lower heat fluxes it was extremely unlikely that a drop would occur during any particular sweep.

Figure 2 is a photograph of a typical oscilloscope trace with a relatively high heat flux of 135,000 B.t.u./(hr.) (sq. ft.). The sweep rate was fast enough that some of the detail of the drop and subsequent recovery can be seen. The temperature dropped 20° to 30°F. in about 2 msec. Other photographs taken at faster sweep rates are shown in Figure 3. These photographs are identified in Table 1 which also gives the average period between drops. These periods were obtained by counting the number of dips occurring in several photographs at slower sweep rates and then dividing this into the total time represented by the photographs.

At very low heat fluxes it was possible to see the action of individual bubbles. Bubbles did not originate from the site of the thermocouple any more frequently than from other areas of the surface. At heat fluxes high enough to give a reasonable chance of observing a temperature drop the boiling was so vigorous that all details of individual bubbles were obscured.

Figure 4 shows a plot of heat flux vs. the difference between surface and saturated temperature. Shown for comparison are data reported by Addoms (*1*) and Perry (*18*).

DISCUSSION

The unexpected appearance of the rapid drops in surface temperature required interpretation. They result from the rapid extraction of heat from the surface during the time while the temperature is dropping. An estimate of the amount of heat that must be removed is of interest.

An appreciation of the temperature drops can be obtained by comparing them with the results of a related problem and noting the similarities. Imagine a semi-infinite solid initially at zero uniform temperature, and suppose that for a short time heat is removed from the surface at a constant rate so that a maximum temperature drop is produced. The surface temperature at any time is given by (*5*)

$$T/T_{max} = -\sqrt{t/t_o}\,;\; O < t/t_o < 1 \quad (1)$$

$$T/T_{max} = -[\sqrt{t/t_o} - \sqrt{t/t_o - 1}];\quad t/t_o > 1$$

They are plotted in Figure 5. Note that when heat removal begins the temperature suddenly drops and when it ceases the temperature starts back up at a rapid rate. A comparison of Figure 5 with the oscilloscope photographs makes it clear that during the drop in temperature heat is being removed rapidly, and when the temperature starts back up the heat removal ceases or at least decreases sharply.

An estimate of the heat removed during the drop has been made with the following simplifying assumptions. The boiling surface was assumed to be equivalent to the surface of a semi-infinite solid initially at zero temperature and with later temperatures dependent only on distance from the surface. The temperature distribution in the solid resulting from a surface temperature variation with time of $\phi(t)$ was calculated from

$$T = \frac{2}{\sqrt{\pi}} \int_{\frac{x}{2\sqrt{\alpha t}}}^{\infty} \phi\left(t - \frac{x^2}{4\alpha\mu^2}\right) e^{-\mu^2}\, d\mu \quad (2)$$

The total amount of heat per unit area that flowed out was computed by subtracting the enthalpy per unit area at any particular time from the initial enthalpy (taken as zero):

$$Q/A = -c\rho \int_0^{\infty} T\, dx \quad (3)$$

With the use of the temperature drop given in Figure 3a, the temperature distribution in the solid was calculated at the instant the temperature began to rise. The temperature at the instant the sudden drop began was assigned a value of zero for convenience. The resulting distribution is shown in Figure 6. Examination of Figure 6 shows that the heat removed from the surface resulted from lowering the temperature very near the surface. Substitution of the temperature distribution in Equation (3) gave the total heat removed as 0.415 B.t.u./sq. ft.

The heat removed during the other rapid temperature drops shown in Figure 3 was computed in the same manner, and the results appear in Table 1. Also appearing is the average heat flux during the temperature drop. This was obtained by dividing the heat removed during the drop by the time between when the drop began and ended. Note that this is indeed high, being close to 10^6 B.t.u./(hr.) (sq. ft.).

The assumption that the solid is initially at a uniform temperature neglects the heat generation within the solid and any peculiar temperature distribution that might exist initially. The validity of this assumption must be examined. The average heat flux from the surface was 135,000 B.t.u./(hr.) (sq. ft.). The average heat flux during the temperature drop was computed as 815,000 B.t.u./(hr.)(sq. ft.). Thus heat was withdrawn from near the surface more rapidly than it was generated throughout the depth of the solid; therefore neglecting the effect of heat generation seems reasonable. Furthermore the calculated amount of heat removed would be low but by no more than 15% judging from the values. Observing that there were no

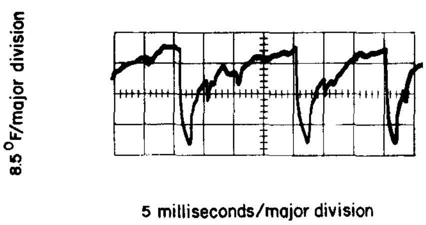

Fig. 2. A typical photograph of the oscilloscope face showing the surface temperature behavior.

drastic temperature changes immediately preceding the drop gave one reasonable assurance that the initial temperature of the solid near the surface was uniform.

Also requiring examination is the assumption that the temperature depends only on the distance from the surface. The best justification would be to show that the average depth from which the heat flows is small compared with the distance across the area where the temperature drop is occurring. No good measure of this is available. The fact that the thermocouple senses such a large temperature drop is some indication that the temperature drop is occurring at least over an area larger than the thermocouple which has a diameter of 0.005 in. As can be seen in Figure 6 more than half of the heat flows from a depth no greater than 0.005 in.

The calculation of the heat flux from surface temperature data is a technique which has been used in shock tubes (*22*). An analogue electrical circuit to yield an instantaneous heat flux directly without the long calculations used here has been devised and should be of use in the extension of this work (*17*).

The heat removed during the temperature dips has been calculated with the properties of Chromel P. This is an approximation because the thermal properties of Alumel and Nichrome V are different. The heat removed per dip is directly proportional to the value of $k/\sqrt{\alpha}$ as shown by Meyer (*17*). The presence of the Alumel with its higher value of $k/\sqrt{\alpha}$ would tend to increase the heat removed. The Nichrome V is far enough away that it would not effect the results of the heat transfer calculation.

Since electrical resistivity of the Chromel P is slightly lower than the Nichrome V, the heat generated per unit volume within the Chromel would be slightly less than that generated in the Nichrome. Flow of heat into the Chromel and the effect of any contact resistance between the two would tend to compensate for the lower heat generation rate in the Chromel.

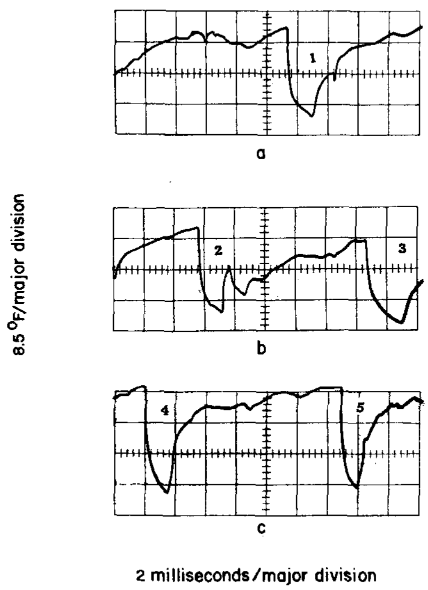

Fig. 3. Typical photographs of the oscilloscope face showing the surface temperature behavior.

No corrections were made for these errors because the combined error is not believed greater than 20%, the combined effect of the error indicates that the temperature drops account for even a larger amount of the heat removed, and the errors are rather uncertain.

SIGNIFICANCE

The occurrence of these temperature drops provides a new test for the basic hypotheses upon which theoretical and semiempirical work on nucleate boiling has been based. It is first necessary to summarize the existing hypotheses.

The usual hypothesis of nucleate boiling is that the bubbles agitate the liquid, thus promoting the excellent heat transfer (*3*). This idea was held by Jakob (*12*). Rohsenow and Clark (*20*) concluded from some motion pictures of subcooled nucleate boiling that the dominant factor in subcooled boiling was agitation. Rohsenow (*19*) later published a method of correlating heat transfer data for surface boiling of liquids which applied to both subcooled and saturated pool boiling. This correlation was based on the Jakob premise that "the increased heat transfer in boiling was attributed to the agitation of the liquid by the bubble motion." In the discussion which accompanied the report of Rohsenow and Clark (*20*) Zmola questioned conclusions of the authors in that they had failed to consider the possibility of mass transfer across the bubble.

Levy (*13*) has recently published a generalized correlation of boiling heat transfer based on the same premise

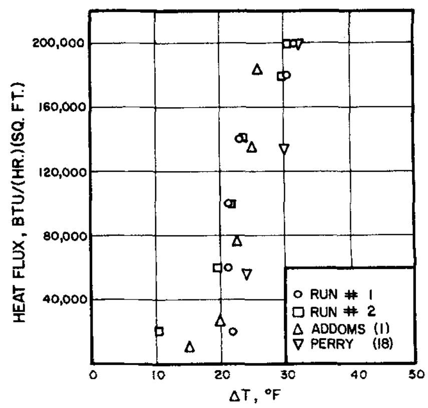

Fig. 4. Heat transfer curve for water.

that "growth of the bubbles and their escape velocity create large turbulence within the fluid, thus producing the large heat transfer rates normally associated with boiling heat transfer."

Forster and Grief (*10*) favor a vapor-liquid exchange action for the mechanism of nucleate boiling. They visualize vapor bubbles as displacing superheated liquid from the surface. The authors interpret their viewpoint as a case of bubbles agitating the liquid. There are many other writers who have written along similar lines.

Intimately connected with the idea of bubbles furnishing the agitation is the concept that when a bubble departs it allows cold liquid to contact the surface. The cold liquid readily carries the heat away from the hot surface.

Another hypothesis is that liquid at the base of the bubble is vaporized into the bubble. Edwards (*8*) and Snyder (*3*) among others (*2*) have advocated such a view. Although Edwards made a concerted effort to obtain experimental justification for such a view, he was unsuccessful. Snyder actually suggested an experiment similar to the one the authors have preformed as a possible means of obtaining experimental justification that vaporization at the base of the bubble is significant. The following was attributed to him in 1956 (3). "Snyder noted that essential to his argument in favor of mass transfer was a thin liquid film at the base of the bubble from which evaporation would take place continuously. The temperature of such a film would be expected to drop significantly after mass transfer had begun; thus, Snyder felt that making an experiment in which a measurement of the temperature at the base of the bubble was made would lend information as to whether or not the film is actually present. He felt that a successful measurement of this type would do much toward determining

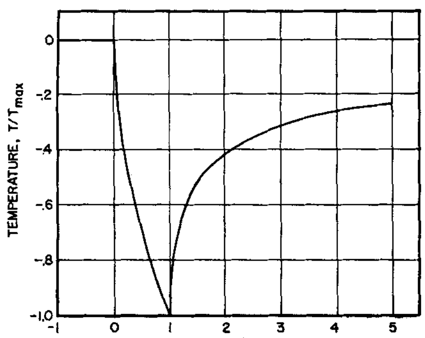

Fig. 5. Surface temperature response for a constant rate of heat removal during the interval $0 < \frac{t}{t_0} < 1$ with zero initial temperature.

whether or not mass transfer could be an important mechanism."

Zmola showed in his comments on the paper of Rohsenow and Clark (20) that he was alert to a possibility of mass transfer across the bubble.

The authors' interpretation of the temperature drop they observed is that heat is being removed at an especially rapid rate from the surface during the drop. Nothing in the bubble agitation hypothesis seems to predict this. It is difficult to argue that there would be agitation only during the short periods when the temperature drops occur.

At first thought it might appear that cold liquid rushing into the surface could account for the temperature drop. Why then would the cooling suddenly stop shortly after it had begun? It is possible to calculate the surface temperature that would result if a large body of cold water were brought in perfect thermal contact with a hot metal surface. The surface temperature with heat flows assumed only by conduction is given by (5)

$$T = \frac{k_1/\sqrt{\alpha_1}}{k_1/\sqrt{\alpha_1} + k_2/\sqrt{\alpha_2}} T_1 \quad (4)$$

The initial temperatures were taken as T_1 for the metal and zero for the water. With values for Chromel P and water the surface temperature decreases by only 17% of the difference in initial metal and water temperatures. To cool the metal surface 25°F. would require water 147°F. colder than the metal, and such water is not present. The assumption of pure conduction and the neglect of the effect of convection appears justified because the time while the heat transfer occurs is so short. Furthermore an approximate heat transfer coefficient obtained by dividing the heat removed during the temperature drop by the maximum tem-

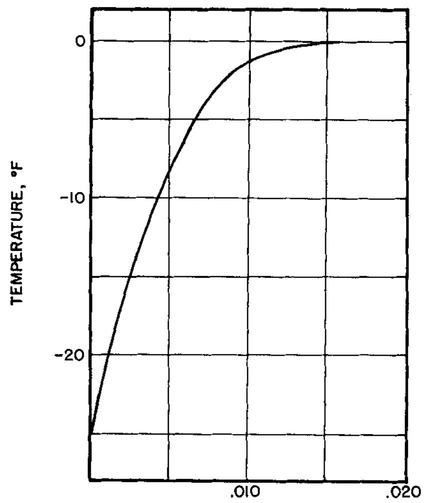

Fig. 6. Temperature beneath the surface calculated from the data in Figure 3a.

perature drop lies between 29,000 and 47,000 B.t.u./(hr.)(sq. ft.)(°F.) for data in Table 1. These coefficients are well above what would be expected if convection was an important factor.

The only hypothesis that appears to be consistent with the author's observations is one which proposes vaporization at the base of the bubble. The authors visualize the details of what occurs as follows. As a bubble grows on the surface it exposes the heating surface wet with a microlayer of liquid to the interior of the bubble. This microlayer rapidly vaporizes removing heat rapidly from the surface until it is completely vaporized. This simple sequence of events is the only way that the authors have been able to explain the rapid removal of heat occurring during the short period of time when they observed the surface temperature dropping rapidly. Figure 7 shows two extreme possibilities of bubble growth and formation of the microlayer.

Examine the concept of the existence of a vaporizing microlayer to see if it is in accord with what might be expected.

First, is it reasonable that a microlayer would be formed? Liquid next to the surface is not easily displaced because of the wetting action between the liquid and the solid and because of the fluidity of the liquid. A microlayer might thus be expected to form as a growing bubble advanced over a surface. In addition the existence of liquid films between static bubbles and solid surfaces has been reported by Euverard and Hurley (9) and by Derjaguin and Kussakov (7).

Second, can the thickness be estimated, and is it reasonable? The thickness can be estimated by calculating the thickness of a film of water

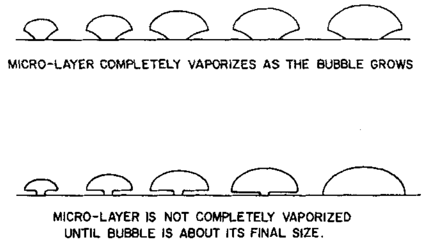

Fig. 7. Sketches of two ways the microlayer might vaporize.

that has the same latent heat as the heat removed during the temperature drop. Such estimates are given in Table 1 and range from 78 to 89 μin. A film of this thickness would not be noticeable under usual boiling conditions, and a scheme for detecting such a film by means other than have been used has not occurred to the authors. Derjaguim and Kussakov measured a water film 6 μin. thick between a static air bubble and a mica surface. Since the microlayer the authors visualize would be formed very rapidly, its thickness being an order of magnitude greater than the film under a static bubble is not disturbing.

Third, does other evidence indicate rapid bubble growth that might result from the rapid vaporization of the microlayer? Westwater (23) and Corty (6) report that their photographs of bubbles show that initial bubble growth is extremely rapid. The rate of growth is so fast that the first frame in a sequence showing a bubble growing was always blurred even with an exposure time of 0.1 msec. (23). Complete vaporization of the microlayer in the 2 msec. it takes for the temperature to drop would predict this rapid initial bubble growth.

Fourth, is the average rate of vaporization of the microlayer less than the absolute rate of vaporization as computed from kinetic theory (21)? Assuming an evaporation coefficient of unity one can compute the absolute rate of evaporation to be 20 lb./(sq. ft.) (sec.) This corresponds to a heat

Table 1. Identification of the Temperature Drops Shown in Figure 3 and Results Calculated from Them

Drop	Average heat flux, B.t.u./(hr.)(sq. ft.)	Interval between max. and min. temperatures, msec.	ΔT max., °F.	Average period, msec.
1	135,000	1.80	24.2	14.3
2	135,000	1.51	23.6	14.3
3	135,000	2.28	22.6	14.3
4	202,000	1.46	29.3	8.8
5	202,000	1.12	27.6	8.8

Drop	Q/A, B.t.u./(sq. ft.)	Average heat flux over temp. drop, B.t.u./(sq. ft.)(hr.)	$f \cdot Q/A$, B.t.u./(sq. ft.)(hr.)	δ, min.
1	0.415	830,000	105,000	82
2	0.398	920,000	100,000	78
3	0.420	660,000	106,000	83
4	0.446	1,100,000	183,000	89
5	0.407	1,310,000	166,000	81

removal rate of 19 B.t.u./sq. ft./msec. which is about a factor of 80 higher than the average evaporation rates observed here.

Fifth, is the average vapor velocity leaving the microlayer during vaporization reasonable? For the cases analyzed here it was a modest velocity falling between 5 and 10 ft./sec.

Finally, is the concept of microlayer vaporization compatible with the lack of a nucleate boiling behavior as has been reported when the liquid fails to wet the heating surface (*14*)? If wetting does not occur, then formation of a microlayer would be unlikely to occur. Thus nucleate boiling would not be expected if it is dependent upon microlayer vaporization.

Nucleate boiling is a complicated phenomenon. Undoubtedly a combination of factors account for the excellent heat transfer. Different factors are probably dominant at high heat fluxes than at low. The surface temperature drop observed so frequently at high heat fluxes appears to be associated with the dominant factor at high heat fluxes. A measure of the importance can be obtained if one first multiplies the frequency of the temperature drops by the heat removed per drop. This quantity appears in Table 1 and is 70 to 90% of the average heat flux. This accounts for most of the heat that is transferred. The validity of this comparison is based on the assumption that the entire boiling surface is behaving in the same manner as is measured by the thermocouple. The visual observation that at low heat fluxes the site of the thermocouple did not show any unusual behavior is the strongest evidence in support of this assumption. The temperature drops appear to offer an important clue to the dominant factor even if the role visualized for the bubble proves to be incorrect.

None of the published attempts at correlating nucleate boiling data have utilized anything similar to the microlayer vaporization hypothesis. It may be possible to achieve better correlations if consideration is given to microlayer vaporization.

CONCLUSIONS

The surface temperature during nucleate boiling of water at atmospheric pressure varies with time. An interesting characteristic of the variation is that occasionally the temperature suddenly drops 20° to 30°F. in about 2 msec. This drop indicates rapid removal of heat from the surface during these short intervals. This observation furnishes an important new clue to a better understanding of nucleate boiling.

ACKNOWLEDGMENT

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NOTATION

- c = specific heat per unit mass
- f = frequency
- k = thermal conductivity
- Q/A = heat transferred per unit area
- t = time
- t_o = short time while heat is removed
- T = temperature
- T_{max} = maximum temperature drop
- x = distance

Greek Letters

- α = thermal diffusivity = $\rho c/k$
- δ = microlayer thickness, μin.
- μ = variable of integration
- ρ = density
- ϕ = measured function of time

Subscripts

- 1 = metal
- 2 = water

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