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AN INVESTIGATION INTO THE EFFECTS OF VARIOUS PLATINGS ON THE FILM COEFFICIENT DURING NUCLEATE BOILING FROM HORIZONTAL TUBES

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Abstract—Tests were conducted using stainless-steel tubes heated electrically from which nucleate boiling took place. These tests were repeated when the tubes had been plated with a thin layer of different materials. Plating materials used were copper, zinc, tin, nickel, cadmium, and chromium. It was found that the presence of the plating resulted in a change in the film coefficient by as much as 200 to 300 per cent in the case of copper or zinc. An analytical solution was obtained for the action of a single bubble on a flat plate. From this solution it is concluded that the effect of the plating material is not due solely to its thermal properties.

NOMENCLATURE

h, film coefficient;
k, thermal conductivity;
q, heat flux;
$\dot{q}$, heat generation rate per unit volume;
r, radius;
R_b, bubble radius;
t, thickness;
T, temperature;
ΔT, excess of surface temperature over saturation temperature;
u, unit step function;
z, normal distance.

Greek symbols

α, thermal diffusivity;
θ, temperature deviation;
ξ, prescribed temperature gradient;
τ, time;
τ_0, time of departure of bubble.

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Subscripts

p, plating;
b, base;
s, steady-state;
f, fluid.

INTRODUCTION

THE BASIC mechanism of nucleate boiling is as yet not understood. Many factors affect the bubble-growth rate, period of bubble formation, number of active sites present, and heat-transfer rate. These factors include liquid properties, heating-surface properties, surface condition and roughness, liquid pressure and temperature, and the temperature of the heating surface.

There are currently two widely varying schools of thought which attempt to explain the very high heat-transfer rates characteristic of nucleate boiling. The older school of thought attributes them to convection currents induced by the stirring action of the bubbles [1, 2]. It is reasoned that most of the heat is transferred from the heater surface to a layer of superheated liquid which covers the surface except for the region occupied by the bubbles. Heat is then transferred to the liquid–vapor interface at the bubble boundary, where vaporization occurs. The presence of convection currents greatly facilitates this heat-transfer process. Because of the normally small values of film coefficient between a solid surface and a vapor, only a small fraction of the total heat-transfer rate occurs directly from the heater surface to the bubble. Much research has been done along the lines of this theory [3–10].

The newer school of thought postulates the existence of a thin film, or micro-layer, of liquid trapped between the heater surface and the base of the bubble [11]. This is illustrated in Fig. 1.

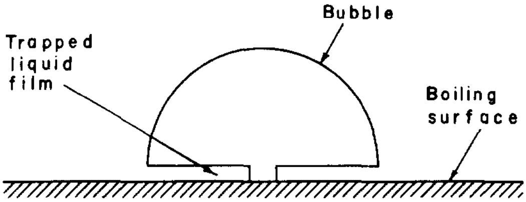

FIG. 1. Sketch showing bubble with trapped liquid film or microlayer.

Heat is readily conducted through this thin layer, with consequent rapid evaporation of liquid from the microlayer, and possible condensation of vapor on the top surface of the bubble. According to this theory, the heater surface experiences a rapid drop in temperature immediately beneath the bubble during the period of rapid bubble growth.

Hsu and Schmidt [12] measured surface-temperature fluctuations which they attributed to the influence of numerous bubbles surrounding their thermocouple probe. Moore and Mesler [13] measured surface-temperature fluctuations as large as 20°F to 30°F, much larger than those attributable to the stirring action of the bubbles. Their calculations indicated a transient heat flux some six times as large as the average heat flux. To account for this they suggested the existence and subsequent evaporation of a layer of liquid 78–89 thick at the base of the bubble.

Rogers and Messler [14] created an active site on a small surface thermocouple. Temperature variations were recorded and correlated with photographs taken of the bubbles during growth. Sudden temperature drops of the order of 8°F to 19°F were observed during the first stages of bubble growth. Upon bubble departure the surface temperature increased to its initial value. No further significant change in temperature was observed until the onset of formation of the next bubble.

Cooper and Lloyd [15] have measured the heat flux at a point underneath a growing bubble as a function of time and from this have estimated the initial thickness and rate of decay of the microlayer as a function of position under the bubble.

The degree of roughness of the heater surface affects the heat-transfer rate, as demonstrated by many experiments [12, 16–20]. Increased roughness usually results in a lower surface temperature for a given heat flux.

Several investigators have observed an effect of surface material on the convective film coefficient during nucleate boiling. Drew and Mueller [21] have observed this phenomenon. Bonilla and Perry [22] observed that when ethanol was boiled from a horizontal flat plate provided with several different surfaces, the boiling curves were significantly different from one another. Farber and Scorah [23] observed different values of film coefficient when boiling occurred on wires of different materials. Berenson [20] indicated that the temperature difference required to produce a given heat flux for materials finished with the same surface-finishing technique depends on the surface material. His data also indicated that at least part of this effect is due to the thermal properties of the surface material.

Sharp [24] obtained optical proof to substantiate the theory that a micro-layer exists at the base of a growing vapor bubble. He reasoned that since experiment indicates a sudden drop in surface temperature when the bubble begins to grow, and since the micro-layer temperature remains constant during evaporation, this process can be approximated by transient conduction in a semi-infinite body due to a temperature pulse on its surface. The mathematical solution for this case shows that the heat flux out of the solid at a given time is proportional to $(k/\sqrt{\alpha})$. Sharp then concluded that the micro-layer evaporation rates should vary as $k/\sqrt{\alpha}$. He used data from several experiments to show that the surface material of highest $k/\sqrt{\alpha}$ gives the steepest boiling curves, that is, gives the largest heat flux for a given temperature difference.

Agarwal [25] conducted a series of experiments using wires of different materials to boil FC-75 liquid. He obtained much steeper curves for some materials than for others. However, in this case the slopes of the curve were not proportional to $k/\sqrt{\alpha}$.

There is strong evidence that the thickness of the heating surface appreciably affects nucleate-boiling heat transfer. Moore and Mesler [13] observed a pulse of two millisecond duration and pointed out that most of the extraction during this phase occurs within 0·010 inch of the heating surface. Hendricks and Sharp [26] observed microlayer evaporation on a 0·001-inch thick ribbon and found that the evaporative pulse was strongly limited by the energy content of the ribbon. Edwards [27] has suggested that thin platings of materials with high $k/\sqrt{\alpha}$ can be used to yield greater heat-transfer coefficients and possibly to raise the burnout point as well.

Thus the observed effects of surface material and heater-wall thickness on nucleate boiling indicate the need for analytical and experimental investigations into the effects of various thin platings on nucleate pool boiling.

EXPERIMENTAL APPARATUS AND PROCEDURE

Test specimens

The test specimens were six seamless stainless-steel tubes of 1 in. o.d., 0·035 in. wall thickness and 26 in. length with thermocouples installed for the purpose of measuring surface temperature. The thermocouples consisted of chromel and alumel wire of 0·0075 in. dia. contained in a stainless-steel sheath of 0·040 in. o.d. and insulated from each other and from the sheath by magnesium-oxide powder. Each thermocouple sheath was 2 in. long with 1 in. of the chromel and alumel leads protruding from one end and having the junction formed on the other end by welding the sheath and wires together.

Before the thermocouples were installed X-rays were made of each one to determine the thickness of the welded junctions. An attempt was then made to file down the junctions to 0·004 in. thickness and subsequent X-rays showed that this was very nearly accomplished. Next, six feet of 24-gage chromel–alumel thermocouple wire were attached to each thermocouple. They were then installed in the tube by soldering with a soft solder of silver content. Great care was taken to insure that each thermocouple was flush with the tube surface. Figure 2 is a schematic diagram showing the thermocouple positions and the method of sealing the inside of the tubes and the thermocouple leads from the surrounding water.

Test set-up

A stainless-steel tank containing distilled water and the test specimens was equipped with

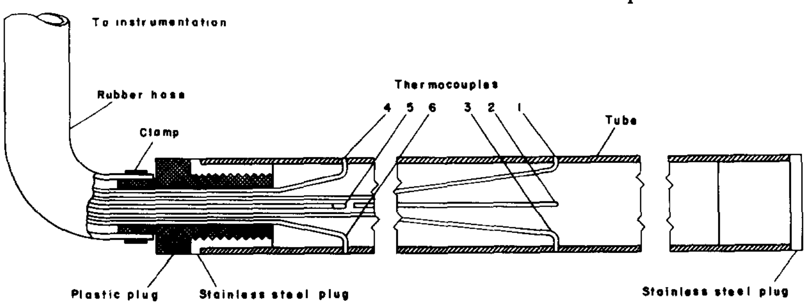

FIG. 2. Schematic diagram showing tube with thermocouples and end plugs installed.

a jacket, through which steam could be passed to maintain the water in the tank at saturation temperature. Two windows were installed in the tank at the level of the test specimen to permit observation and photography of the boiling taking place on the tubes.

The test specimens were heated by using the tubes themselves as resistance heaters. Power was supplied as 60-cycle alternating current. This circuit was capable of producing current in excess of 1200 amp and a maximum power of 12·5 kW.

Preparation of test specimens

The test specimens were prepared as follows: The stainless-steel tubes with thermocouples installed were surface finished in a lathe using varying sizes of silicon–carbide paper. Finishing began with a medium paper and then 180, 240, 320, 400, and 500 grit were used in that order. Once the surface finishing was completed the tubes were pumiced to remove the Beilby layer and any associated dirt and grit with it.

Next each tube was tested for its root-mean-square surface roughness with a surface profilometer. The roughness of each tube was found to be the same, varying between 3·5 and 6 μin. rms with the exception of a few rough spots. However, these rough spots were present on only a small percentage of the total surface.

Tests were then run and data collected on all tubes for the portion of the boiling curve under investigation. Once these tests were completed the tubes were then plated as follows: Two tubes were copper plated, two tin plated, and the remaining two were zinc plated, each plating being 0·005 in. in thickness as determined by plating time and current density. The tubes were again tested for roughness and no appreciable change was detected.

Tests identical to those run with the bare stainless-steel tubes were run with the plated tubes. After completion of these tests the plating was removed and two each of the tubes were then replated with cadmium and nickel and one of the tubes replated with chromium. Again the rms roughness was determined and found to be essentially unchanged.

Experimental procedure

The experimental procedure was as follows: The tube to be tested was first washed thoroughly. Then it was rinsed repeatedly with tap water and finally several times with distilled water. It was then clamped in bus bars and placed in the tank containing distilled water. Power of approximately 7 kW was then supplied to the tube and at the same time steam was supplied to the jacket of the tank. Since the water was receiving heat from both the tube and the tank wall the saturation temperature was soon reached and vigorous boiling ensued.

The boiling was allowed to proceed in this manner for at least three hours before any usable data were collected. However, after two hours of boiling, the thermocouple outputs were monitored frequently to determine if the temperature had reached a steady-state condition. If at the end of three hours steady state had been reached, the collection of data was begun; otherwise the process was allowed to continue until steady state was reached. This long period of time before a steady-state condition developed is believed to be due primarily to the time required to remove adsorbed gases from the surface of the tube. Another influencing factor with some surface materials is the time required to form a uniform oxide film on the surface; this is not believed to be of significance on the stainless-steel, tin, nickel, or chromium surfaces. During this waiting period make-up water was added as needed.

The collection of data began by supplying maximum power to the tube. This varied with tubes of different platings, but a current of 1280 amp was used as the starting point for most tubes. Other values of current at which data were collected were 1120, 960, 800, 640, 480, 320 and 160 amp in that order. At each amperage input the voltage drop across the tube was recorded and numerous readings of each thermocouple were printed out on a multi-point recorder.

Four complete runs, of eight data points each, were made on every tube. At the end of each run make-up water was added if needed and the system was allowed to return to a steady-state condition before the next run was started. The duration of each run was approximately 30 min.

EXPERIMENTAL RESULTS

Experiments were performed to measure the effect of surface plating upon the film coefficient in nucleate boiling. This was accomplished basically by measuring the heat flux and the temperature difference between the bulk liquid and the heater surface. However, surface temperature is more easily discussed than measured.

As previously mentioned the thermocouples used in this investigation had a junction of approximately 0·004 in. thickness. This alone excluded an actual surface-temperature measurement. In addition, although the positioning of the thermocouples in the tubes was done with great care, exact alignment with the surface was always questionable. Thus, it was decided to identify by number each thermocouple in each tube and to run tests on all of the bare stainless-steel tubes before they were plated. In this way, the effect of each plating could be determined without knowing the exact surface temperature or making the assumption that the thermocouple installations were all identical.

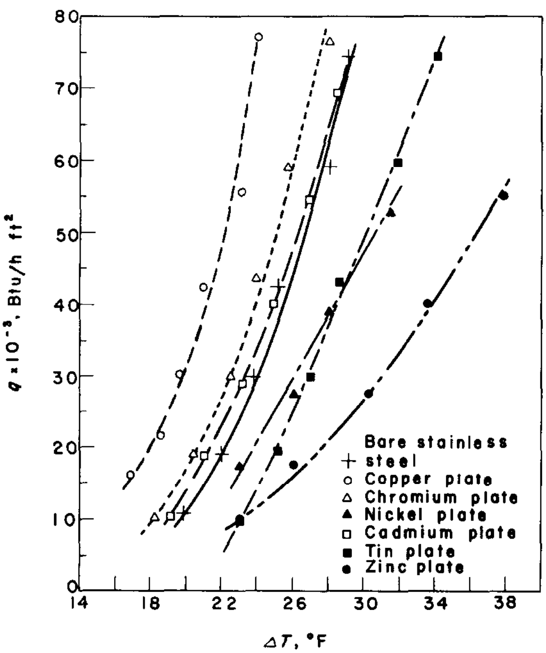

FIG. 3. Combined experimental results for all surface materials.

Figure 3 presents the averaged data for all thermocouples and all runs with each individual surface material. It is seen that different platings can vary the required temperature excess for a given heat flux by more than 50 per cent. Also the effect of the plating may either increase or decrease the required temperature excess. Thus the effect of plating cannot be accounted for by the increased distance from the surface to the effective thermocouple junction.

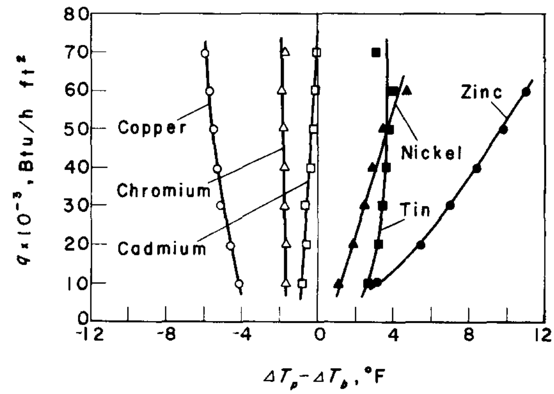

FIG. 4. Average effect of plating for each of several different plating materials.

In Fig. 4 the average effect of plating is shown for each plating material. The abscissa in this graph represents the difference in temperature excess between the plated and corresponding unplated surfaces. It is obtained by taking the temperature excess measured by each thermocouple when plated and subtracting from this the temperature excess measured by the same thermocouple before plating, then averaging these over all runs over all thermocouples plated with a single material.

Figure 5 shows data points each of which is obtained by averaging over all runs the temperature excess measured at a given heat flux for each individual thermocouple in each tube when

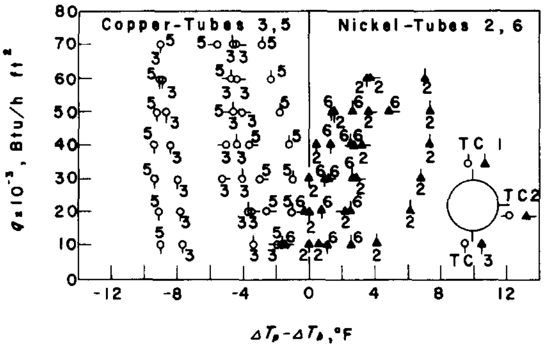

FIG. 5(a). Effect of copper and nickel platings upon each individual thermocouple.

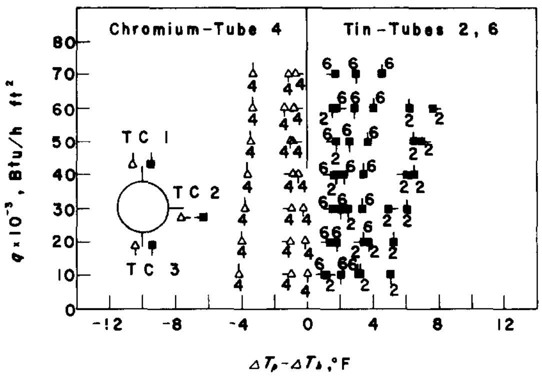

FIG. 5(b). Effect of chromium and tin platings upon each individual thermocouple.

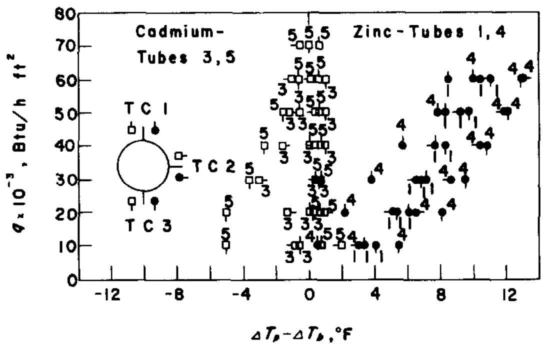

FIG. 5(c). Effect of cadmium and zinc platings upon each individual thermocouple.

plated with a specific material and subtracting from this the corresponding average for the same thermocouple when unplated. The number associated with each data point indicates the location of the thermocouple on the tube as top, side, or bottom. It is seen that considerable scatter exists in these data, much of it attributable to the tangential location of the termocouple on the tube.

Based on the original data it was noticed that thermocouple 3, located at the bottom of the tube, generally indicated a lower temperature than did thermocouple 1, located at the top of the tube. Variations in this pattern are believed to be due mainly to variations in depth of the thermocouple junction below the tube surface. This suggests the existence of a temperature gradient around the tube. To verify this conclusion tests were run in which readings were taken before and after the tube had been rotated by 180°, thus reversing the position of the top and bottom thermocouples. The results of one of these tests are shown in Fig. 6. It may

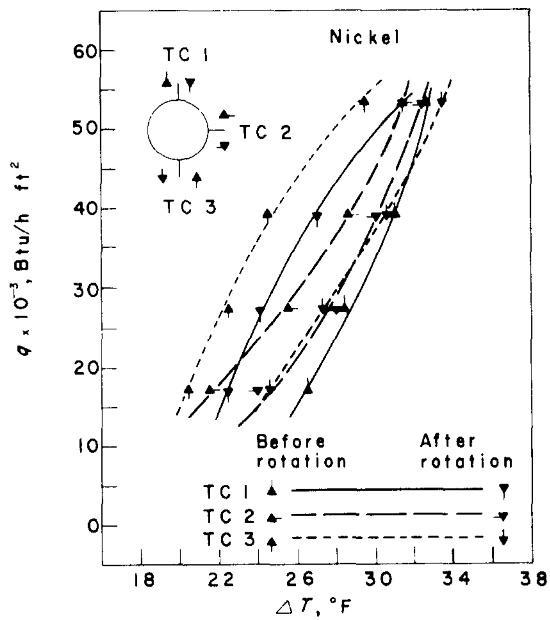

FIG. 6. Effect of 180° rotation of tube 2 (nickel plated) upon the temperature excess measured by each thermocouple.

be seen that thermocouples having the same relative position before and after rotation indicate temperatures which agree to within 2°F. Thermocouple 2 should theoretically indicate the same value of temperature before and after rotation; this discrepancy may be due to a difference in convection currents on opposite sides of the tube as influenced by the proximity of the tank walls, or perhaps to boundary-layer effects in which a slight misalignment of the thermocouple could cause a considerable variation in indicated temperature.

Noticeable changes in the surface appearance were observed on three of the plated materials after one hour of boiling. The least pronounced effect occurred on the copper which turned to a slightly rusty color from an original bright finish. The zinc plating turned blackish blue and a soot-like powder formed on its surface. The cadmium plating first turned brown and then to a bluish gray. No changes were observed in the other materials.

Data showing temperature fluctuations at each thermocouple were taken. For a discussion of these data and for additional details [28] may be consulted.

ANALYSIS

To estimate the local temperature fluctuations in the base material and in the plating, a two-dimensional transient analysis has been performed in cylindrical coordinates. The bubble is assumed to have a fixed radius of attachment R_b and to transfer heat from the surface at a constant rate ξ/k_pA uniformly over this circle of attachment, during the period from $\tau = 0$ to τ_0, where τ_0 is the time at which the bubble departs. Otherwise heat is transferred away from the surface by simple forced convection. A two-layer system is used as shown in Fig. 7.

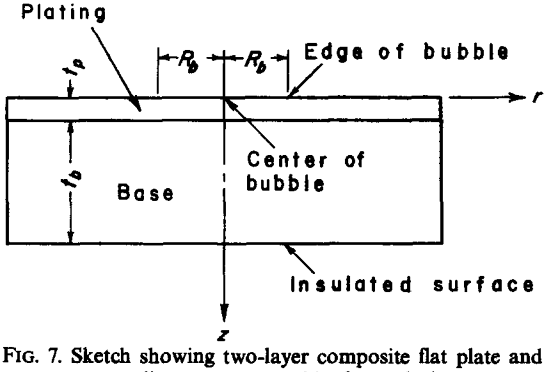

FIG. 7. Sketch showing two-layer composite flat plate and coordinate system used in the analysis.

The differential equation and boundary conditions which describe this process are:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial \tau} - \frac{\dot{q}}{k} \tag{1}$$

($T = T_p$, $\dot{q} = \dot{q}_p$ for $0 < z < t_p$; $T = T_b$, $\dot{q} = \dot{q}_b$ for $t_p < z < t_p + t_b$)

$$\frac{\partial T_p}{\partial z} = \frac{h}{k_p}(T_p - T_f) \text{ when } z = 0, r > R_b, \tau > 0 \tag{2}$$

$$\frac{\partial T_p}{\partial z} = \xi \text{ when } z = 0, r < R_b, 0 < \tau \leqslant \tau_0 \tag{3}$$

$$\frac{\partial T_p}{\partial z} = \frac{h}{k_p}(T_p - T_f) \text{ when } z = 0, r < R_b, \tau > \tau_0 \tag{4}$$

$$T_p = T_b \text{ when } z = t_p, r > 0, \tau > 0 \tag{5}$$

$$k_p\frac{\partial T_p}{\partial z} = k_b\frac{\partial T_b}{\partial z} \text{ when } z = t_p, r > 0, \tau > 0 \tag{6}$$

$$\frac{\partial T_b}{\partial z} = 0 \text{ when } z = t_p + t_b, r > 0, \tau > 0. \tag{7}$$

To solve this system T is divided into two parts: a steady-state solution $T_s(z)$ which includes the entire effect of the heat-generation term in equation (1); and a transient solution $\theta(r, z, \tau)$ which takes into account the effect of the bubble. The solution for T can be written

$$T = T_s + \theta. \tag{8}$$

In writing the boundary condition at $z = 0$ for the steady-state temperature T_s, a term $h\theta/k_p$ is neglected for $r > R_b$. The numerical evaluation shows that outside the bubble this term can be neglected with good accuracy. The steady-state solution is then

$$T_{sp} = -\frac{\dot{q}_p}{2k_p}z^2 + \frac{\dot{q}_pt_p + \dot{q}_bt_b}{k_p}z + \frac{\dot{q}_pt_p + \dot{q}_bt_b}{h} + T_f \tag{9}$$

(for $0 < z < t_p, r > 0$)

$$T_{sb} = -\frac{\dot{q}_b}{2k_b}(z^2 - 2t_pz - 2t_bz + t_p^2 + 2t_pt_b) - \frac{\dot{q}_p}{2k_p}t_p^2 + (\dot{q}_pt_p + \dot{q}_bt_b)\left(\frac{t_p}{k_p} + \frac{1}{h}\right) + T_f \quad (10)$$

$$(\text{for } t_p < z < t_p + t_b, r < 0)$$

Transient solution

The transient analytical solution developed here considers only a single layer, whose properties are interpreted as those of the base material. The following system of equations results

$$\frac{\partial^2\theta}{\partial r^2} + \frac{1}{r}\frac{\partial\theta}{\partial r} + \frac{\partial^2\theta}{\partial z^2} = \frac{1}{\alpha}\frac{\partial\theta}{\partial\tau} \quad (11)$$

$$\frac{\partial\theta}{\partial z} = \xi' \text{ when } z = 0, r < R_b, 0 < \tau < \tau_0 \quad (12)$$

$$\frac{\partial\theta}{\partial z} = 0 \text{ when } z = 0, r > R_b, \tau < 0 \quad (13)$$

$$\frac{\partial\theta}{\partial z} = 0 \text{ when } z = 0, r < R_b, \tau > \tau_0 \quad (14)$$

$$\frac{\partial\theta}{\partial z} = 0 \text{ when } z = t, r > 0, \tau > 0. \quad (15)$$

In the above equations

$$t = t_b + t_p \quad (16)$$

$$\xi' = \xi - \frac{h}{k_p}(T_{sp} - T_f). \quad (17)$$

In addition, the following initial condition holds

$$\theta = 0 \text{ when } z > 0, r > 0, \tau = 0. \quad (18)$$

The solution of equations (11)–(15), (18) has been obtained, using the Laplace-transform technique. When these equations have been transformed, they can be solved by separation of variables. This solution can then be inverted to give

$$\theta = -\frac{\xi' R_b}{2}\left(\int_0^\infty \frac{J_1(\lambda R_b)J_0(\lambda r)}{\lambda}\sum_{n=1}^{\infty} -\exp\{\lambda[z + 2(n-1)t]\}\,\text{erfc}\left[\lambda\sqrt{(\alpha\tau)} + \frac{z + 2(n-1)t}{2\sqrt{(\alpha\tau)}}\right]\right.$$
$$+ \exp\{-\lambda[z + 2(n-1)t]\}\,\text{erfc}\left[-\lambda\sqrt{(\alpha\tau)} + \frac{z + 2(n-1)t}{2\sqrt{(\alpha\tau)}}\right]$$
$$- \exp[\lambda(-z + 2nt)]\,\text{erfc}\left[\lambda\sqrt{(\alpha\tau)} + \frac{-z + 2nt}{2\sqrt{(\alpha\tau)}}\right]$$
$$\left. + \exp[-\lambda(-z + 2nt)]\,\text{erfc}\left[-\lambda\sqrt{(\alpha\tau)} + \frac{-z + 2nt}{2\sqrt{(\alpha\tau)}}\right]\,d\lambda\right) + \frac{\xi' R_b}{2}.u(\tau - \tau_0)$$
$$\times\,[\text{Above integral with } \tau \text{ replaced by } (\tau - \tau_0)]. \quad (19)$$

In this equation $u(\tau - \tau_0)$ is zero if $\tau < \tau_0$ and unity otherwise.

DISCUSSION OF RESULTS

The transient analytical solution, equation (19), was solved on a digital computer for stainless steel and for copper. Figure 8 shows the temperature history for a point on the surface at the center of the bubble. The solid curve is the solution for a semi-infinite solid initially at zero temperature, which is subjected for a short time period to removal of heat at a constant rate from its entire surface. The surface temperature is then given by [29]

$$\frac{\theta}{\theta_{\max}} = -\sqrt{\left(\frac{\tau}{\tau_0}\right)} + \sqrt{\left(\frac{\tau}{\tau_0} - 1\right)}\,.\,u\left(\frac{\tau}{\tau_0} - 1\right). \quad (20)$$

Since the thermal conductivity of stainless steel is relatively small, the surface-temperature response of a point near the center of the bubble should approach that of the semi infinite solid, as given by equation (20). It is seen from Fig. 8

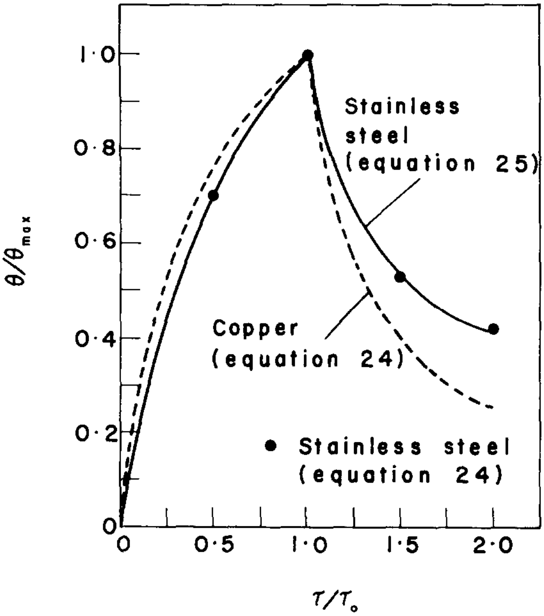

FIG. 8. Comparison of solutions for the temperature deviation at a point on the surface at the center of a bubble. $\tau_0 = 5{\cdot}66 \times 10^{-7}$ hr; $k\xi = 4 \times 10^5$ Btu/hft^2; $t = 2{\cdot}92 \times 10^{-3}$ ft; $R_b = 3 \times 10^{-3}$ ft; $\alpha = 0{\cdot}15$ ft^2/h for stainless steel and $4{\cdot}0$ ft^2/h for copper.

that equations (19) and (20) give almost identical results in the case of stainless steel; for copper the two equations give noticeably different results.

Figure 9 shows the temperature-time relationship for various points in the body. It may be observed that at a radius just outside the bubble ($r = 0{\cdot}0033$ ft) θ is quite small compared to the peak value occurring inside the bubble. This justifies the neglect of θ outside the bubble radius in the analytical solution.

These curves also illustrate how critical is the depth of the thermocouple beneath the surface when temperature fluctuations are measured. This depth was not greater than 0·0004 ft in all cases. From the curves, temperature fluctuations in the range 4–13°F may be expected if a bubble happens to be located above a thermocouple. Fluctuations of this magnitude were indeed observed on several of the thermocouples.

As discussed previously it has been observed that the presence of a plating of a material different from the base material causes in

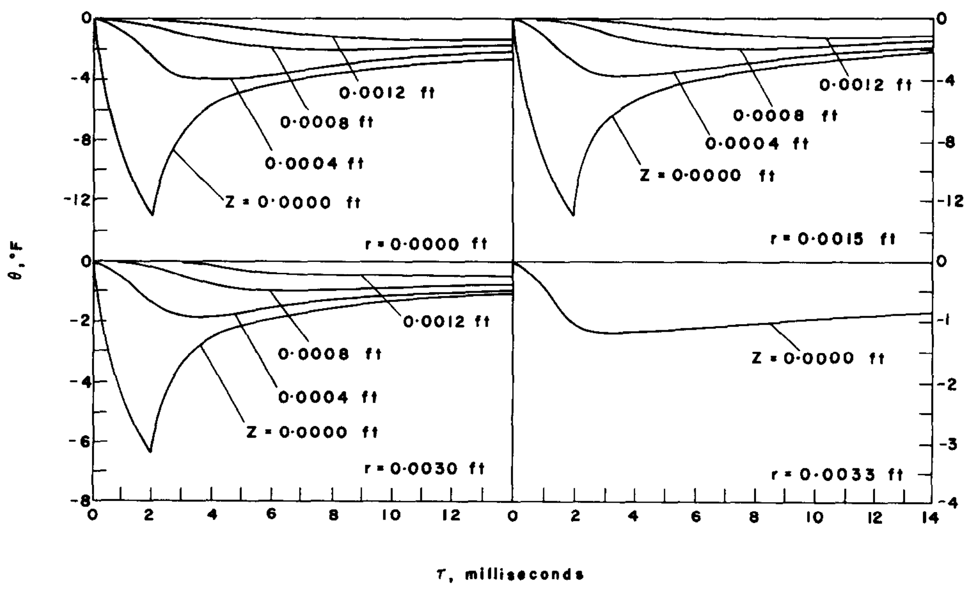

FIG. 9. Computer solution for temperature distribution in stainless-steel plate, $\tau_0 = 2{\cdot}04$ ms; $R_b = 0{\cdot}003$ ft; $t = 0{\cdot}00292$ ft; $k\xi = 4 \times 10^5$ Btu/hft^2; $\alpha = 0{\cdot}15$ ft^2/h.

certain instances a marked change in the nucleate-boiling heat-transfer coefficient. The transient analytical solution can be applied to show that this effect is not due solely to the different thermal properties of the plating material. The transient solution was developed on the basis of a single material. Consequently it cannot be applied directly to evaluate the effect of the plating, but rather a limiting case can be determined by applying the solution to certain extreme conditions.

The experimental results showed that, of all the platings tested, copper produced the largest increase in the boiling heat-transfer coefficient at a given surface temperature. Also, the thermal conductivities of copper and stainless steel differ most, whereas their products of density and specific heat are about the same. Thus, such difference in the heat-transfer coefficient as is attributable to the thermal properties of the plating, should be most pronounced for the copper plating.

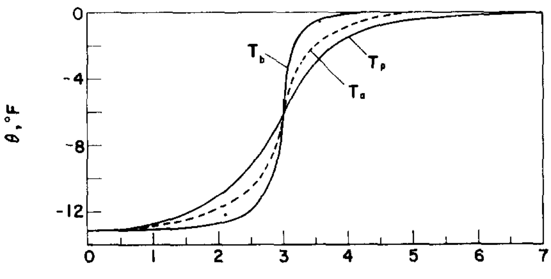

FIG. 10. Temperature profiles as a function of distance from the bubble center at the time of bubble departure. $\tau = \tau_0 = 2{\cdot}04$ ms; $R_b = 0{\cdot}003$ ft; $t = 0{\cdot}00292$ ft; $k\xi = 4 \times 10^5$ Btu/h ft^2; $\alpha_b = 0{\cdot}15$ ft^2/h; $\alpha_p = 4{\cdot}0$ ft^2/h.

Figure 10 shows two extreme temperature distributions T_p and T_b in the plated material. It is assumed that at any point on the surface at any time the temperature does not change across the thickness of the plating. These curves are computed at the instant when the bubble departs from the surface. The curve T_p represents the surface-temperature distribution occurring in a single layer of copper of thickness t if the maximum temperature drop is adjusted to equal that which occurs in the stainless steel. The curve T_b is the surface-temperature distribution of the unplated stainless steel. The copper-plated stainless-steel composite will have a surface-temperature distribution which lies between T_b and T_p, designated as T_a in Fig. 10.

The heat transferred to the bubble can be divided into three component parts: (1) the heat transferred to the bubble from the bulk stainless steel through the plating at $r < R_b$; (2) the internal energy of the plating given up to the bubble; and (3) heat conducted through the plating material from the stainless steel at $r > R_b$ to the bubble. Since the temperature drop across the thickness of the plating is very small, then for fixed surface temperature the first component of heat transfer is essentially unchanged by the addition of the plating. Thus the second and third components, which do not occur in the unplated case, represent the change in the heat-transfer rate attributable to the presence of the plating.

The second component of heat transfer, as mentioned in the preceding paragraph, was computed using curve T_p in Fig. 10, integrating the temperature deviation from zero to infinite radius. The third component was evaluated from curve T_b using its slope at the edge of the bubble. This procedure overestimates both heat-transfer components.

Using the above procedure the maximum contribution possible for the plating has been calculated using an assumed heat flux of 400 000 Btu/h ft^2 and an assumed bubble radius of 0·003 ft. This bubble radius is in the same range of bubble radius observed by Rogers and Mesler [14]. However, a slightly larger radius was assumed since examination of the photographs taken in this investigation showed the bubbles at the bottom of the tube to be larger than those observed by Rogers and Mesler. Also, the calculations of Moore and Mesler [13] indicate a heat-flux rate at the bubble base in the neighborhood of 800 000 Btu/h ft^2 with an average rate of heat transfer of about 135 000 Btu/f ft^2. Since in this investigation significant boiling was taking place in the range of 50 000 to 80 000 Btu/h ft^2, a heat transfer rate at the bubble base of 400 000 Btu/h ft^2 was chosen. For these particular values the results of the transient solution show that the copper plating can account for at most a 32 per cent increase in the boiling film coefficient. However, the average experimental results showed that the copper-plated tube had from 200 per cent to 250 per cent more heat transferred from its surface than did the bare stainless steel tube at the same surface temperature.

The above calculations were based on the transient solution. The effect of the plating on the steady-state solution should also be considered. However calculations showed that the copper plating has no appreciable affect upon the steady-state temperature distribution.

From these calculations it is seen that for one run at least involving the copper plating the observed increase in heat-transfer coefficient cannot be attributed solely to the thermal properties of the plating. However, the thermal properties do have an effect and for thicker platings this effect would be more significant.

As suggestions for future research to account for the increased heat-transfer coefficient, the effect of the plating process on the number of nucleation sites may be investigated. Also the growth of a vapor bubble should be established in detail as influenced by the particular wall material and surface conditions.

CONCLUSIONS

It may be concluded that the surface material strongly influences the heat-transfer coefficient during nucleate boiling of water from horizontal tubes. The effect can be either to increase or decrease the heat-transfer coefficient. It has been shown that the thermal properties of the plating material do not by themselves account for this effect. The mechanism to which this effect is due remains of course unknown.

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Résumé—Des essais ont été effectués en employant des tubes en acier inoxydable chauffés électriquement à partir desquels a lieu une ébullition nucléée. Ces essais ont été répétés lorsque les tubes ont été recouverts d'une couche mince de divers matériaux. Les matériaux employés pour le revêtement étaient le cuivre, le zinc, l'étain, le nickel, le cadmiun et le chrome. On a trouvé que la présence du revêtement avait pour résultat un changement du coefficient de film allant jusqu'a 200 à 300 pour cent dans le cas du cuivre ou du zinc. Une solution analytique a été obtenue pour l'action d'une bulle unique sur une plaque plane. On conclut à partir de cette solution que l'effet du matériau de revêtement n'est pas dû seulement à ses propriétés thermiques.

Zusammenfassung—Es wurden Versuche durchgeführt mit elektrisch beheizten Rohren aus rostfreiem Stahl, an denen Blasensieden stattfand. Diese Versuche wurden wiederholt, nachdem die Rohre mit einem dünnen Überzug aus verschiedenen Metallen versehen waren. Die verwendeten Plattierungsmaterialien waren Kupfer, Zinn, Zink, Nickel, Kadmium und Chrom. Es stellte sich heraus, dass die Anwesenheit von Kupfer oder Zink eine Änderung des Wärmeübergangskoeffizienten um etwa 200 bis 300 Prozent zur Folge hatte. Für das Verhalten einer Einzelblase auf einer ebenen Platte wurde eine analytische Lösung gefunden. Aus dieser Lösung wurde gefolgert, dass der Einfluss des Plattierungsmaterials nicht allein auf dessen thermische Eigenschaften zurückzuführen ist.

Аннотация—Опыты проводились с нержавеющими электрообогреваемыми трубками, на поверхности которых происходит пузырьковое кипение. В других опытах трубки покрывались тонким слоем различных материалов. В качестве материала покрытий использовались медь, цинк, олово, никель, кадмий и хром. Найдено, что наличие покрытия приводит к изменению пленочного коэффициента примерно на 200–300% для случая меди или цинка. Получено аналитическое решение для единичного пузырька на плоской пластине. Из решения найдено, что влияние материала покрытия не может быть объяснено только его теплофизическими свойствами.