

# The effects of heating methods on pool boiling

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**Abstract**—Saturation pool boiling is studied analytically and experimentally using a 0.5 mm tungsten wire in methanol under atmospheric pressure. Under constant voltage heating, transition boiling is an 'unsteady' two mode boiling which may be followed by a 'steady' two mode boiling. The locus of 'steady' two mode boiling is the equilibrium line which divides the nucleate and film boiling curves into stable and metastable sections. Along this line, the electric current is constant and the lever arm rule applies. Under constant current heating, transition boiling is 'unsteady' two mode boiling which changes faster as the current differs more from the equilibrium line current.

## INTRODUCTION

BASIC studies on boiling have often been conducted with a metal wire horizontally installed in a pool of liquid. As the electric energy is increased, three boiling regions are observed on the wire. At first, nucleate boiling is the only mode of boiling. Then with a sufficient increase in energy, a hot spot appears on the wire and develops into film boiling which forces the nucleate boiling to recede to a section of the wire. This is two mode boiling. With further increase in energy, film boiling becomes the only mode of boiling. This mode continues until the wire temperature attains the melting temperature of the metal and burnout occurs. Of these three regions of boiling, the two 'one mode boiling' regions have been investigated by a great number of investigators. For two mode boiling, it appears that there is the need for further investigation.

The coexistence of film and nucleate boiling on a wire has been investigated by Semeria and Martinet [1], Kovalev [2], van Ouwerkerk [3], and Madsen [4], as reported in ref. [5]. The present authors have shown analytically that a steady two mode boiling on a wire exists when the wire is heated electrically under a constant voltage condition. Unal [6] investigated the two mode boiling on a fin and proposed a simple empirical relation for the heat flux and the excess temperature. Winterton [7] gave a comprehensive review on transition boiling. Zhukov and Barelko [8] investigated the heating methods and transition boiling.

In this paper, an experimental and analytical study are conducted on saturation boiling from a metal wire horizontally installed in a pool of methanol under atmospheric pressure. Quantitative results for two mode boiling are presented.

## EXPERIMENTAL

Figure 1(a) shows the pool. It was designed to give well-defined flow and temperature fields for the heat-

ing wire. The test chamber is  $0.16(W) \times 0.05(D) \times 0.40(H)$  m in dimension and has front and back view glasses for observation. In the lower section of this chamber, a preheater, 1 kW in capacity, was installed. The hot liquid rising in the test chamber overflows into the reservoir chamber which is  $0.16(W) \times 0.16(D) \times 0.40(H)$  m in dimension. This chamber is vented to atmospheric pressure through a glass condenser. The electrical energy to the heating wire was supplied by a d.c. generator of capacity 500 A, 24 V, and output ripple less than 0.5%. The voltage, current, and liquid temperature at different locations were monitored by a data acquisition system shown in Fig. 1(b).

Two methods of heating, constant voltage (CV) and constant current (CC), were used. By CV method, the d.c. generator is set at a chosen voltage  $V_T$  while the current is allowed to vary. The current adjusts itself to satisfy the experimental conditions and stabilizes at a special ampere value. When the voltage is reset to a new value, the current again adjusts itself to a new steady condition. By the CC method, the d.c. generator is set at a chosen current value  $I$  while voltage is allowed to vary. The voltage adjusts itself to satisfy the experimental conditions and stabilizes at a special value. Resetting the current to a new value causes the voltage to stabilize at a new steady value.

Tungsten (99.99%) wires of 0.5 mm diameter and lengths 9.4 and 8.7 cm were used as the heating wires. Tungsten has a very high melting point and a low thermal expansion coefficient. It is less expansive than platinum and can be used in methanol (not in water). Table 1 shows the properties. Fresh wires are aged before experimental runs by boiling in methanol for about an hour to make sure that reproducible curves can be obtained. The aged tungsten wires are darker in colour. For high temperature runs, methanol decomposition produces carbon. But the concentration is not high and the effect on boiling is neglected. For a group of wires, the ends were elec-

## NOMENCLATURE

$A$	function defined in equation (7b) [dimensionless]	$R_1$	resistance of external circuit [ $\Omega$ ]
$A_c$	cross-sectional area [ $m^2$ ]	$s$	resistance ratio defined in equation (7a) [dimensionless]
$C_m$	specific heat capacity of metal [ $J kg^{-1} K^{-1}$ ]	$T$	temperature [K]
$D$	diameter [m]	$T_{sat}$	saturation temperature of liquid [K]
$f_R$	equivalent to $(D/4)q_g$ [ $W m^{-2}$ ]	$V$	voltage [V]
$I$	electric current [A]	$V_T$	total voltage drop [V].
$L$	length of heating wire [m]	Greek symbols	
$Q_g$	rate of electrical energy generated [W]	$\kappa$	temperature coefficient of electrical resistivity [ $K^{-1}$ ]
$q$	average heat flux [ $W m^{-2}$ ]	$\rho$	resistivity at temperature $T$ K [ $\Omega\cdot m$ ]
$q_g$	rate of electrical energy generated per unit volume [ $W m^{-3}$ ]	$\rho_m$	density of metal [ $kg m^{-3}$ ]
$q_B$	boiling heat flux [ $W m^{-2}$ ]	$\rho_{sat}$	resistivity at saturation temperature [ $\Omega\cdot m$ ].
$q_{cond,i}$	conduction heat loss at end $i$ [ $W m^{-2}$ ]		
$R$	electrical resistance at $T$ K [ $\Omega$ ]		

troplated with copper to provide low resistance paths for the electric current. This prevents bubbling at the wire junctions with the copper electrodes. For another group of wires, the ends were left as they were (bare ends). Some wires were bent into a U shape to reduce the end effects. The differences in the experimental results between U-shaped wires and straight wires were small.

The procedure for each boiling experiment is as follows. The preheater and the heat exchanger are activated to maintain the pool at the saturation tempera-

ture. Then the preheater is turned off. Experiments start from a low nucleate boiling region. With CV heating, the d.c. voltage is set at a chosen value and a steady state is attained. The relevant data are then recorded. The voltage is then changed to a new value and the process is repeated. For the high heat flux region, for some of the runs, the voltage increments were such that the heat flux increments were not more than 1% of the critical heat flux. With CC heating, the two mode boiling is unsteady. Transient recordings of data at 0.5 s intervals were made. Experiments were also conducted for which the electrical energy was reduced step by step. In two mode boiling, a He-Ne laser was used to measure the length of wire occupied by each mode of boiling.

The electrical energy input  $q_g$ , the average heat flux  $q$ , and the average excess temperature  $\Delta T$  of a test wire are computed by a program installed in the computer. It should be noted that all variables recorded and calculated are either for the entire wire or averaged for the entire wire.  $\Delta T$  of the wire is found by calculating the electrical resistance  $R$  by Ohm's law and the resistivity  $\rho$  by its definition. As the thermal coefficient of resistivity  $\kappa$  is known, the excess temperature can then be found by using equations (8a) and (8b) listed in Table 1. Equation (8b) is a regression equation obtained by using the data from the cited references.

## ANALYSIS FOR TRANSITION BOILING

The transition path by CC or CV heating is investigated as follows. The heat balance equation for a wire under boiling is

$$\frac{\partial(A_c L \rho_m C_m T)}{\partial t} = A_c L q_g - \pi D L q_B$$

$$- A_c (q_{cond,1} + q_{cond,2}).$$

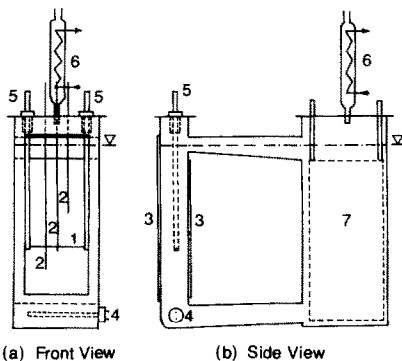


FIG. 1(a). Diagram of the pool: 1, heating wire; 2, thermocouples; 3, view glass; 4, auxiliary heater; 5, electrodes; 6, condenser; 7, heat exchanger.

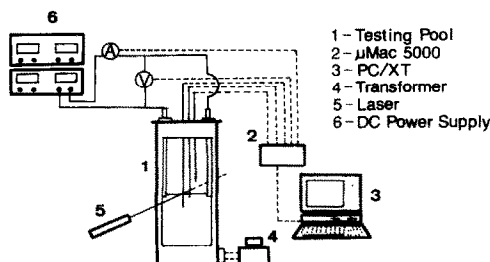


FIG. 1(b). Experimental setup.

Table 1. Properties of tungsten

No.	Property	Value	[Ref.]
1	density	19 300 kg m <sup>-3</sup>	9
2	heat capacity	138 J kg <sup>-1</sup> K <sup>-1</sup>	9
3	melting point	3400 °C	9
4	thermal expansion coefficient, at 100 °C	4.5E-6 K <sup>-1</sup>	9
	at 1000 °C	4.6E-6 K <sup>-1</sup>	9
5	electrical resistivity at 20 °C	5.4E-8 Ω-m	9
6	temperature coefficient of electrical resistivity	4.8E-3 K <sup>-1</sup>	9
7	electrical resistivity at 64.7 °C	6.56E-8 Ω-m	9
8a	electrical resistivity, 300 K < T < 1240 K	<sup>a</sup>	10
8b	electrical resistivity, T > 1240 K	<sup>b</sup>	9, 11

$${}^a \rho = 4.33471 \times 10^{-14} T^2 \text{ (K)} + 2.19691 \times 10^{-10} T \text{ (K)} - 1.64011 \times 10^{-8}.$$

$${}^b \rho = 3.39 \times 10^{-10} T \text{ (°C)} - 1.98 \times 10^{-8}.$$

Since the unsteady state term is small when compared with the others, pseudo-steady state may be assumed. By neglecting conduction heat loss from the ends, the above equation is then reduced to

$$q_B = \left(\frac{D}{4}\right) q_g. \quad (1)$$

The left-hand side represents the rate of heat flux from the wire due to boiling and is a function of  $\Delta T$ . The right-hand side is from the electrical heat generation and will be represented by the symbol  $f_R$ . By solving equation (1), the excess temperature of boiling can be found. This is equivalent to finding the intersection point of the two curves representing each side of equation (1). Taking the boiling curve to be already known, then it is only necessary to find an equation and its curve for  $f_R$ . For this purpose, the rate of electrical energy generation can be written as

$$Q_g = A_c L q_g = I^2 R \quad (2)$$

where electrical resistance  $R$  is related to resistivity  $\rho$  and then to temperature  $T$  by

$$R = \frac{L}{A_c} \rho = \frac{L}{A_c} \rho_{\text{sat}} [1 + \kappa(T - T_{\text{sat}})] \quad (3)$$

where the temperature coefficient of resistivity  $\kappa$  is positive for most metals.

For the case of CC heating, by using equations (1)–(3),  $f_R$  is found as

$$f_R = \left(\frac{D}{4}\right) \left(\frac{Q_g}{A_c L}\right) = \frac{4\rho_{\text{sat}}}{\pi^2 D^3} I^2 [1 + \kappa(T - T_{\text{sat}})]. \quad (4a)$$

As current  $I$  is constant, the only variable in the above equation is temperature. Differentiation with respect to  $\Delta T$  results in

$$\frac{df_R}{d\Delta T} = \frac{4\rho_{\text{sat}}\kappa}{\pi^2 D^3} I^2. \quad (4b)$$

All terms that appear on the right-hand side are positive. Therefore, the slope is positive and constant.

Thus, for CC heating,  $f_R$  is a straight line with positive slope.

For the case of CV heating, equation (4a) still applies but  $I$  is no longer constant. As the heating wire is a part of the electric circuit, the voltage indicated by the d.c. generator is not the true voltage drop across the heating wire. Using  $V_T$  as the total voltage indicated by the d.c. generator, and  $V$  as the voltage drop across the heating wire, the current is then expressed by

$$I = \frac{V_T}{R_1 + R} \quad (5)$$

where  $R_1$  and  $R$  are respectively the resistance of the external circuit and the heating wire. Substituting equation (5) into equation (2) results in

$$Q_g = \left(\frac{V_T}{R_1 + R}\right)^2 R. \quad (6a)$$

Substituting equation (3) into the above equation and rearranging, we obtain

$$Q_g = \left(\frac{V_T^2}{R_1^2}\right) \frac{\left(\frac{R_{\text{sat}}}{R_1}\right) [1 + \kappa(T - T_{\text{sat}})]}{\left\{1 + \frac{R_{\text{sat}}}{R_1} [1 + \kappa(T - T_{\text{sat}})]\right\}^2} = \left(\frac{V_T^2}{R_1^2}\right) \frac{A/s}{(1 + A/s)^2} \quad (6b)$$

where

$$s = \frac{R_1}{R_{\text{sat}}} \quad (7a)$$

$$A = [1 + \kappa(T - T_{\text{sat}})]. \quad (7b)$$

Equation (6b) in dimensionless form is

$$\frac{Q_g}{V_T^2/R_1} = \frac{A/s}{(1 + A/s)^2}. \quad (8)$$

With equation (6b),  $f_R$  is written as

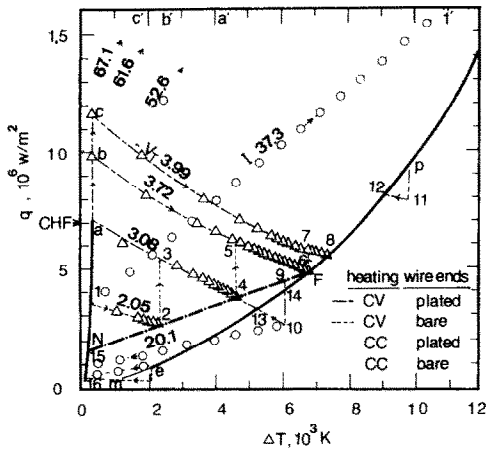


FIG. 2. Heat flux vs excess temperature with CV ( $s = 0.7$ ) or CC heating. Plated and bare end wires. Methanol, tungsten wire, diameter 0.5 mm, length 94 and 87 mm.  $\Delta$ ,  $\circ$ , CV and CC data at 0.5 s intervals.

$$f_R = \left(\frac{D}{4}\right) \left(\frac{Q_g}{A_c L}\right) = \left(\frac{V_T^2 / R_1}{\pi D L}\right) \frac{A/s}{(1 + A/s)^2} \quad (9a)$$

As  $V_T$  is constant, the only variable in equation (9a) is  $A$ , that is, temperature. Differentiating the above equation with respect to  $\Delta T$  results in

$$\frac{df_R}{d\Delta T} = \frac{4\rho_{sat}k}{\pi^2 D^3} f^2 \left(\frac{1 - A/s}{1 + A/s}\right) \quad (9b)$$

or, in dimensionless form

$$d\left(\frac{f_R}{V_T^2 / R_1 \pi D L}\right) = \left(\frac{\kappa}{s}\right) \frac{(1 - A/s)}{(1 + A/s)^3} d\Delta T \quad (9c)$$

As  $s > 0$ , the sign of the slope is dependent on the variable  $A/s$ . Thus, for CV heating,  $f_R$  is dependent on  $V_T$  and  $s$  and is non-linear.

## RESULTS AND DISCUSSIONS

The steady state nucleate and film boiling curves are independent of the methods of heating and are unique for the given experimental conditions. The transition from nucleate to film boiling, or vice versa, however, is dependent on the method of heating. Details are given below.

### CV experiments

*Wires with plated ends.* In this case, the electrical resistance at the junction to the electrode is small. Therefore, the junction cannot become the hot spot. Film boiling is initiated on the wire after the heat flux reaches the CHF (critical heat flux) which is the limiting heat flux by hydrodynamic stability analysis [12]. Figure 2 shows the case of  $s = 0.7$ . The solid curves are for steady nucleate and film boiling. The CHF indicated in the figure is calculated according to

Lienhard [13]. Consider point 'a' near the CHF. The entire wire is under nucleate boiling. Now voltage  $V_T$  is increased by a step to a new constant value. If the step is sufficiently small, boiling may continue to be nucleate boiling and the heat flux is almost at the CHF. If the step is not that small, then, a bright hot spot appears at some point on the wire. This hot spot spreads to form film boiling on the wire, while the nucleate boiling recedes. This is transient two mode boiling. The triangular symbols are data at 0.5 s intervals. They show that spreading of film boiling gradually loses speed and eventually stops. An equilibrium is attained between the film and the nucleate boiling and a steady two mode boiling is established at point 4.

If the step increment in voltage is large, the response will be as shown by curve a-b-6. The hot spot is brighter than the previous case and film boiling spreads over on a longer section of the wire. Eventually a steady two mode boiling is attained at point 6. In this case, point 6 happens to be such that nucleate boiling is just swept out of the wire. If the step increment in voltage is very large, the response will be as shown by curve a-c-8. Film boiling spreads over the entire wire and a steady state film boiling with heat flux higher than point 6 is attained at point 8.

Points 4 and 6 are connected by a dot-dash line which intersects the nucleate and film boiling curves at points N and F. On line NF, nucleate and film boiling coexist and are at equilibrium. This line will be referred to as the equilibrium line, the steady two mode boiling line, or the steady coexisting line. The dashed curves a-4, b-6, and c-8 were calculated by equation (9a) and show good agreement with the experimental data.

For wires with plated ends, a hot spot occurs at a random point on the wire. The heating wire, however, may be conditioned artificially to produce a hot spot at a chosen point. One easy way to do this is to clip the wire with a clip to produce a spot of large bubbling. Two mode boiling can be induced at this spot at a heat flux far below the CHF.

*Wires with bare ends.* Under normal conditions, nucleate boiling is sustained all the way to the CHF if the wire has plated ends. However, for wires with bare ends, the junction where the wire meets the electrode has high electrical resistance and therefore is the cradle for large bubbling and a hot spot. The bare ends may be clamped to the electrodes with different tightness and orientation. As the electrical energy to the wire is increased, the hot joint initiates a transient two mode boiling at a heat flux much below the CHF. That is, a critical heat flux that can be attained by a bare end wire or by a wire with flaw is in general less than the CHF shown in Fig. 2. Point 1 of the figure is such an example.

Now, if the CV experiment is conducted with a series of small step-by-step increments in voltage, transition from nucleate boiling to film proceeds as follows. A small step increment in voltage may pro-

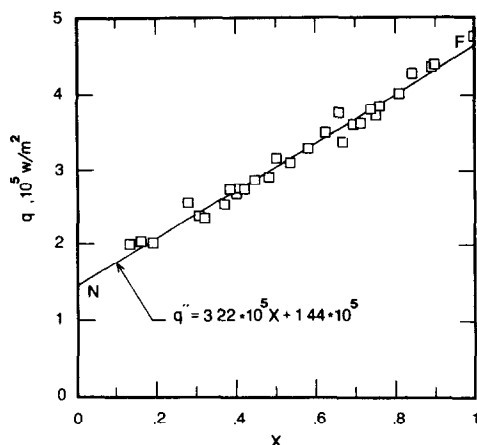


FIG. 3. Heat flux vs fractional length of film boiling during steady two mode boiling. CV heating. Methanol, 0.5 mm tungsten wire, length 94 and 87 mm.

duce a hot spot which then spreads to form a section of film boiling on the wire. Curve 1-2 shows the path. The spreading stops at some point on the wire and an equilibrium between film and nucleate boiling is attained. A steady state two mode boiling is now established at point 2. If the voltage is again increased by a step, film boiling advances further to a new point on the wire and path 2-3-4 is followed. A new equilibrium is attained at point 4. In a similar way, paths 4-5-6 and 6-7-8 can be obtained. Steady two mode boiling other than that indicated by points 2, 4, and 6 can be obtained by controlling the size of voltage increment. Point 2 is on the equilibrium line NF.

In Fig. 3, the heat fluxes of experimental points that are on the equilibrium line are plotted against  $X$ , the fractional lengths of the wire under film boiling. These data points are regressed on the straight line shown in the figure. At end point N, boiling is totally nucleate boiling, and at end point F, boiling is totally film boiling. Any point on the line represents a mixed film and nucleate boiling. The heat flux of this point can be calculated by using the lever arm rule if conditions at N and F are known. This result also applies to the equilibrium line NF in Fig. 2. The equilibrium line is unique for a wire of given material and diameter and is irrelevant to whether the ends of a wire are plated or not.

The response of the electric current to the step change in voltage is shown in Fig. 4. Starting from point 1 in Fig. 2, a step increase in voltage induces a transient two mode boiling, as shown by curve 1-2. The response of the electric current to this change is shown by curve 1-2 of Fig. 4. A marked decrease in the current from point 1 to 24.3 A is observed. At point 1, the entire wire is under vigorous nucleate boiling. At point 2, nucleate boiling is only over a section of the wire and is subdued. For further consecutive step increments in voltage, as shown by curve 2-3-4-5-6-7-8 in Fig. 2, the response of electric cur-

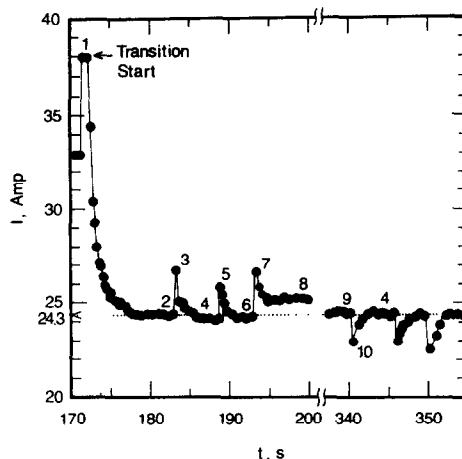


FIG. 4. The response of electric current to CV heating. Methanol, 0.5 mm tungsten wire.

rent is shown by curve 2-3-4-5-6-7-8 of Fig. 4. Figure 4 shows that current  $I$  increases with the step increase in voltage, but then decreases to the value from which it has risen, that is to 24.3 A as shown by the dotted line in the figure. Therefore, the steady two mode boiling curve is at a constant current. Experimental observation shows that at a step increase in the voltage, the wire under film boiling brightens up and film boiling begins to spread. With the advancement of film boiling, the brightness decreases, while the nucleate boiling recedes with boiling maintained at about the same strength. Eventually, a new equilibrium is attained. This process is repeated at each step increase in voltage until the entire wire is under film boiling. At point 6, with a further step increase in voltage, the wire is still under film boiling but is at an increased heat flux and excess temperature, as shown by point 8 of Fig. 4.

If at point 9 of Fig. 2, the voltage is decreased by a step, then path 9-10-4 will be followed, with the corresponding response of current shown by path 9-10-4 of Fig. 4. It is seen again that the current returns to 24.3 A as equilibrium is established at point 4. Thus, the current on the steady mode boiling line is a constant. It may be said that the equilibrium line can be easily established by experiments using CV heating. The voltage on the equilibrium line is not constant but the current is. The magnitude of this constant is dependent on the wire metal and its diameter.

*Abrupt response to power input.* By Fig. 4, the steep path shown by a-b and a-c in Fig. 2 can be explained. As  $V$  is increased by  $\Delta V$  at point a, current  $I$  instantly increases by  $\Delta I$ . By Ohm's law, the electrical resistance of the wire is  $(V + \Delta V)/(I + \Delta I)$ , and therefore is about the same as that before the step increment of voltage. With the resistance remaining at about the same value, the wire temperature remains about the same in spite of the increase in the energy input. Thus, a steep response a-b or a-c is obtained. However, because the current soon drops back to a constant

value, the wire resistance will increase and therefore  $\Delta T$  will increase, resulting in curves b-6 and c-8 of Fig. 2.

**Power reduction.** By the CV method, the voltage may be decreased step by step. Starting at point p on the steady film boiling curve of Fig. 2, by a step decrease in voltage, a transition path p-11-12 is followed. Points p and 12 are at steady film boiling and curve p-12 forms a section of the steady film boiling curve. In this way, the steady boiling curve p-F may be constructed and extended below point F.

At any point on curve p-F, if the step decrease in voltage is sufficiently large, nucleate boiling may break in and boiling changes from film boiling to two mode boiling. If at a point below F, such as at point 14, the voltage is decreased by a step, film boiling may be sustained if the step is sufficiently small, if not, path 14-10-4 in the figure is followed and boiling on the wire changes from film boiling to steady two mode boiling, with the film boiling section receding to give way to nucleate boiling while the colour of the wire under film boiling brightens up with the recession.

The above described breaking out of the vapour film by nucleate boiling is easier by wires with plated ends than by wires with bare ends. For a wire with plated ends, film boiling curve p-F terminates at a point not far below point F and boiling changes from film boiling to steady two mode boiling. For a wire with ends bare, the joints at the electrodes are hot and thus the vapour film is less easy to break. Therefore, a step decrement in voltage at a point near F may not cause nucleate boiling to break in, as shown by path 14-10-13, and a new state of film boiling is established. Thus, the film boiling curve p-F can be extended to a point way below point F, as shown by curve F-e. Of course, if the step decrement in voltage is sufficiently large, film boiling can no longer be sustained and boiling changes from film boiling to steady two mode boiling, just like in the case of a wire with plated ends.

Near point e, the amplitude of the waves of film boiling is very small. At a point near e, a decrease in voltage may cause the vapour over the wire to shrink and vanish, and nucleate boiling takes over film boiling. This change is shown by the dashed line in Fig. 2. Also, if power is cut off at a point on p-F, the waves instantly flatten out and the vapour film that covers the wire shrinks and vanishes. The lowest film boiling observed in this experiment is at point e. Point m indicates the intersection of the extended F-e curve and the minimum heat flux calculated according to Lienhard's equation [13]. In short, the change to steady two mode boiling from film boiling is easier with wires with plated ends (as well as for wires of larger diameters) than with wires with bare ends (as well as for wires of smaller diameters). For the latter, the film boiling curve can be extended further down and closer to the minimum film boiling point m.

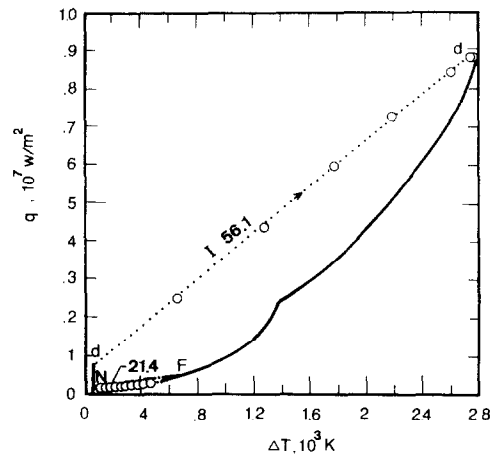


FIG. 5. A complete cycle of heat flux vs excess temperature with CC method. Methanol, 0.5 mm tungsten wire with plated ends, length 87 mm.  $\circ$ , data at 0.5 s intervals.

#### CC experiments

In Fig. 2, the heat flux at point 'a' may be increased by the CC method. If the current is increased by a small step, boiling continues to be nucleate boiling. If the step increase is not that small, a hot spot appears and initiates film boiling which advances all the way until the wire is entirely under film boiling. The two mode boiling is transient. This is in contrast to the case of CV experiments. The explanation was given in ref. [5].

Paths a-a', b-b', and c-c' of Fig. 2 show the transient two mode boiling initiated at point a. These paths are represented by equation (4a). Figure 5 shows an example of a complete cycle. By a step increment, the current was set to 56.1 A. Transient two mode boiling that followed path d-d' was initiated. The circles represent experimental points at 0.5 s intervals. They were taken under the transient condition and show approximately constant advancing motion of the film boiling. In this case, about 3 s are needed for the wire to change from totally nucleate boiling to totally film boiling. The transition path intersects the film boiling curve at a very high excess temperature of 2800 K. The wire was in incandescent brightness and boiling was extremely vigorous. For a current greater than 56.1 A, the wire temperature may attain the melting point of tungsten wire and burnout results. The steady film boiling curve shown in Fig. 5 is in the region of extremely high excess temperature and not much information is available for film boiling in this region. In Fig. 5, at a point below F, a drop in the current to 21.4 A initiates a transient two mode boiling which ends at the nucleate boiling curve. In this case, it takes about 5 s to transit from film to nucleate boiling.

For a wire with bare ends, as at point 1 of Fig. 2, a step increase in current to 37.3 A initiates transient two mode boiling that follows path 1-1'. This path intersects the film boiling curve at an excess tem-

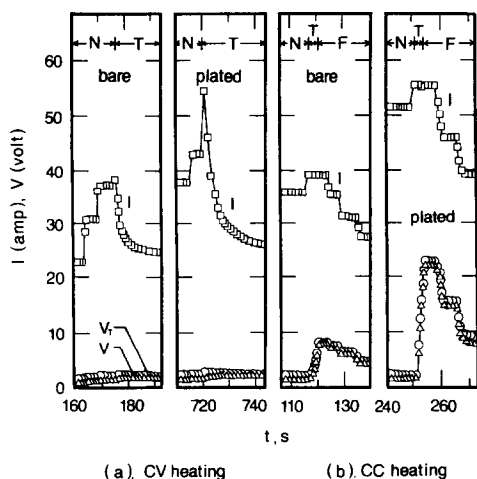


FIG. 6. (a) The response of  $I$  and  $V_T$  to CV heating. (b) The response of  $V$  and  $V_T$  to CC heating. Methanol, 0.5 mm wire, bare or plated ends, tungsten wire.

perature over 1200 K. More than 8 s is taken to complete the transition. Similarly, at point 14, if the current is decreased by a step to 20.1 A, path 14–10–15 is followed. A little over 4 s is taken to complete the transition. For path e–16, about 2 s is taken. Thus, the closer the path is to the equilibrium line, the longer the time taken for transition. On the equilibrium line, a CC path in itself, an infinite time is needed for the transition, that is, this is a line of steady two mode boiling. In CC experiments, in general, two mode boiling is transient. However, a steady two mode boiling can be entered by interrupting the transient two mode boiling on path 10–15 by abruptly giving a step increase in current to 24.3 A.

In Fig. 6, the response of voltages,  $V_T$  and  $V$ , in CC experiments for wires with plated and bare ends are shown in (b). CV experiments are also shown in (a) for comparison.

**Boiling stability**

The nucleate boiling under the equilibrium line and the film boiling above the equilibrium line are in stable boiling. The nucleate boiling above the equilibrium line and the film boiling below the equilibrium line are in metastable boiling. In CC experiments, function  $f_R$  intersects the nucleate and film boiling curves. In CV experiments,  $f_R$  intersects the nucleate boiling curve, the equilibrium line, and the film boiling curve to give three intersection points.

**The effects of  $s$  in CV experiments**

For CV experiments,  $f_R$  is affected by  $s$ , as shown by equation (9a). For a given external circuit,  $s$  is small with a small heating wire because of its large resistance, and  $s$  is large with a large heating wire because of its small resistance. For a given wire,  $s$  may be changed by changing the resistance of the external circuit. The value of  $s$  is large when the external resistance is large.

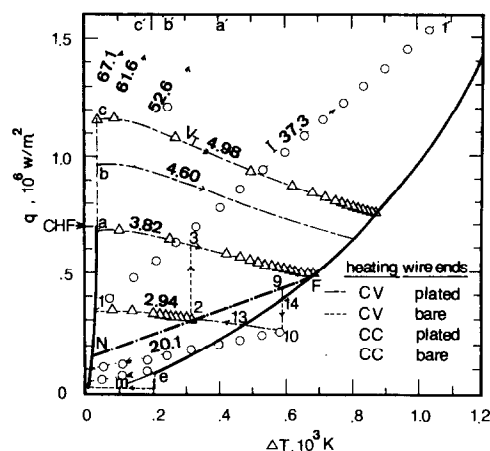


FIG. 7. Heat flux vs excess temperature with CV ( $s = 1.35$ ) or CC heating. Plated and bare end wires. Methanol, 0.5 mm tungsten wire. Length 94 and 87 mm.  $\Delta$ ,  $\circ$ , CV and CC data at 0.5 s intervals.

Figure 7 shows a plot similar to Fig. 2. For CV experiments,  $s$  is now equal to 1.35. The dot-dash curves a–F, 1–2, etc. are plots of equation (9a). The effect of  $s$  is that as  $s$  increases, the maximum of the path shifts toward the right-hand side, and vice versa. The dimensionless slope, as shown by equation (9c), at zero excess temperature may give a general idea about the transient path. This slope is zero when  $s$  is equal to 0, 1, and  $\infty$ . For  $0 \leq s \leq 1$ , the slope reduces from 0 to some negative values and then increases back to 0; for  $1 \leq s \leq \infty$ , the slope increases from 0 to some positive values and then decreases back to 0. The effect of  $A/s$  on the dimensionless heat flux,  $Q_g/(V_T^2/R_1)$ , is shown by equation (8) and is plotted in Fig. 8. This figure shows that the largest dimensionless heat flux and also the maxima of paths a–F, 1–2, etc. in Fig. 7 occur at  $A/s = 1$ .

**CONCLUSIONS**

The following conclusions were obtained from an experimental and analytical study of saturation pool

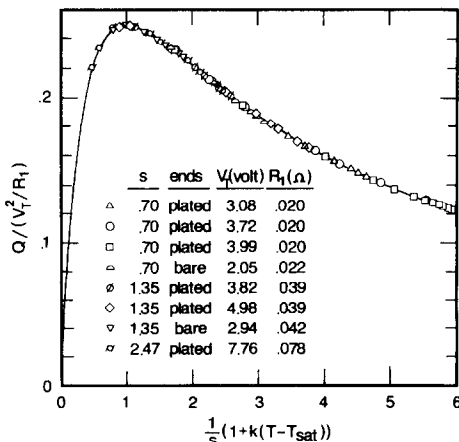


FIG. 8. Dimensionless heat flux vs  $A/s$ . CV heating. Methanol, 0.5 mm tungsten wire.

boiling using electrically heated tungsten wire immersed horizontally in methanol.

(1) The transition boiling induced by the constant current heating is transient two mode boiling. The transition path is a line of positive slope. The transition boiling induced by constant voltage heating is transient two mode boiling which may be followed by steady two mode boiling. The transition path is a curve that depends on the applied voltage and the ratio of electrical resistance of the external circuit to that of the wire.

(2) The locus of steady two mode boiling is the equilibrium line along which the electric current is a constant that depends on liquid-wire (metal and diameter) combination. The lever arm rule applies on this line. The equilibrium line cuts the nucleate and film boiling curves into stable and metastable sections.

(3) The velocity at which transition takes place by the CC method decreases as the transition path approaches the equilibrium line. This velocity is zero on the equilibrium line.

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## LES EFFETS DES METHODES DE CHAUFFAGE SUR L'EBULLITION EN RESERVOIR

**Résumé**—On étudie analytiquement et expérimentalement l'ébullition à saturation dans un réservoir en utilisant un fil de tungstène dans du méthanol à la pression atmosphérique. Avec un chauffage à tension constante l'ébullition de transition est une ébullition "instable" à deux modes qui peut être suivie par une ébullition "stable" à deux modes. Le lieu de l'ébullition stable est la ligne d'équilibre qui divise les courbes d'ébullition nucléée et en film, en sections stable et métastable. Le long de cette ligne, le courant électrique est constant et la règle du bras de levier s'applique. Avec un chauffage à intensité électrique constante, l'ébullition de transition est une ébullition instable à deux modes qui change plus vite quand le courant est écarté de sa valeur sur la ligne d'équilibre.

## DER EINFLUSS DER ART DER BEHEIZUNG AUF DAS BEHÄLTERSIEDEN

**Zusammenfassung**—Das Behältersieden bei Sättigung wird analytisch und experimentell an einem 0,5 mm dicken Wolframdraht in Methanol unter Atmosphärendruck untersucht. Bei Beheizung mit konstanter Spannung erweist sich das Übergangssieden als instationärer Vorgang, bei dem sich zwei Siedezustände abwechseln. Unter Umständen folgt darauf ein stationärer Siedezustand mit gleichzeitiger Anwesenheit zweier Zustände. Der geometrische Ort dieses stationären Siedezustandes ist die Gleichgewichtslinie, die die Kurven für Blasen- und Filmsieden in stabile und metastabile Abschnitte teilt. Entlang dieser Linie ist der elektrische Strom konstant, und die Hebelarmregel ist anwendbar. Bei Beheizung mit konstantem Strom erweist sich das Übergangssieden als instationäres Sieden mit zwei Zuständen, wobei die Schwankungen schneller sind, wenn der Strom stärker von der Gleichgewichtslinie abweicht.

## ВЛИЯНИЕ СПОСОБОВ НАГРЕВА НА КИПЕНИЕ В БОЛЬШОМ ОБЪЕМЕ

**Аннотация**—Аналитически и экспериментально исследуется кипение насыщенной жидкости в большом объеме метанола при атмосферном давлении с использованием вольфрамовой проволоки диаметром 0,5 мм. В условиях нагрева с постоянным напряжением кипение в переходном режиме является "нестационарным" двухрежимным кипением, которое может сопровождаться "стационарным" двухрежимным. Геометрическим местом "стационарного" двухрежимного кипения является линия равновесия, разделяющая кривые зародышеобразования и пленочного кипения на стабильные и метастабильные участки. Вдоль этой линии электрический ток не изменяется и применимо правило левой руки. При нагреве с постоянным током кипение в переходном режиме представляет собой "нестационарное" двухрежимное кипение, изменяющееся с изменением величины тока от значения, соответствующего линии равновесия.