Effects of Heater and Heating Methods on Pool Boiling

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In a pool boiling from an electrically-heated wire, there are three modes of boiling: nucleate, film, and coexisting nucleate and film boiling. These are shown in Figure 1. The latter has been studied by Semeria and Martinet (1965), Kovalev (1966), Van Ouwerkerk (1972), and Madsen (1973, 1979). Zhukov and Barelko (1983) found different states of mixed boiling.

In this work, the effects of the physical properties of heating wires on steady-state pool boiling were investigated analytically. The cases of constant voltage heating and constant current heating were solved.

Analysis

Consider the boiling of a liquid from an electrically heated wire suspended horizontally in a pool of a liquid. For a heating wire of diameter D and length L, the heat balance equation is

$$\rho C_p \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial x^2} + \frac{4}{D} q_b - \frac{16}{\pi^2 D^4} I^2 \rho_T = 0, \qquad 0 \leq x \leq L,\ t \geq 0 \quad (1)$$

The initial condition is $T(x, 0) = f(x)$. It is assumed that wire diameter is small compared to those of copper electrodes and that temperature of the electrodes is at the saturation temperature of the liquid. Thus, the boundary conditions are $T(0, t) = T(L, t) = T_{sat}$. In dimensionless and steady-state form, the problem becomes

$$\frac{d^2\Theta}{dx_D^2} + F(\Theta) = 0 \quad (2)$$

$$\Theta(0) = \Theta(1) = 0 \quad (3)$$

Function F contains q_{bo} and q_b, where q_{bo} is a reference heat flux and is set to be 7.81×10^5 W/m^2 and q_b is boiling heat flux that can be obtained from our experimental boiling curve for wire. As the latter is highly nonlinear, Eq. 2 is also highly nonlinear. This equation shows that N_g and N_b affect the boiling. In this work, L, D, and T_{sat} are fixed, then, by the definitions of N_g and N_b, the properties of wire that affect boiling are the thermal conductivity and the electrical resistivity. Electrical resistivity is related to temperature by $\rho_T = \rho_{298}\ [1 + \kappa(T_{sat} - 298)]$. For metals, κ is positive. When compared with electrical resistivities, thermal conductivities of common metals are less sensitive to temperature and thus the averaged values between 0 and 200°C were used. For pure metals (excluding semiconductors), it is known that thermal conductivity and resistivity have a nearly reciprocal relation. This relation can be represented by $\rho_{298} k - 10^{-5}$ Ohm · W/K. Thus, the dimensionless groups, N_g and N_b, are each inversely proportional to k^2 and k, that is, $N_g \propto 1/k^2$, $N_b \propto 1/k$.

Constant voltage (CV) heating and constant current (CI) heating are considered. For the CV case, as the electrical resistance of a wire is definite for a given temperature and a given wire material, the current cannot be an independent variable. The current should adjust itself to a value to fit the situation. For a steady-state nucleate or film boiling, the magnitude of the current finally attains a steady value. Only when it arrives at a steady state, both voltage and current will remain at constant values. To go to another steady state, the voltage is given a new constant value and the current again adjusts itself to a new value to fit the new steady state. In this case, current I in N_g is calculated by Ohm's law, $I = V/R$. The resistance R, whether CV or CI, is expressed by

$$R = \frac{4\rho_{298} L}{\pi D^2} [1 + \kappa(T_{sat} - 298)] \int_0^1 (1 + K\Theta) dx_D \quad (4)$$

Resistance is dependent on wire temperature. Therefore, for the CV case, the current I and thus N_g are dependent on temperature.

For the CI case, as the resistance of a heating wire at a given

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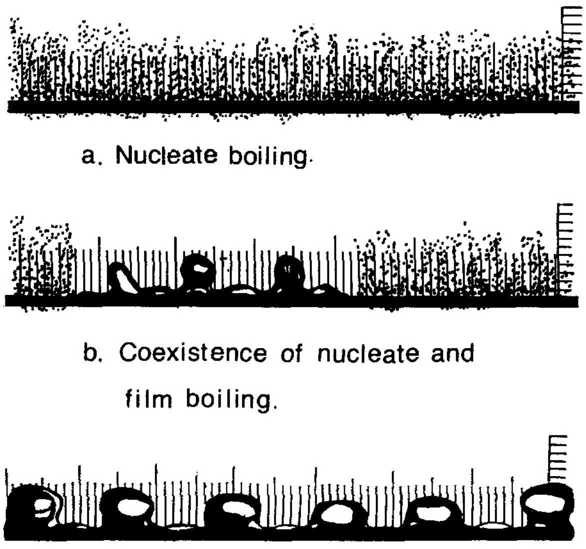

a. Nucleate boiling.

b. Coexistence of nucleate and film boiling.

c. Film boiling.

Figure 1. Modes of pool boiling on a wire.

temperature and for a given wire material is definite, the voltage cannot be an independent variable. The voltage will adjust itself to a value to fit the situation. For the steady-state boiling, the voltage will finally attain a steady value. For a new constant current I, the voltage will again adjust itself to a new constant value and a new steady state will be attained. As I itself is presented in N_g, the latter can be calculated directly once I is given.

Numerical Solution

Different methods may be used to solve Eq. 2. To obtain a stable steady-state solution, Eq. 2 was written into a finite difference equation, and the false transient method (Kubicek and Hlavacek, 1983) was applied. For the CI case, the method of lines was used to solve the resulting difference equation. Gill's method was used for integration. For the CV case, a similar method was used except that the difference equation, Ohm's equation, and Eq. 2 were solved simultaneously. q_b is needed in calculation. Experimental data are not available for wide varieties of wire materials. Therefore, for the following example calculations, which cover wide varieties of wire materials, the boiling heat loss is approximated by using the experimental data of tungsten wire in methanol as obtained in our laboratory. This will naturally introduce errors. The basic features obtained in this analysis, however, are not affected.

Results and Discussions

In the steady-state boiling, given the diameter, length, and surface conditions of a heating wire, liquid type, and saturation temperature, the effects of wire material on boiling are then shown by thermal conductivity and electrical resistivity which are present in N_g and N_b. Therefore, with all other variables invariant, the differences in wire metals are reflected by the magnitudes of N_g and N_b.

The ratios of the thermal conductivities of various pure metals to that of tungsten are in the range of 0.066 to 2.44. For simplicity and for comparison purposes, the range of 0.01 to 10 is used. The numerical values of N_g and N_b for tungusten are

Table 1. Tungsten Wire

L mm	D mm	k W/m · K	κ 1/K	ρ_{298} Ohm · m
68	5.9	174	4.8×10^{-3}	5.4×10^{-8}
I(A)	N_g	N_b	T_{sat}(K)	q_{bo}(W/m^2)
49.05	162.8	417.6	337.3	7.81×10^5

evaluated by using the data given in Table 1. For other metals, the values of N_g and N_b are obtained from those of tungsten by multiplying proper numbers which depend on the magnitude of thermal conductivity.

Figure 2 shows the results of calculation for the CI case. Curve 1 represents the case of tungsten wire. The magnitude of I in this figure is such that curve 1 is at heat flux near its critical heat flux and, therefore, nucleate boiling exists over the entire wire. Other curves on the figure represent wires of other materials with thermal conductivities greater or smaller than tungsten. Curve 2 represents the case of a wire made of a metal with thermal conductivity ten times that of tungsten. The whole wire is also under nucleate boiling, but with a smaller excess temperature. If the wire's thermal conductivity is one tenth of tungsten, boiling on the entire wire is film boiling, as shown by curve 3. For a wire with a still smaller thermal conductivity, for example, one hundredth of tungsten, as shown by curve 4, the entire wire is also under film boiling but with excess temperature greater than the case of curve 3. It can then be said that at a steady state, with all variables except the wire material fixed, the mode of boiling on a wire depends on the wire material. For very low currents, the input electrical energy is small and nucleate boiling prevails on wires of most metals. At high currents, where the input electrical energy is sufficiently high, wires of high thermal conductivity (low resistivity) metals are likely to be entirely in nucleate boiling, while wires of low thermal conductivity (high resistivity) metals are likely to be entirely in film boiling. In fact, this result is apparent from the physical consideration of the problem.

Figure 3 shows the results of calculation for the CV case. Curve 1 is again for tungsten wire. This curve shows a stable two-mode boiling on a wire: a nucleate boiling with low excess temperature and a film boiling with high excess temperature.

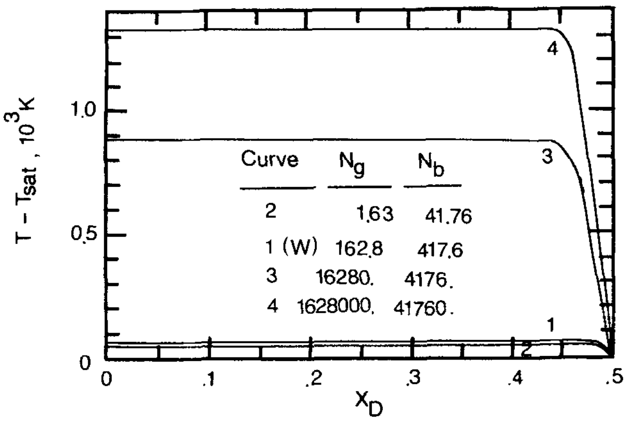

Figure 2. Effects of thermal conductivity and electrical resistivity on excess temperature, constant current, in methanol, 1 atm.

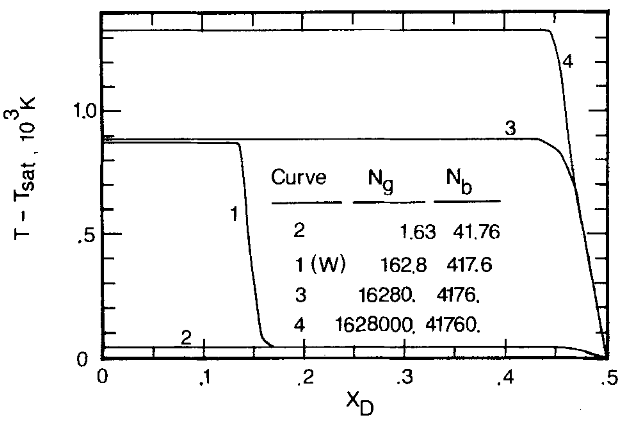

Figure 3. Effects of thermal conductivity and electrical resistivity on excess temperature, constant voltage, in methanol, 1 atm.

The wire with thermal conductivity ten times tungsten's is entirely under nucleate boiling, as shown by curve 2. In the wire with thermal conductivity smaller than that of tungsten, nucleate and film boilings coexist on the wire just as in the case of tungsten. The excess temperature is about the same, but the film boiling region is longer. The wire with still smaller thermal conductivity will eventually be entirely under film boiling, as shown by curve 3. In the wire with a metal of very small thermal conductivity, as shown by curve 4, film boiling exists over the entire wire, as shown by curve 3, but with an excess temperature greater than the case of curve 3.

It has thus been shown that, for the CI case, as heating is increased, film boiling will eventually occur. The onset of film boiling depends on the magnitude of thermal conductivity of the wire. There is only one steady boiling mode on the wire: that is, the entire wire is either on nucleate boiling or on film boiling. The wire, except for the region very near the ends, is always at a uniform temperature and the magnitude of this temperature is dependent on the input energy. For the CV case, as heating is increased, film boiling will eventually occur over a section of the wire. The onset of the coexistence of nucleate and film boiling and the ratio of the lengths of nucleate and film boiling regions depend on the magntiude of the thermal conductivity of the wire. The coexistence of nucleate and film boilings is stable. At a sufficiently high energy input, the entire wire will be under film boiling. In comparison with the CI case, the CV case is marked by the existence of a stable two-mode boiling in the course of transition from total nucleate boiling to total film boiling.

The above-described differences between the CI and CV cases can be explained by using Ohm's law. For the CI case, the influx of electrical energy raises the wire temperature and thus raises the electrical resistance. As I is constant, voltage must increase to obey Ohm's law. The energy input is IV watt; therefore, more energy will be input to the wire. If the increasing energy input can be balanced by the heat loss due to boiling, a steady state will be attained. This balance is possible for nucleate boiling. As heat input increases, the wire temperature increases and the heat loss due to nucealte boiling increases. A steady nucleate boiling over the entire wire is then attained. At a sufficiently high constant current, a hot spot occurs on the wire and from which film boiling begins to spread over the wire. The wire temperature that comes under film boiling increases. This makes electrical resistance and therefore the voltage, according to Ohm's law, increase. The electrical energy input IV is therefore increased. Heat loss due to boiling, however, now decreases because of the decreased heat loss from the film boiling region. Therefore, the wire temperature increases further and this causes a still greater input of electrical energy. Thus, the film boiling keeps on spreading over the wire until the entire wire is under film boiling. Therefore, for the CI case, the steady boiling on the wire will either entirely nucleate boiling or entirely film boiling. There is no stable coexistence of nucleate and film boiling. For the CV case, at a sufficiently high voltage, a hot spot occurs on the wire and film boiling begins to spread over the wire. The temperature of the wire section that comes under film boiling increases and thus the wire resistance increases. As the voltage is constant, the current must decrease to obey Ohm's law. Therefore, the power input IV decreases and a balance in heat will be attained. A stable coexistence of film and nucleate boilings on the wire is therefore obtained.

Acknowledgment

The authors are grateful to National Science Council, R. O. C., for the support of project NSC76-0402-E002-14.

Notation

D = diameter, m
$F = N_g(1 + \mathrm{K}\Theta) - N_b q_D$
$f(x)$ = initial condition
I = electrical current, A
k = thermal conductivity, J/m · K · s
L = length of a wire, m
$N_g = 16L^2\{\rho_{298}[1 + \kappa(T_{sat} - 298)]I^2\}/(\pi^2 D^4 k T_{sat})$
$N_b = (4L^2 q_{bo})/(kDT_{sat})$
q_b = boiling heat flux, $\overline{\mathrm{w}}/\mathrm{m}^2$
q_{bo} = a reference heat flux, $\overline{\mathrm{W}}/\mathrm{m}^2$
$q_D = q_b/q_{bo}$
R = electrical resistance, Ohm
T = temperature, K
T_{sat} = saturation temperature, K
V = voltage, V
x = coordinate
$x_D = x/L$

Greek letters

$\Theta = (T - T_{sat})/T_{sat}$
$\mathrm{K} = \kappa T_{sat}/[1 + \kappa(T_{sat} - 298)]$
κ = temperature coefficient of electrical resistivity, 1/K
ρ_T = resistivity at T K, Ohm · m

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Manuscript received Oct. 10, 1988, and revision received June 15, 1989.