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APPLICATION OF ELECTRON-BOMBARDMENT HEATING FOR BOILING LIQUID METALS

by

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APPLICATION OF ELECTRON-BOMBARDMENT HEATING FOR BOILING LIQUID METALS

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R. E. Holtz

Reactor Engineering Division

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ABSTRACT

The problem of obtaining a curve of the heat flux vs. temperature difference for boiling liquid metals is discussed. Various heating techniques are discussed, with special emphasis given electron-bombardment heating. It is shown that electron-bombardment heating will supply high uniform heat fluxes to liquid metals at high temperatures.

I. INTRODUCTION

One of the more severe problems involved in obtaining experimental information about heat transfer involving boiling liquid metals is the design and construction of a satisfactory heated section. Many of the difficulties stem from the inability of heater sections to function properly. Most of these heater failures have been caused by material expansions at higher temperatures.

A variety of different heating techniques have been applied in heat transfer experiments involving liquid metals. This report briefly presents some of the heating techniques available for use in boiling liquid metal systems and examines the electron-bombardment-heating technique in detail.

II. BACKGROUND INFORMATION ABOUT HEATED SECTION

The convective heat transfer coefficient h is defined by the equation

$$q'' = h(T_i - T_s). \quad (1)$$

To determine the boiling curve, the heat flux q" and the difference between the temperature of the wall in contact with the fluid T_i, and the saturation temperature T_s corresponding to the system pressure must be known.

A considerable amount of information about nucleate boiling has been published. Much of this information has been in the form of empirical results for use in boiling water systems. Recent interests have been focused

toward the nucleate-boiling characteristics of liquid metals because of their potential use as coolants in nuclear reactors. It has been estimated that heat fluxes well above 10^6 Btu/hr-ft^2 may be required for studying the boiling liquid metal characteristics up to the occurrence of the critical heat flux.

Boiling water studies have taken place at temperatures relatively low compared with the temperatures required for studies of boiling liquid metals. Hence, the material requirements of equipment in liquid metal studies are more severe.

In boiling water studies resistance heating of a tube containing the water is often employed. The generated heat flows from the metal tube to the water. An insignificant amount of heat is generated in the water because the electrical resistivity of the water is large compared with that of the metal tube. However, this heating technique is not applicable in experiments dealing with liquid metal heat transfer because the electrical resistivity of the liquid metal is approximately of the same order of magnitude as that of the containing walls. It is apparent that different heating techniques must then be used.

Listed below are some of the techniques presently being considered for investigations of boiling liquid metal heat transfer:

1. modified resistance heating;
2. induction heating;
3. binary system heating;
4. radiant heating;
5. electron-bombardment heating.

In this report only electron-bombardment heating is discussed in detail.

In the case of liquid metals, resistance-heating technique must differ from that used in boiling water systems. For example, the resistance heater must be electrically insulated from the tube containing the liquid metal.

Scientists at General Electric,(1-3) the University of Michigan,(4,5) and Atomics International(6) have considered the use of this technique for heating liquid metals. The systems employed consisted of a tube with a sprayed ceramic coating several mils thick. The ceramic was then coated with a metallic heater by a plasma spray process. The expansion problems were quite severe.(3,7) Several heaters were electrically short-circuited between the tube and the heater. Others failed due to pulling away of the heater from the ceramic, resulting in melting of the resistance heating element.(7)

Induction heating of a boiling liquid metal system has been discussed by Chen[8] and Balzhieser.[9]

Binary-system heating is based on the use of a hotter liquid metal surrounding a tube containing the cooler liquid metal. Heat from the hotter liquid metal is conducted through the tube wall to the liquid metal inside the tube. Personnel at General Electric[1] and the University of Michigan[4] have examined this heating technique. Difficulty has been experienced in obtaining uniform heat fluxes. Problems similar to those encountered in modified resistance heating may be experienced in supplying heat to the primary fluid.

Radiant heating for liquid metal heat transfer experiments has been studied at General Electric,[7] the University of Michigan,[9] and Argonne National Laboratory.[10] The basic system consists of a tube containing the liquid metal surrounded by the radiant heating element. In the use of radiant heating in a liquid metal system, all three modes of heat transfer occur in getting the heat from the heating element to the liquid metal: transfer by radiation between the heating element and the container of the liquid metal, conduction through the walls of the container, and convection from the inside container wall to the liquid metal. One of the difficulties in radiant heating is determination of the heat supplied to the liquid metal. Much of the heat emitted by the heating element may be absorbed by a surface other than the surface of the tube containing the liquid metal. Radiation shields have been employed to minimize the heat losses from radiantly heated sections.[7]

The remainder of this report is concerned with the use of electron-bombardment heating in boiling liquid metals studies. It should be noted that the discussion, although applied to liquid metals, may be also utilized in heating other fluids.

III. THE ELECTRON-BOMBARDMENT HEATER

Electron bombardment may be applied in an experimental loop for the study of heat transfer phenomena of the liquid metals. Taylor and Steinhaus[11] have shown that electron-bombardment heating is a satisfactory technique for this application, in both forced-convection and natural-convection systems.

The basic electron-heating system in a forced-convection loop consists of two concentric tubes with heat applied to the inside surface of the inner tube while the liquid metal flows in the annulus between the tubes (see Fig. 1). The heating is accomplished by placing an electron emitter (cathode) inside the evacuated inner tube, heating the cathode, and drawing the electrons to the inner tube (anode) with an accelerating voltage. The generated heat then flows through the tube wall to the liquid metal inside the annulus.

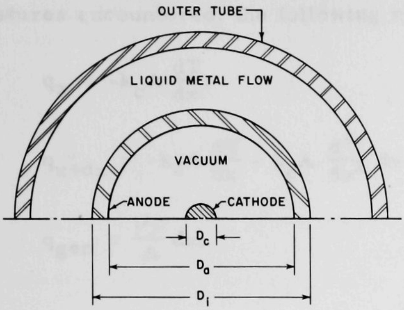

Fig. 1

Half-section of Electron-bombardment-heating Section

In a natural-convection or pool-boiling arrangement, the heating system is identical with that of the forced convection system except that the anode may be immersed in a pool of liquid metal instead of having the liquid metal contained in an annulus.

The heat generated at the anode surface is the product of the emission current and the accelerating potential. The temperature variation along the length of the emitter is of interest because electron emission from a cathode is a function of temperature as predicted by Richardson's Equation:(12)

$$i = aT^2 e^{-b/T}. \tag{2}$$

As the voltage difference between cathode and anode in the vacuum is increased, the electron emission from the cathode increases beyond that which is predicted by Richardson's Equation. Further discussion as to the effect of accelerating voltage upon emission current is found in Reference 13.

IV. TEMPERATURE ANALYSIS OF EMITTERS

Since the accelerating voltage is essentially constant over the length of the cathode and anode, the uniformity of emission current is dependent upon the temperature of the emitter only. Hence, it is necessary to examine the cathode temperature.

A differential element of cathode showing Joule heating inside the element (q_{gen}), radiation heat transfer from the element (q_{rad}), and heat conduction into and from the element (q_x and q_{x+dx}) is shown in Fig. 2. A heat balance for this differential element yields

$$q_x + q_{gen} = q_{x+dx} + q_{rad}. \tag{3}$$

For a constant-diameter cathode with constant properties over the temperatures encountered, the following may be formulated:

$$q_x = -k_c A \frac{dT}{dx}; \tag{4}$$

$$q_{x+dx} = -k_c A \frac{dT}{dx} - k_c A \frac{d^2T}{dx^2} dx; \tag{5}$$

$$q_{gen} = \frac{I^2 \rho}{A} dx; \tag{6}$$

and

$$q_{rad} = \pi D_c \gamma \sigma (T^4 - T_a^4) dx, \tag{7}$$

where

$$\gamma = \frac{1}{\frac{1}{\epsilon_c} + \frac{D_c}{D_a}\left(\frac{1}{\epsilon_a} - 1\right)}. \tag{8}$$

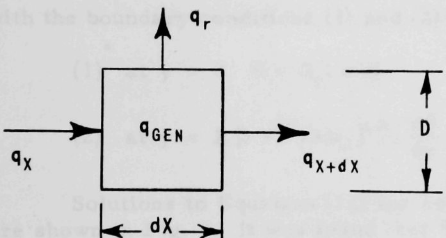

Fig. 2
Differential Element of Cathode

Substitution of Equations (4), (5), (6), and (7) into (3) yields

$$\frac{d^2T}{dx^2} = \frac{4\sigma\gamma}{k_c D_c}(T^4 - T_a^4) - \frac{16 I^2 \rho}{\pi^2 D_c^4 k_c}. \tag{9}$$

For a fixed emission current (i), an equivalent cathode temperature ($\overline{T}$) may be defined as that uniform temperature required for emission current i when all the heat generated is radiated from the cathode. For this equivalent temperature, $d^2T/dx^2 = 0$; hence

$$\overline{T}^4 = \frac{4 I^2 \rho}{\pi^2 D_c^3 \sigma \gamma} + T_a^4. \tag{10}$$

Since nearly all the Joule heating leaves the cathode by radiation, the introduction of $\overline{T}$ serves as a tool for prediction of a proper magnitude of heating current I.

Thus, Equation (9) may be written,

$$\frac{d^2T}{dx^2} = \frac{4\sigma\gamma}{kD_c}(T^4 - \overline{T}^4). \qquad (11)$$

The boundary conditions for Equation (11) are $T = T_b$ at $x = 0$ and $x = L$. Due to the symmetrical conditions, the above boundary conditions are equivalent to the boundary conditions

(1) at $x = 0$, $T = T_b$, and

(2) at $x = L/2$, $dT/dx = 0$.

Making the substitutions $\theta = T/\overline{T}$ and $y = 2x\,[\sigma\gamma\overline{T}^3/kD_c]^{1/2}$, Equation (11) may be normalized to

$$\frac{d^2\theta}{dy^2} = \theta^4 - 1 \qquad (12)$$

with the boundary conditions (1) and (2):

(1) at $y = 0$, $\theta = \theta_b$, and

(2) at $y = L\,[\sigma\gamma\overline{T}^3/kD_c]^{1/2}$, $\frac{d\theta}{dy} = 0$.

Solutions to Equation (12) for selected values of θ_b and $L\,[\sigma\gamma\overline{T}^3/kD_c]^{1/2}$ are shown in Fig. 3. It was found that θ is independent of cathode length for $L\,[\sigma\gamma\overline{T}^3/kD_c]^{1/2}$ greater than 2.5.

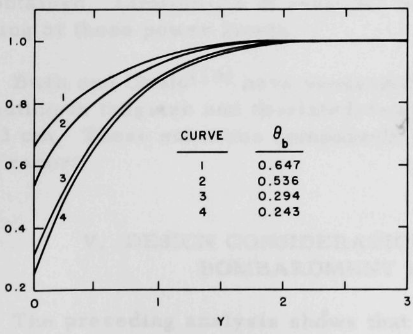

Fig. 3

Temperature of Electron Emitter vs. Length

Figure 4 shows the plot of temperature ratio vs. cathode length for values of $\overline{T}$, T_b, and D_c chosen to simulate both tungsten and thoriated-tungsten cathodes. The following values were chosen: $\rho = 50 \times 10^{-6}$ ohm-cm, k = 60 Btu/hr-ft-°F, and $\gamma = 0.38$. The temperature was found to be essentially constant over the entire length of the cathode except for a rapid temperature decrease to T_b at the cathode ends. This temperature drop is independent of length and takes place over a length of the order of one inch for the selected values of T_b, $\overline{T}$, and D_c. Conditions selected in this analysis are more severe than those expected during the operation of an electron-bombardment-heated liquid metal loop. The uniform cathode temperatures predicted in the analysis show that uniform heat fluxes may be expected from electron-bombardment heating of fairly short to extremely long sections.

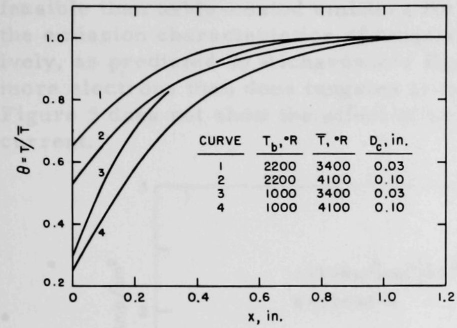

Fig. 4. Temperature of Electron Emitter vs. Length for Simulated Tungsten and Thoriated Tungsten

A small-scale electron bombardment heater was constructed to verify the uniform heat fluxes expected. This model consisted of a 0.020-in.-diameter, thoriated-tungsten cathode surrounded by a $\frac{1}{2}$-in.-OD, type 316 stainless steel tubular anode of a 0.035-in. wall thickness. The heated length was 4 in. Thermocouples were placed $\frac{1}{2}$ in. from the ends of the heated length on the outside anode surface and in the center of the anode on the outside surface. It was found that the thermocouples at the center and at the ends gave identical readings at given heat fluxes. Heat fluxes up to approximately 8000 Btu/hr-ft^2 on the outside anode surface were obtained. Limitations of available power supply caused termination of testing at these power levels.

Bush and Gould[14] have presented solutions for the temperature distribution in tungsten and thoriated-tungsten filaments with diameters of 0.01003 cm. These solutions compare favorably with the results presented in this report.

V. DESIGN CONSIDERATIONS IN ELECTRON-BOMBARDMENT HEATING

The preceding analysis shows that the cathode design may be of considerable importance in electron-bombardment heating. Two of the most important factors are the cathode material and the cathode shape.

The three most commonly used electron emitters are tungsten, thoriated-tungsten, and oxide-coated cathodes. Because of the high voltages associated with the high heat fluxes required in boiling liquid metal studies, it appears that tungsten and thoriated-tungsten emitters are more feasible than oxide-coated emitters for this application. Figure 5 shows the emission characteristics of tungsten and thoriated tungsten, respectively, as predicted by Richardson's Equation. Thoriated tungsten emits more electrons than does tungsten at the usual operating temperatures. Figure 5 does not show the effect of accelerating voltage upon emission current.

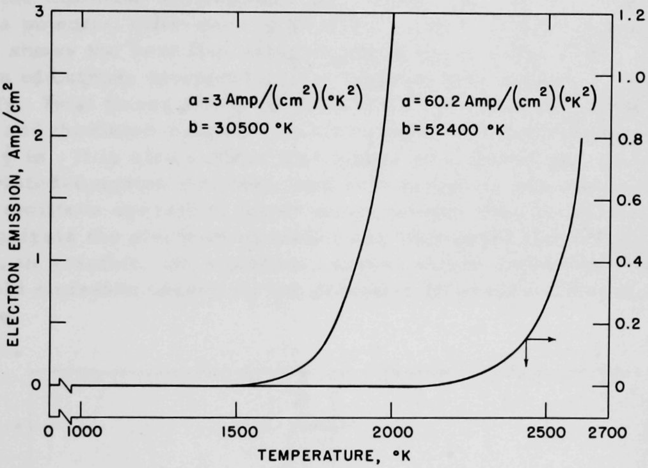

Fig. 5. Electron Emission of Tungsten (a = 60.2 Amp/ $cm^{2}{}^{\circ}K^2$, b = 52400°K) and Thoriated Tungsten (a = 3 Amp/$cm^{2}{}^{\circ}K^2$, b = 30500°K)

Figure 5 also shows that the electron emission per unit area increases with increasing temperature; thus, the larger the area emitting electrons, the lower the temperature required for a given heat flux. For a fixed temperature, the total number of electrons leaving a cathode of a given material is directly proportional to the cathode area. It is desirable to operate an electron emitter at a lower temperature so that better control of the emission current may be obtained; thus, a cathode with a larger emitting area may be superior over a cathode of smaller area for high-heat-flux applications. Hence, the cathode shape is of considerable importance in the design of an electron-bombardment heater.

There are two likely cathode configurations which may be used: the wire or solid cathode, and the tubular cathode. The solid cathode will have a larger cross-sectional area than the tubular cathode; therefore, more current will be required for heating a solid cathode than will be needed for heating a tubular cathode of the same emitting area. In systems where higher heat fluxes are needed, it may prove advantageous to use a tubular cathode.

To demonstrate further the feasibility of an electron-bombardment heater for supplying high heat fluxes, consider the heater shown in Fig. 1. Assume the following dimensions: $D_c = \frac{1}{8}$ in., $D_a = \frac{7}{16}$ in., and $D_i = \frac{1}{2}$ in. Assume a potential difference of 20,000 V exists between cathode and anode. Figure 6 shows the heat flux being supplied to the liquid metal plotted as a function of cathode temperature for tungsten and thoriated tungsten, respectively. Heat fluxes above 10^6 Btu/hr-ft^2 may be obtained with both tungsten and thoriated-tungsten emitters for a system in which $D_c = \frac{1}{8}$ in. and $D_i = \frac{1}{2}$ in. It is also evident that higher heat fluxes may be obtained with thoriated-tungsten emitters than with tungsten, and that thoriated-tungsten emitters operate at lower temperatures than tungsten emitters. In this analysis the electron emission was calculated from Richardson's Equation; in practice, the emission current will be somewhat higher due to the field emission caused by the potential difference between cathode and anode.

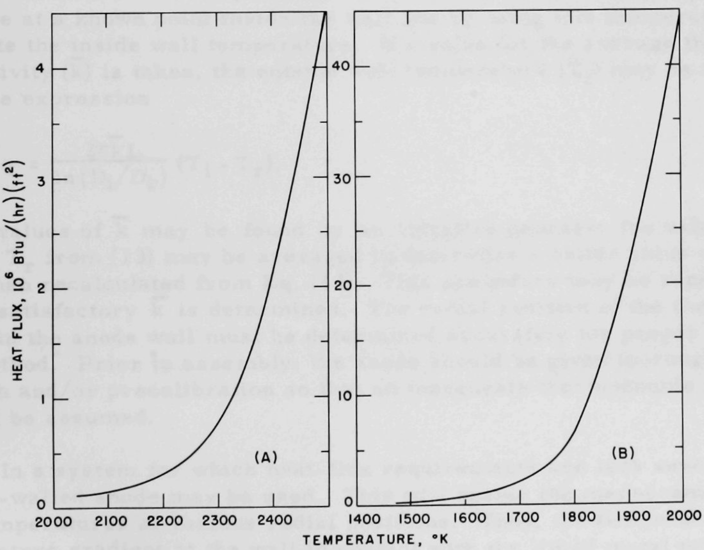

Fig. 6. Heat Flux vs. Temperature for (A) Tungsten and (B) Thoriated-Tungsten Emitters

Since the anode aids in containing the liquid metal, this tube must be compatible with the liquid metal as well as being a satisfactory anode material. Of the available materials, the most satisfactory for this application appears to be:

1. the 300 group stainless steels;
2. niobium, and
3. molybdenum.(12)

Since the heat flows from the inside anode surface to the liquid metal outside the anode, the heat flux at the inside anode surface will be greater than the heat flux at the anode-liquid metal interface. Therefore, the anode wall thickness should be kept to a minimum. This also will result in a reduced temperature drop across the wall.

Since T_s may be assumed to be the saturation temperature corresponding to the system pressure, the heat flux and outside anode wall temperature must be known to determine the boiling curve. The heat supplied may be obtained from the product of the emission current and the potential difference between the cathode and anode. Dividing the heat supplied by the outside anode area yields the required heat flux.

The inside wall temperature may be obtained by measuring the temperature at a known point inside the wall and by using this temperature to calculate the inside wall temperature. If a value for the average thermal conductivity ($\overline{k}$) is taken, the outside wall temperature (T_i) may be found from the expression

$$q = \frac{2\pi \overline{k} L}{\ln(D_i/D_r)} (T_i - T_r). \qquad (13)$$

Better values of $\overline{k}$ may be found by an iterative process: the values of T_i and T_r from (13) may be averaged to determine a better value of $\overline{k}$; T_i is then recalculated from Eq. (13). This procedure may be repeated until a satisfactory $\overline{k}$ is determined. The radial position of the thermocouple in the anode wall must be determined accurately for proper use of this method. Prior to assembly, the anode should be given thorough inspection and/or precalibration so that an inaccurate thermocouple position will not be assumed.

In a system for which heat-flux requirements are less severe, a thicker-walled anode may be used. This will enable the measurement of wall temperatures at various radial positions. Thus, the temperature and temperature gradient at the wall in contact with the liquid metal may be found graphically. Since the heat flux at any point in the wall is given by

$$q'' = -\pi D L k(T) \frac{\partial T}{\partial r}, \quad (14)$$

the heat flux may also be determined from measurements of the wall temperature.

VI. CONCLUSIONS

The following conclusions are reached from the preceding analysis and discussion:

1. Electron-bombardment heating appears quite promising for applications to liquid metals.

2. Usability of an electron-bombardment heater is largely dependent upon system design.

3. Heat fluxes well above 10^6 Btu/hr-ft^2 appear quite feasible with electron-bombardment heating.

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NOMENCLATURE

q''	Heat Flux	$Ft^{-1}\ell^{-1}$
h	Heat Transfer Coefficient	$Ft^{-1}\ell^{-1}\beta^{-1}$
A	Area	ℓ^2
D	Diameter	ℓ
ϵ	Emissivity	-
k	Thermal Conductivity	$Ft^{-1}\beta^{-1}$
ρ	Electrical Conductivity	ohm-ℓ
x	Axial Position along Cathode	ℓ
I	Cathode-heating Current	Amp
i	Electron Emission Current	Amp
γ	$\{(1/\epsilon_c) + (D_c/D_a)[(1/\epsilon_a) - 1]\}^{-1}$	-
σ	Stefan Boltzmann Constant	$F\ell t^{-1}\beta^{-4}$
T	Temperature	β
$\overline{T}$	Equivalent Temperature	β
θ	$T/\overline{T}$	-
y	$2x/[\sigma\gamma T^{-3}/kD]^{1/2}$	-
a	Constant in Richardson's Equation	Amp $\ell^{-2}\beta^{-2}$
b	Constant in Richardson's Equation	β
q	Heat Supplied	$F\ell t^{-1}$
$\overline{k}$	Average Thermal Conductivity	$Ft^{-1}\beta^{-1}$
L	Cathode Length	ℓ

where:

ℓ	Unit of length	t	Unit of time
F	Unit of force	β	Unit of temperature

Subscripts

c	Cathode	x	Axial location
a	Anode	i	Surface in contact with liquid metal
gen	Generated	s	Saturation
rad	Radiation	r	Radial location