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Radial Temperature Profile of Sodium Pool Boiling Heater Assembly

I STATEMENT OF PROBLEM
A. Determine the accuracy, with which the thermocouple in the well of the heater assembly, will predict the heater surface temperature.

B. Determine the temperature distribution around the thermocouple well of the heater assembly, for a steady state heat flux of $5 \times 10^6$ Btu/hr-ft$^2$ with boiling in water.

II SUMMARY OF RESULTS

Some means must be found, to bond the thermocouple to the molybdenum sleeve. Without bonding, the thermocouple temperatures may differ from that of the heater surface by as much as 650°F.

A rectangular two-dimensional model of the heater cross section, was found by the method of conformal mapping. The model, when analyzed by the TIGER II as well as by the IBM-709 steady state code, appears to represent the physical system correctly. Temperature profiles which were calculated for two conditions of radial steady state heat transfer, agree with values obtained by analytical methods (Figure 3) as well as experimental measurements (Reference 1).
The temperature distribution around the thermocouple well for a heat flux of $5 \times 10^5$ Btu/hr-ft$^2$, shows a radial temperature drop across the center of the well of about 680°F, (Figure 3) or an average temperature difference to the bulk coolant of 330°F. This is within 6% of the actual value, which was found by experiment. (Reference 1)

The temperature drop across the .001" helium gap between the heater and the heater sleeve, at all angular distances sufficiently away from the thermocouple well to minimize its heat transfer perturbations, was found to be 656°F. Since this drop is not significantly smaller than the temperature drop across the well, it appears that the latter is primarily dependent upon the thickness of the helium gap. Or in other words, the thickness of the helium gap determines the well temperature drop. This large temperature drop however, will result in an equally large variation in thermocouple reading, depending on where in the well the end of the thermocouple is located. To minimize this variation and find a dependable correlation for true sleeve wall temperature measurements, the thermocouple will have to be bonded to the sleeve.

III METHOD USED

A. Description of Heater Assembly

The heater consists of a solid molybdenum rod, covered with alternate layers of alumina and molybdenum. (Figure 1 and 2) The actual heating surface is a layer of molybdenum .01 in. thick, sandwiched between two layers of alumina. The heating rod fits into a molybdenum sleeve, (Figure 2) containing a uniform slot or well, along part of its length. This well will contain the thermocouple during actual operation. The clearance between heating rod and sleeve is approximately .001 inches; this gap, as well as the slot for the thermocouple, is filled with gas at essentially atmospheric pressure*. The radial dimensions of the heater assembly used in this analysis are given in Table 1. The dimensions of the thermocouple well are shown in Figure 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>OD (in)</th>
<th>Thickness (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molybdenum</td>
<td>.205</td>
<td></td>
</tr>
<tr>
<td>Alumina</td>
<td>.225</td>
<td>.01</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>.245</td>
<td>.01</td>
</tr>
<tr>
<td>Alumina</td>
<td>.265</td>
<td>.01</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>.281</td>
<td>.008</td>
</tr>
<tr>
<td>Helium</td>
<td>.283</td>
<td>.001</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>.381</td>
<td>.049</td>
</tr>
</tbody>
</table>

* The gas in this space depends on the history of the heating element. When initially fabricated, the gas is air. Due to diffusion, it is replaced by nitrogen or helium during operation. For these calculations helium was assumed to occupy the gap. In the experience referred to, air occupied the gap.
Figure 3.

Radial temperature distribution of heater assembly and node center temperatures for 11 radial nodes.
B. Description of Rectangular Model and Code Used

Only a radial heat transfer analysis was made for this assembly, since it is assumed that variations in longitudinal heat conduction due to the presence of the thermocouple well are negligible. It is assumed furthermore, that the temperature distribution is symmetrical around a line bisecting the cross section through the center of the thermocouple well.

By plotting the angular distance in radians from the bisector at the well to any arbitrary angle less than \( \pi \) radians, versus the natural logarithm of the radial distance, a rectangular model is formed, in which the rings of the various materials are transformed into parallel strips of equal length, or expressed in coordinates of the mathematical model:

\[
x = \ln \frac{r}{a} \\
y = \theta
\]

where

- \( a \) = constant
- \( r \) = radial distance
- \( \theta \) = angle in radians

By sub-dividing now the \( x \) and \( y \) coordinates of the model into an arbitrary number of sections, a rectangular grid is formed in which each rectangle can be made to correspond to a node in a two-dimensional relaxation method analysis. Care has to be taken however, to express the heat generation rate in that part of the model which corresponds to the cross section of the heating layer, in the units of the grid. The difficulty of employing a small number of nodes, without sacrifice to the required accuracy in the region of high temperature disorderliness, can be resolved by dividing the transformed radial distance into a large number of small intervals and the transformed angular distance into small intervals near the well and into large ones at large angular distances.

The code used in the determination of the temperature profile for a heat flux of \( 3 \times 10^5 \) Btu/hr-ft\(^2\), was the IBM-709 code in which the matrix of heat balance equations is solved by the Gauss-Seidel method of iteration. The constants used are given in Table 2.
TABLE 2 (Reference 2 & 3)

<table>
<thead>
<tr>
<th>Material</th>
<th>$q$ (Btu/hr-ft°F)</th>
<th>$C_p$ (Btu/Lbf°F)</th>
<th>$f$ (Lb/In³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molybdenum</td>
<td>75</td>
<td>0.069</td>
<td>0.37</td>
</tr>
<tr>
<td>Alumina</td>
<td>3</td>
<td>0.02</td>
<td>0.087</td>
</tr>
<tr>
<td>Helium</td>
<td>0.121</td>
<td>1.21</td>
<td>0.10</td>
</tr>
</tbody>
</table>

The value for the density of helium is fictitious and has been chosen for reasons of convergence speed. Letting $K$ be equal to the product $\int C \text{ will for a steady state problem decrease the total machine time without affecting the answer.}$

The bulk temperature of the boiling water was chosen to be 250°F, corresponding to a saturation pressure of 30 psia. The heat generation rate is as follows:

Total heat generation of heater assembly

$$q = 5 \times 10^5 \text{ Btu/hr-ft}^2$$

Heat generation rate per unit volume of heating layer of model

$$Q = q \frac{W \cdot D}{\theta_o \ln \frac{r_i}{r_o}}$$

Where

$D$ = heater outside diameter

$\theta_o$ = 2 $\pi$ (radians)

$r_o$ = inside radius of heating layer

$r_i$ = outside radius of heating layer

$Q$ is found to be

$$Q = 8819$$

The units are Btu per hour, inches, radians.
The total number of nodes chosen in this analysis was 122, 1 boundary, 11 radial and 11 angular nodes.

Figure 3 is a plot of the radial temperature distribution of the heater assembly with superimposed node center temperatures for 3 different radii as found by the computer analysis. The temperature distribution was calculated (ignoring the thermocouple well) by the following formulas:

\[ T_1 = T_0 + \frac{q^*}{2 \pi k} \ln \frac{r_0}{r_1} \]

for all sections without internal heat generation, and

\[ T_1 = T_0 + \frac{q^*}{4 \pi k} \left[ 1 - \frac{r_1^2}{r_0^2 - r_1^2} \ln \frac{r_0}{r_1} \right] \]

for the heating layer.

Where

- \( r_1 \) = inside radius of particular layer
- \( r_0 \) = outside radius of particular layer
- \( T_1 \) = inside surface temperature of layer
- \( T_0 \) = outside surface temperature of layer
- \( q^* \) = heat generation rate per unit length of heater

In this calculation because of the large film coefficient, it was assumed that the heater sleeve temperature is at 250°F.

IV REFERENCES

1. R. C. Noyes personal conversation
