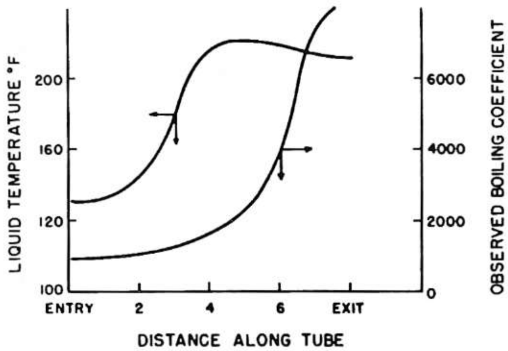

Fig. 8 Evaporation of subcooled water calculated from a-c less d-c resistance thermometer temperatures

flux. The linear velocity of the steam passing over the outside of the tube was varied 10-fold at a high rate of heat transfer. The results still showed the relation given in Fig. 5, despite the much increased tendency of condensate to be swept off the tube wall.

Conclusions

The resistance thermometer method has been developed to evaluate mean wall temperature of a circular metal tube. This temperature can be measured over any short interval to ±4 F for one observation of a stainless-steel tube.

The method given has been extended to include a means of measuring heat flux passing through the tube wall. Single determinations are accurate to about ±20,000 Btu/hr ft². The method is based on the variation of alternating current density with radius in a circular conductor. Independent measurements may be made for any number of intervals along a tube.

The two methods may be combined to evaluate wall surface temperature in any interval. When combined with bulk liquid or bulk steam temperatures, local film heat-transfer coefficients can be calculated entirely from observed quantities.

References

1 H. L. Callendar and J. T. Nicolson, "Some Experiments on the Condensation of Steam," *Engineering*, vol. 64, 1897, p. 481.

2 C. E. Dengler, "Heat Transfer and Pressure Drop for Evaporation of Water in a Vertical Tube," ScD thesis in Chemical Engineering, M.I.T., 1952.

3 H. B. Dwight, "Electrical Elements of Power Transmission Lines," The Macmillan Company, New York, N. Y., 1954.

4 A. J. Lowery, Jr., and J. W. Westwater, "Heat Transfer to Boiling Methanol—Effect of Added Agents," *Industrial and Engineering Chemistry*, vol. 49, 1957, pp. 1445–1448.

5 A. I. Morgan, T. Wasserman, A. H. Brown, and G. S. Smith, "Commercial-Scale Evaporation of Tomato Products in Flash Evaporators," *Food Technology*, vol. 13, 1959, p. 232.

6 E. N. Sieder and G. E. Tate, "Heat Transfer and Pressure Drop of Liquids in Tubes," *Industrial and Engineering Chemistry*, vol. 28, 1936, pp. 1429–1435.

DISCUSSION

R. Eichhorn[3]

This paper represents a simple, yet truly clever attack, on an important problem. The difficulty of determining both heat flux and tube wall temperatures are well known to workers in the heat-transfer field. As the authors point out, standard methods become nearly impossible under high heat flux rates.

From the data scatter pointed out by the authors, it appears that accuracies of the order now achieved using resistance heating were not obtained in the present study. Clearly the d-c resistance of the test tube is unaffected by the presence of the flanges and iron jacket which surround it. Equally clear is the possibly large effect of these components on the a-c resistance of the test tube. The flanges and jacket are subject to eddy current and hysteresis losses which augment the effective resistance of the test tube. These will clearly be temperature sensitive and thus possibly affect the calibration of the apparatus. This writer would like the authors to comment on the probable magnitude of such errors and the feasibility of redesigning the jacket and flanges so as to reduce eddy current and hysteresis losses.

Considerable space was devoted to a discussion of the statistical analysis of the data. The method of calibration employing centrifugal separation should be subject to an independent statement of error. This writer would like to see such a statement.

[3] Assistant Professor of Mechanical Engineering, Princeton University, Princeton, N. J.

E. M. Sparrow[4]

This paper represents an interesting contribution to our knowledge of heat-transfer measurement techniques. There are, however, a few points on which further discussion might be useful.

First of all, let us consider the derivation of equation (7). From equation (6) with $Q/A = 0$, there is obtained

$$\frac{1}{R'} = \frac{2\,x\,\pi D}{Lr_0}\,e^{-at}$$

then, forming the ratio of this with the expression for $1/R$ as given in the paper [following equation (6)], we get

$$\frac{R'}{R} = e^{-a(t_m - t)}\,\frac{\sinh\left(\dfrac{ax}{k}\,\dfrac{Q}{A}\right)}{\left(\dfrac{ax}{k}\,\dfrac{Q}{A}\right)}$$

which is not in agreement with equation (7) of the preprint. Only when $R'/R = 1$ does it follow that

$$e^{a(t_m - t)} = \frac{\sinh\left(\dfrac{ax}{k}\,\dfrac{Q}{A}\right)}{\dfrac{ax}{k}\,\dfrac{Q}{A}}$$

Perhaps there is a misprint in the reprint. Even so, the remarks following equation (7) appear to apply only to the condition $R/R' = 1$, which is not explicitly stated.

Next, in the paragraph just preceding Fig. 4, it is noted that the a-c, d-c difference was interpreted as total heat transfer. It would be appreciated if this point were enlarged upon. In what quantitative manner is the interpretation made; is equation (11) used in some way?

In introducing equation (8), it is indicated that this equation expresses the results. Then it is later remarked that equation (9) describes the results. Since (8) and (9) are not the same, it is not clear which one is actually appropriate.

Finally, it would be an aid to clarity if both additional explanation and mathematical details were given between equations (10) and (11).

Authors' Closure

The accuracy of the method as we used it is such that it would not appeal to workers using resistance heating. The flanges used on the jacket may have affected the end intervals but probably not the six center intervals. The method was usable for heat flux measurement both from outside into the tube and from the

[4] Professor of Mechanical Engineering, University of Minnesota, Minneapolis, Minnesota. Assoc. Mem. ASME.

tube into the outside. For these reasons, we believe that the eddy current effects did not unduly influence the results.

The apparatus has been used extensively with colored fluids, such as tomato juice. The visible stream of condensed vapor product has always been colorless. The unit has been operated over a range of centrifugal separator pressures such that there has been a tenfold variation in vapor velocity at the same true heat flux without any increase in apparent heat flux. For these reasons, we believe that the error contribution from the separation of vapor and liquid products is negligible.

In deriving equation (7), one inserts the condition $Q/A = 0$ in the unintegrated form of equation (6) and obtains after integration

$$\frac{1}{R'} = \frac{\pi D}{L r_0} e^{-a t_m} 2x$$

which results in

$$\frac{R'}{R} = \frac{\sinh\left(\frac{ax}{k}\frac{Q}{A}\right)}{\left(\frac{ax}{k}\frac{Q}{A}\right)}$$

In order to interpret the ratio of resistances as temperatures we write

$$\frac{R'}{R} = \frac{r_0 e^{a t_m}}{r_0 e^{a t}} = e^{a(t_m - t)}$$

The a-c, d-c difference was calibrated experimentally against heat flux. When using the entire heated length of the tube as a thermometer, the difference was calibrated against the total average heat flux as measured by the total evaporation rate. Equation (11) is not used in any way. It is a mere description of the effect using the form dictated by the previous equations.

Equation (8) describes the effect of frequency and temperature on the impedence of an isothermal tube. Equation (9) merely introduces the effect of radius, which is pertinent only when the skin effect is considered.

As in the step from equation (6) to equation (7), the change from equation (10) to equation (11) is only that needed to interpret impedance as temperature by the relation

$$\frac{z}{z'} = e^{a(t - t_m)}$$

and since t_m is essentially $t_{d\text{-}c}$, then

$$\frac{z}{z'} = e^{a(t_{a\text{-}c} - t_{d\text{-}c})}$$