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# A HEAT FLUX METER TO DETERMINE THE LOCAL BOILING HEAT FLUX DENSITY DURING A QUENCHING EXPERIMENT

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**Abstract**—The use of a modified Gardon-type heat flux meter [2] for measuring the local boiling heat flux density around a large diameter horizontal cylinder which is quenched from a high temperature in saturated or subcooled water is described. The fabrication and calibration procedures are provided along with a detailed conduction analysis of the temperature field in and around the meter. An approximate boiling heat flux density-vs-temperature curve is predicted from the measured cooling curve for a point on the cylinder. It is shown that this boiling curve agrees well with that recorded by a calibrated heat flux meter. It is concluded that heat flux meter can be used effectively to provide reproducible measurements of the entire boiling curve during quenching experiments.

## NOMENCLATURE

| | |
|---|---|
| $A$, | surface area $[m^2]$; |
| $CF$, | calibration factor; |
| $C_p$, | heat capacity [J/kg K]; |
| $k$, | thermal conductivity [W/cm K]; |
| $L$, | cylinder half length [m]; |
| $n$, | coordinate normal to the surface [m]; |
| $NR$, | number of mesh points in the $r$-direction; |
| $NZ$, | number of mesh points in the $z$-direction; |
| $Q$, | heat content [J]; |
| $(q/A)$, | heat flux density $[W/m^2]$; |
| $R$, | cylinder radius [m]; |
| $r$, | radial coordinate [m]; |
| $R_0$, | disk radius [m]; |
| $T$, | temperature [K]; |
| $t$, | time [s]; |
| $t_d$, | disk thickness [m]; |
| $\Delta T$, | temperature difference on the disk [K]; |
| $V$, | volume $[m^3]$; |
| $z$, | axial coordinate [m]. |

### Greek symbols

| | |
|---|---|
| $\alpha$, | thermal diffusivity $[m^2/s]$; |
| $\rho$, | density $[kg/m^3]$. |

### Subscripts

| | |
|---|---|
| app., | apparent; |
| $f$, | final; |
| $i$, | initial; |
| $(i,j)$, | (radial, axial) mesh point; |
| 0, | at time zero; |
| $\theta$, | angular location. |

DURING studies on determining the boiling heat flux density around large horizontal cylinders [1] a need was established for a local heat flux meter which would respond essentially instantaneously to the local heat flux which existed at the point in question.

Such a meter has been constructed by modifying one which was originally suggested by Gardon [2]. This modified meter was used effectively previously by Dernedde [3] and Rao [4] in their experimental studies on the boiling of turbulently flowing liquid films. Since that time the fabrication and calibration techniques have been perfected and its performance has been studied in detail. This is reported herein.

## EXPERIMENTAL SYSTEM

The experiment involves quenching a 12.7 cm dia by 7.62 cm long copper (high purity) cylinder (see Fig. 1), which has been previously heated to about

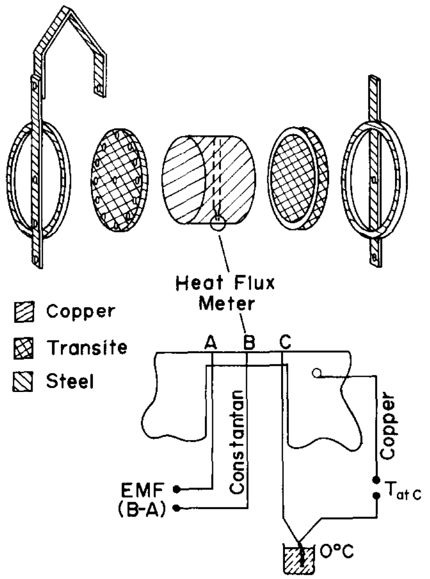

FIG. 1. Apparatus for quenching experiments showing cylinder, holder and heat flux meter construction. The cylinder is 12.7 cm O.D. by 7.62 cm long and the heat flux meter is 0.476 cm dia and 0.051 cm thick.

250°C, into a tank of water which has been heated to a desired subcooled or saturated condition. The responses from a heat flux meter which has been fabricated at a particular point in the cylinder are then transmitted to and stored in a minicomputer at specific time intervals.

Copper cylinders are used in these experiments to provide a cylinder with a high thermal conductivity in order to minimize thermal gradients within the cylinder, thus ensuring that the boiling heat flux at the surface was not limited by conduction within it. Anomalous behaviour has been observed if an appreciable oxide layer is allowed to accumulate on the surface. Indeed, this experience and that with chrome-plated cylinders suggests that much of the controversy relating to the differences observed between steady-state and unsteady-state boiling heat transfer can be traced to the surface thermal resistance offered by either oxide layers or electroplated surfaces or the internal conduction problem. In our experiments, the cylinders were heated in a nitrogen atmosphere and any thin oxide layer that resulted from continued use was removed by light cleaning with fine (4/0) emery paper.

In order to simulate the behaviour of a very long cylinder, the end faces of the cylinder were insulated with 1.3 cm thick transite plates which were glued onto the copper faces with a high temperature silicone adhesive (Dow Corning RTV 899). The cylinder length was chosen to minimize end effects that might affect the boiling process over the central section. At the same time, it was desirable to minimize the enthalpy content of the cylinder so that upon cooling the cylinder, it would not add appreciable enthalpy to the water into which it was quenched.

The cylinder was equipped with a heat flux meter of the Gardon type. This heat flux meter requires that a thin disk of suitable metal be built into the heat transfer surface. In the original design [2], the disk was made of constantan; one copper wire was soldered into the disk and one attached to the copper body onto which the foil was mounted. The copper–constantan thermocouples so formed were used to measure the temperature difference between the centre and the edge.

By a simple one-dimensional conduction analysis on the disk, assuming an insulated inner face of the disk and radial heat flow only, the average heat flux density over the outer face of the disk can be related to the centre-to-edge temperature difference, $\Delta T$, by:

$$q/A = \frac{4kt_d\Delta T}{R_0^2} \tag{1}$$

where $t_d$ and $R_0$ are the thickness and radius of the disk, respectively, and $k$ is the thermal conductivity of the disk material at the average temperature of the disk and $\Delta T$ is the measured temperature difference.

This original design has been modified for use in high heat flux density situations as exist under boiling conditions by making the heat flux meter an integral part of the cylinder, thereby avoiding thermal contact resistances that may arise. Originally the disk was machined directly in the copper cylinder. Unfortunately, because of the size of the cylinder, considerable difficulty was experienced in obtaining a good solder connection between the constantan wires and the copper disk. For this reason, the fabrication procedure was modified as follows:

The heat flux meter was fabricated on the flat face of a 1.27 cm dia by 2.54 cm long copper cylindrical plug. Because of its size, the three 0.025 cm dia constantan wires could be easily soldered at the edge and centre of the disk using an acetylene torch. The oxide scale formed during this operation was removed with sulfuric acid. A hole was machined in the 12.7 cm dia copper cylinder to accept this plug; it was accurately machined to a diameter which was 0.04 mm undersize and to a depth such that when the plug was fully inserted it would leave a known amount of copper protruding beyond the large copper cylinder. A 0.6 cm hole was also drilled diametrically through the large copper cylinder to accommodate the insulated constantan wires after the plug was inserted. The plug was then pressed into the hole with a force of about 3000 kg using an Instron testing machine. The outer surface of the plug was removed in a lathe. The final step was to polish the entire circumferential surface with 4/0 emery paper. This procedure should produce a disk of the desired nominal thickness, but the exact dimension is unknown because of the obvious difficulties in machining and press-fitting to the desired accuracy, thus the need for later calibration. The boundary of the plug was hardly discernible even under magnification indicating that the press-fitting operation produced a good bond between the plug and the cylinder. This was necessary since it was required that little if any thermal contact resistance existed between the plug and the cylinder.

## FACTORS AFFECTING THE DESIGN OF THE HEAT FLUX METER

To use this heat flux meter in this unsteady-state boiling application, it must be designed with the following factors in mind:

(i) The meter must have a very fast response time. Gardon [6] has shown how the time constant of these meters varies with dimensions and the thermal diffusivity of the meter material. Dernedde [3] has shown that with reasonable dimensions, the time constants for copper heat flux meters are of the order of several milliseconds.

(ii) The radius of the disk must be of sufficient size to be representative of the average heat flux conditions existing under the conditions of the experiment. In this case, this means that it must contain sufficient nucleation sites to be representative of the average boiling behaviour representative of the existing wall temperature condition. It is not known *a priori* how many nucleation sites are required.

(iii) Since the boiling heat flux density is a strong function of the wall temperature, the temperature variation from the edge to the centre of the disk must be relatively small, even at the critical heat flux condition. In our experiments the temperature difference between edge and centre was designed to be no more than 10°C at the critical heat flux condition. This means that it is necessary to measure relatively small e.m.f.'s quite accurately since the heat flux varies 100-fold during a quenching experiment.

In the present use of the heat flux meter, the material of the disk was fixed by the need for a cylinder which would not have the heat flux around its boundary limited by internal conduction – hence the use of copper. Previous experience [3] had indicated that a disk diameter of 0.397 cm (exact radius fixed by available drill sizes) gave results which represented boiling heat transfer quite well. The disk thickness was thus fixed by the need to keep the edge-to-centre temperature difference within the defined limits. In our experiments it was nominally 0.051 cm.

## EXPERIMENTAL PROCEDURE

The instrumented copper cylinder was heated in an electrical oven to a temperature between 200 and 300°C depending upon the level of subcooling of the quenching bath. Nitrogen was admitted continuously into the oven to minimize oxidation of the copper. The copper cylinder was then quenched in a 60 l. tank of distilled water which was heated to the desired subcooled condition.

The cylinder surface temperature (edge) and centre-to-edge temperature difference on the meter were recorded continuously via transmitter/amplifiers to a minicomputer.

This information provides a complete boiling curve, covering film boiling, transition boiling, the critical heat flux and the nucleate boiling regime for any particular point on the cylinder. The computer was programmed to read at discrete time intervals (100 readings/s). These values were averaged over a short time span, this interval being determined by the heat flux level. For example, during saturation boiling, the temperature were averaged over a period of 1 s (100 values) in the region of low heat fluxes and over 0.1 s (10 values) when the heat flux was within about 30% of the critical heat flux. For experiments performed under subcooled conditions, averages were taken even more frequently. Typical curves obtained with this averaging procedure are presented in Fig. 2.

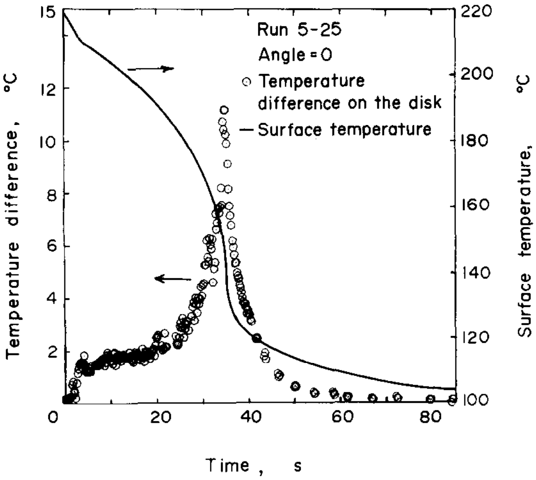

FIG. 2. Typical response of a heat flux meter.

One boiling curve was obtained from each quenching experiment. The angular location of the heat flux meter was changed in a random fashion after carrying out at least two replicate experiments at the same angle. In this series of experiments, boiling curves were determined with the meter located at seven different azimuthal angles (0, 30, 60, 90, 120, 150, 180°). Reproducibility of the data was good (*ca.* 10–15%) as long as the oxidation of the cylinder was slight. This oxidation problem was alleviated by using moderate preheat temperatures and the nitrogen environment in the oven. The copper cylinders were also polished lightly after every two or three experiments with fine (4/0) emery paper, followed by careful cleaning with acetone.

## CALIBRATION

Although, in theory, the heat flux meter can provide a direct measure of the instantaneous heat flux density for any given average wall temperature, in practice, each meter requires calibration to compensate for uncertainties which arise in fabrication, such as:

(i) The heat flux meter may not be constructed according to specifications – that is, the thickness and radius may differ from specification and/or the thermocouples may not be located exactly at the desired points nor recording the expected temperature.*

(ii) When the copper plug containing the heat flux meter is press-fitted into the cylinder, it is possible that the axis of the plug is not exactly parallel to the axis of the hole. The subsequent machining operation would then produce a disk of non-uniform thickness. It was shown by a numerical analysis of such a heat flux meter, that a tilt of only a few degrees could induce quite different edge-to-centre temperature differences depending upon which side thermocouple was used. Such differences were observed experimentally.

Experiments did show, however, that although the calibration factors were different, the final calibrated heat flux results were the same regardless of which actual temperature differences used.

Because these defects can be introduced during fabrication it is imperative to properly calibrate each

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*A few of the meters were sectioned by machining. It was discovered with one that the silver solders ran down the wire and made a junction somewhat below the disk on the wall of the hole.

heat flux meter. Two separate ways were used to obtain a calibration factor; another indirect method was also used to check it. These are discussed in turn.

(i) *Unsteady-state calibration*

A calibration factor ($CF$) of a heat flux meter can be obtained by comparing the total enthalpy loss from the cylinder, over the duration of the experiment, with that obtained by integrating the measured (apparent) local heat flux density over the total heat-transfer area and over the quenching time, viz:

$$\begin{aligned} Q &= \rho V c_p (T_i - T_f) \\ &= \int_A \int_0^t (CF)(q/A)_{\text{app.}}\, \mathrm{d}A\, \mathrm{d}t. \end{aligned} \tag{2}$$

The apparent heat flux density is calculated by equation (1), assuming a uniform (average) heat flux density over the disk. The integral is evaluated numerically by assuming the calibration factor is constant (independent of heat flux) and the measured instantaneous heat flux density at any angle is symmetric, uniform over the length and pertains over an angle of ±15° from the point in question. This calibration procedure, although producing different calibration factors for different meters, did provide excellent reproducibility of the boiling heat flux densities from one test cylinder to another (within 10% in most cases). The calibration factor was essentially the same whether it was evaluated under saturated or subcooled conditions. The average variance of the calibration factor evaluated by this method using only one experiment at each of the seven angular locations was about 3%; if two experiments were used the variance on the calibration factor was less than 0.4%.

(ii) *Steady-state calibration*

As a check on this procedure, a steady-state experiment was designed to determine the calibration factor for a particular meter directly. After the calibration factor had been determined by the indirect unsteady-state method, the cylinder with its meter was used in a steady-state boiling experiment. The copper cylinder was drilled to allow the insertion of fourteen, 500W, 230V (1.25 cm dia by 7 cm long) cylindrical heaters (Fig. 3). The power input was controlled by auto transformers. A double-walled copper chamber was mounted on top of a portion of the copper cylinder surface (contained in a 75° azimuthal angle by 5 cm length) with the heat flux meter located at the centre. The average heat flux density over this surface was determined by measuring the vapour (as condensate) generated by boiling water on a known surface area. It is important to ensure that all the steam generated from the surface is collected. Moreover, since only an average heat-transfer rate is determined, it is important that any end effects, which may affect this average, are minimized. This includes any heat required to bring the incoming water to the temperature of the boiling water on the surface. All of these aspects are accommodated by having a thin-walled inner chamber which almost touches the heated copper cylinder. By leaving a 0.6 cm space between the inner and outer chamber, the steam generated on the outside will keep the inner chamber at the boiling point and prevent condensation of the inner steam; the steam generated at the edge crevices (end effects) will not be included in the measured condensate; and the water continuously added to replenish that vaporized, although very near its boiling point, will be at its boiling point when it flows through the holes into the inner chamber.

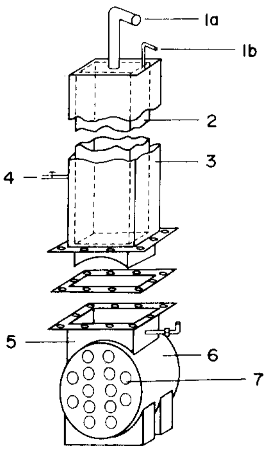

FIG. 3. Apparatus for steady-state calibration of a heat flux meter. 1. (a) Condensate out of inside boiling chamber. (b) Condensate out of outside boiling chamber. 2. Inside boiling chamber. 3. Outside boiling chamber. 4. Water fed at near saturation. 5. Bottom boiling chamber. 6. Precalibrated copper cylinder with heat flux meter centred on boiling surface in boiling chamber 5. 7. 1.27 cm hole drilled to accept a 500 W cartridge heater (6.35 cm long).

Thus the directly measured heat flux density could be compared to that indicated by the heat flux meter and a calibration factor determined. Unfortunately it was found by direct observation of the boiling phenomena that the heat flux density in the immediate vicinity of the heat flux meter was considerably lower than that which occurred over the rest of the surface. A conduction analysis of the temperature field in and around the heat flux meter was performed by solving the Laplace equation in a finite difference form. The heat flux density variation with local surface temperature as determined with the calibration factor from the unsteady-state method was taken into consideration in the solution. Figure 4 shows a typical temperature distribution obtained with this analysis where the surface was submitted to the nucleate regime of the boiling curve. This analysis indicates that the temperature on and in the immediate vicinity of the disk is lower than that at some distance from the meter; hence, the average heat flux density over the meter is considerably different from that over the main surface

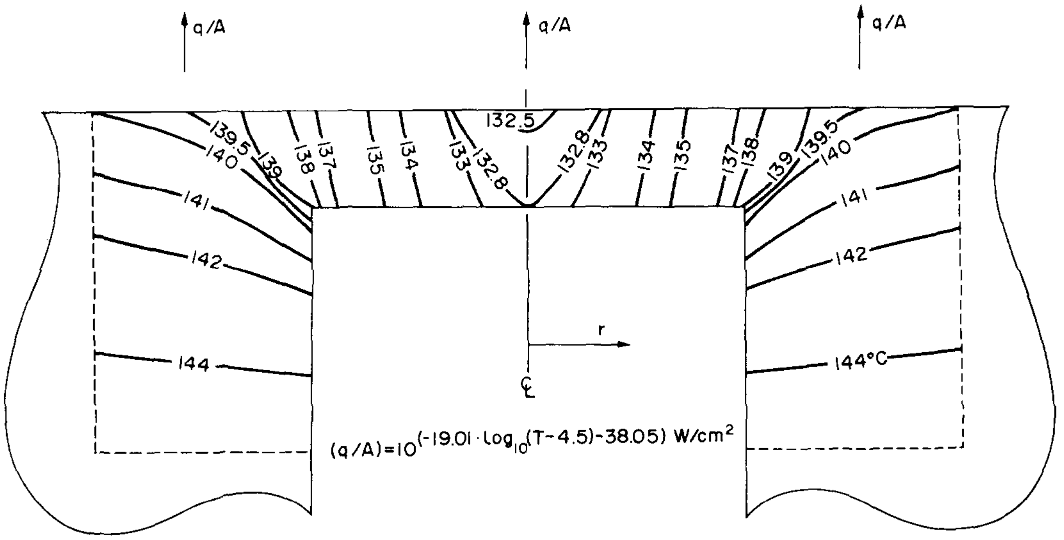

FIG. 4. Temperature distribution on a heat flux meter and its vicinity.

and the calibration method failed.* On the other hand, this effect becomes less severe as the average heat flux density over the surface becomes less and should disappear at zero heat flux. Therefore, the apparent calibration factor at each measured heat flux was extrapolated to zero heat flux. This extrapolated calibration factor was then compared with that obtained by the unsteady-state method and excellent agreement was found. A graphical representation of the extrapolation for a copper cylinder is presented on Fig. 5.

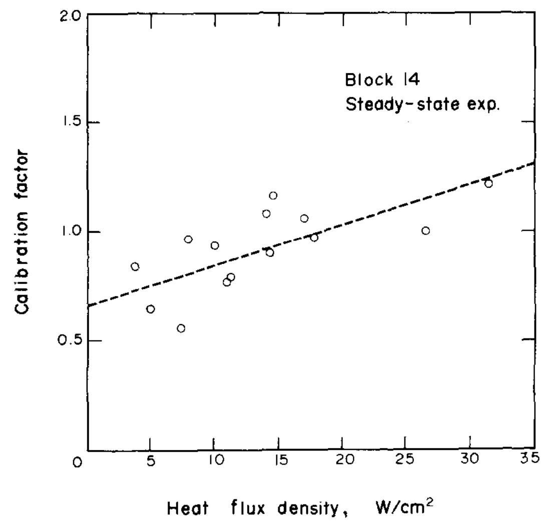

FIG. 5. Plot of the calibration factor obtained during steady-state calibration of an instrumented copper cylinder (dashed line is least-squares fitted straight line used to extrapolate to zero heat flux density).

It should be emphasized that the effect observed during these steady-state experiments will in no way invalidate the use of the heat flux meter during the quenching experiments since the area surrounding the heat flux meter will register a lower average temperature just before the rest of the cylinder. Each local area will still exhibit the boiling phenomena corresponding to the local temperature condition.

Since the surface temperature will be different over the meter and its immediate surroundings, some unknown averaging of the heat flux density by the meter will occur. This will be particularly important at the critical heat flux condition. The conduction analysis referred to above suggested that the heat flux registered by the meter corresponded to the average temperature of the disk (average between the edge and centre temperatures).

### (iii) *Prediction of the boiling curve from the cooling curve of the cylinder*

The edge thermocouple of the heat flux meter traces out a cooling curve for that particular point on the cylinder. If as a first approximation it is assumed that the heat flux density is uniform around the cylinder and corresponds to that from the boiling curve generated by the calibration heat flux meter at the instantaneous temperature condition, it is possible through a finite difference formulation of the unsteady-state conduction equation for the cylinder to predict the temperature–time history of the surface temperature. Appendix A indicates the details of this analysis. Account is taken for the insulation provided by the transite end pieces and the circumferential area covered by them.

The predicted cooling curve may then be compared directly with the measured one to indicate whether the assumed boiling curve is reasonable or not. The difficulty is that the measured heat flux density is observed to be non-uniform around the cylinder (this variation is indicated in Fig. 6); consequently some deviation between the predicted and observed cooling curve is to be expected. Figures

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*A temperature depression around the heat flux meter may also occur because of some thermal contact resistance between the plug and the cylinder.

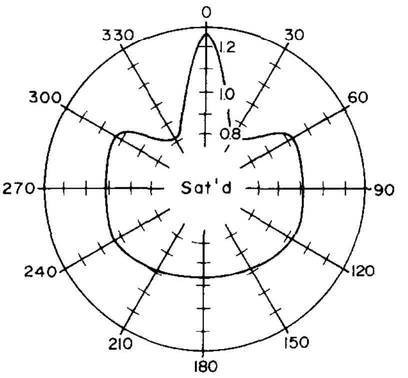

FIG. 6. Variation of local CHF around a cylinder at saturation (radial coordinate = CHF at one particular angle/average CHF around the cylinder).

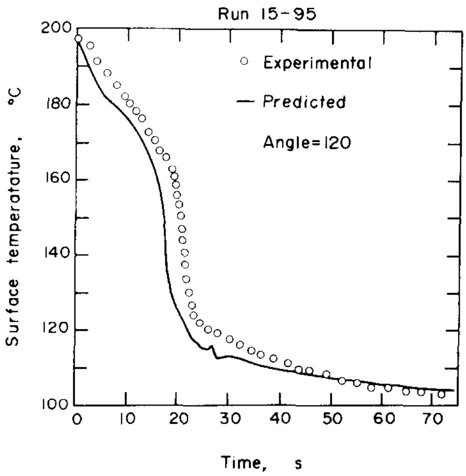

FIG. 7. Comparison between the experimental and the predicted cooling curves (angle 120°).

7 and 8 show typical results (Fig. 7 at 120° for the least deviation* and Fig. 8 at 30° for the worst where the heat flux density shows a minimum). The fact that the cooling curves are predicted reasonably well lends credence to the boiling heat flux density which was used.

It is also possible through this analysis to predict what the boiling curve would have to be to generate the measured cooling curve. In this case, the analysis starts with the initial temperature and, with an assumed boiling heat flux density, predicts what the temperature at the point should be after a small time interval (the interval between measured temperatures). If the predicted temperature is more than 0.05°C different from that measured, the boiling heat flux density, which again is assumed uniform around the cylinder, is adjusted appropriately until this temperature condition is met. The procedure is repeated for each measured temperature in turn. In this way, a boiling flux density curve may be generated. This direct iterative procedure is efficient and effective since the experimental cooling curve represents the lowest surface temperature of the whole cylinder at any time and hence the boundary conditions for all other points may be determined in advance from it. Figure 8 indicates the heat flux density curve generated by this procedure. The severe variations in it arise by virtue of the sensitivity of it relative to the errors in measured temperature. If a cubic spline smoothing technique is used [7] to smooth the temperature data, this variation is minimized, as indicated by the dashed curve in Fig. 9. In any event, the required boiling curve is of the same magnitude as the one generated by the calibrated heat flux meter. There does seem to be an effect of wall temperature (the predicted curve is shifted to lower wall temperatures), but this can be accounted for by the averaging procedure used to assign an appropriate wall temperature to the average heat flux recorded by the heat flux meter.

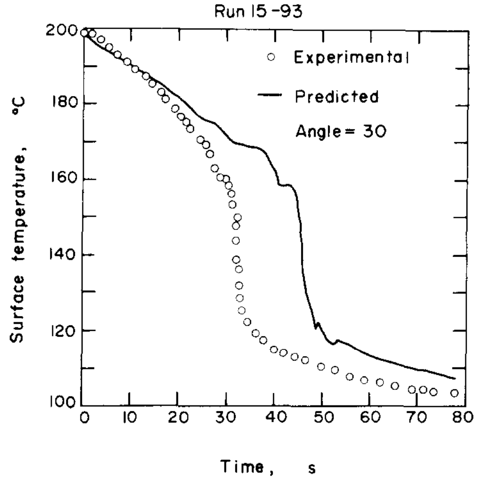

FIG. 8. Comparison between the experimental and the predicted cooling curves (angle 30°).

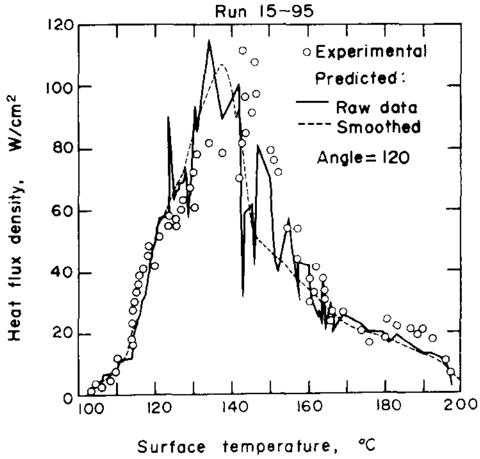

FIG. 9. Comparison between the experimental and the predicted boiling curves (angle 120°).

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*In this case, the boiling curve generated by the heat flux meter (after indirect calibration) when it is located at an angle of 120° was chosen to be representative, since the average critical heat flux density for the entire cylinder was approximately the same as that observed for 120°.

It may also result from the assumption of constant heat flux density around the cylinder. Obviously since the heat flux density does vary around the cylinder, conduction in the $\theta$-direction does occur; hence, for a more accurate prediction, a three-dimensional analysis is required in which account of the varying heat flux is included. It was felt, however, that such an analysis was not warranted for the present purposes of demonstrating that the indirectly calibrated heat flux meter was providing a good measurement of the actual instantaneous heat flux density.

## CONCLUSIONS

The experimental program and analysis reported in this paper has suggested that the modified Gardon-type, thin-disk, heat-flux meter may be used successfully to measure the local instantaneous heat flux density during quenching experiments involving boiling on a heat-transfer surface, including that which occurs at the critical heat flux. The indirect calibration procedure which has been proposed is sufficiently accurate to provide accurate boiling curves under saturated and subcooled conditions by the quenching technique.

*Acknowledgement* — Financial assistance for this project from Atomic Energy of Canada Ltd. is gratefully acknowledged.

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## APPENDIX A

*Description of the numerical technique*

The problem can be formulated in the following terms: consider a finite cylinder ($0 \leqslant r \leqslant R$ and $-L \leqslant z \leqslant +L$) having a constant thermal diffusivity $\alpha$ and initially at a uniform temperature, $T_0$. At time $t > 0$, the cylinder is allowed to lose heat at the surface. In this case the heat flux at the surface is determined by the surface temperature through a boiling curve. The temperature distribution within the cylinder as a function of time is calculated.

It is therefore necessary to solve the unsteady heat diffusion equation:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}. \qquad \text{(A1)}$$

The boundary conditions, taking symmetry into account are:

$$t = 0, \quad T = T_0 \text{ for } 0 \leqslant r \leqslant R \text{ and } 0 \leqslant z \leqslant L \qquad \text{(A2.1)}$$

$$t > 0, \quad \left.\frac{\partial T}{\partial r}\right|_{r=0} = 0 \qquad \text{(A2.2)}$$

$$\left.\frac{\partial T}{\partial z}\right|_{z=0} = 0 \qquad \text{(A2.3)}$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=R} = f(T_{R,z}) \qquad \text{(A2.4)}$$

$$\left.\frac{\partial T}{\partial z}\right|_{z=L} = f(T_{r,L}). \qquad \text{(A2.5)}$$

These boundary conditions indicate that it is only necessary to consider one quarter of the cylinder.

Because of the non-linear character of the surface boundary condition, it is necessary to solve equation (A1) using numerical methods. In this case, the Alternating-Direction Implicit (ADI) method was used [5]. Its main advantage is that resulting matrix of coefficients in the system of finite difference equations is tridiagonal and hence can be solved easily and rapidly.

In this formulation, $T_{ij}$, is defined as the temperature prevailing at the point $(i,j)$ $\{i = 1,2,\ldots NR$ in the radial direction, $j = 1,2,\ldots NZ$ in the $z$-direction$\}$. The radial and axial diffusion terms are expressed by:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{T_{i+1,j} - 2T_{i,j} + T_{i-1,j}}{\Delta r^2} + \frac{1}{(i-1)\Delta r}\,\frac{T_{i+1,j} - T_{i-1,j}}{2\Delta r} \qquad \text{(A3)}$$

$$\frac{\partial^2 T}{\partial z^2} = \frac{T_{i,j+1} - 2T_{i,j} + T_{i,j-1}}{\Delta z^2}. \qquad \text{(A4)}$$

It is extremely important to formulate the boundary conditions correctly in finite difference form to minimize the discretization error [6]. Each is discussed in turn below:

(i) At $r = 0 (i = 1)$, $\partial T/\partial r = 0$.

Therefore by L'Hopital's rule, the term

$$\frac{1}{r}\frac{\partial T}{\partial r} = \frac{\partial^2 T}{\partial r^2} \quad \text{as} \quad r \to 0 \qquad \text{(A5)}$$

and the diffusion equation becomes

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = 2\frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} \qquad \text{(A6)}$$

and because of symmetry

$$\frac{\partial^2 T}{\partial r^2} = \frac{2(T_{2,j} - T_{1,j})}{\Delta r^2}. \qquad \text{(A7)}$$

(ii) At $z = 0 (j = 1)$, $\partial T/\partial z = 0$ and the axial diffusion equation becomes:

$$\frac{\partial^2 T}{\partial z^2} = \frac{2(T_{i,2} - T_{i,1})}{\Delta z^2}. \qquad \text{(A8)}$$

(iii) At the outer surface of the cylinder ($i = NR$ or $j = NZ$), there is a heat flow out of the surface determined by the local temperature and the assumed boiling curve. This heat flux density is expressed by:

$$-k\frac{\partial T}{\partial n} = q/A \qquad \text{(A9)}$$

where $n$ is the normal to the surface (either $r$ or $z$). In finite difference form, equation (A9) has been found to be best represented by the central difference form, viz.:

$$-k\frac{(T_{M+1} - T_{M-1})}{2\Delta n} = (q/A)_\theta \qquad \text{(A10)}$$

where $T_{M+1}$ is a fictitious point located at $\Delta n$ beyond the boundary. This formulation allows, $T_{M+1}$, in the diffusional equation [(A3) or (A4)] to be replaced by:

$$T_{M+1} = T_{M-1} - (q/A)_0 \left( \frac{2\Delta n}{k} \right). \qquad \text{(A11)}$$

In this particular study, the ends of the cylinder were assumed to be perfectly insulated by the transite holders. Also the holders extended over a portion of the metal cylinder and effectively insulated this circumferential surface area. These insulated surfaces caused axial temperature gradients to exist within the cylinder.

The solution of equation (A1) was effected by solving equation (A3) for all of the implicit temperatures in the $r$-direction after a time interval, $\Delta t/2$ ($\Delta t$ being the time interval after which a solution is sought); the temperatures in the $z$-direction were evaluated at time $t$ and therefore known. Equation (A1) was then solved for the temperatures in the $z$-direction after a time $\Delta t/2$ using the updated temperatures in the $r$-direction.

In this solution, a time interval of 0.1 s, 10 mesh points in the $r$-direction and 10 mesh points in the $z$-direction were employed; doubling the number of mesh points or halving the time interval did not change the temperature at any point by more than 0.1%. Moreover, the numerical technique was compared with a numerical solution based on superposition and an analytical solution (employing a constant heat flux with time) and very good agreement was obtained [6].

## FLUXMETRE THERMIQUE POUR DETERMINER LOCALEMENT LA DENSITE DE FLUX PAR EBULLITION PENDANT UNE EXPERIENCE DE TREMPE

**Résumé**—On décrit l'utilisation d'un fluxmètre de type Gardon [2] pour la mesure locale de la densité de flux de chaleur par ébullition autour d'un cylindre horizontal et de grand diamètre, lequel est trempé, depuis une température élevée, dans l'eau saturante ou sous-refroidie. Les techniques de fabrication et d'étalonage sont précisées avec analyse du champ de conduction dans le fluxmètre et autour de lui. Une courbe approchée donnant la densité de flux en fonction de la température est obtenue à partir de la courbe expérimentale de refroidissement pour un point sur le cylindre. On montre que cette courbe d'ébullition s'accorde bien avec celle enregistrée à l'aide d'un fluxmètre calibré. On en conclut que ce fluxmètre peut être effectivement utilisé pour obtenir des mesures reproductibles dans toute l'étendue des expériences de trempe.

## EIN WÄRMESTROMMESSGERÄT ZUR BESTIMMUNG DER ÖRTLICHEN WÄRMESTROMDICHTE BEI EINEM ABKÜHLUNGSEXPERIMENT

**Zusammenfassung**—Es wird die Anwendung eines modifizierten Wärmestromdichtenmeßgeräts (nach Gardon) beschrieben. Mit dem Gerät wird die örtliche Wärmestromdichte an einem horizontalen Zylinder mit großem Durchmesser gemessen, welcher von hoher Temperatur in gesättigtem oder unterkühltem Wasser abgekühlt wird. Die Herstellung und Eichung des Gerätes wird beschrieben. Das Temperaturfeld in und um das Meßgerät wird berechnet. Es wird ein angenäherter Wärmestromdichte-Temperaturverlauf beim Sieden aus der gemessenen Abkühlungskurve eines Punktes des Zylinders bestimmt. Die Siedekennlinie stimmt gut mit des eines geeichten Wärmestrommeßgerätes überein. Es wird gefolgert, daß das Wärmestrommeßgerät mit Erfolg eingesetzt werden kann, um den Verlauf der gesamten Siedekennlinie bei Abkühlungsexperimenten reproduzierbar zu messen.

## ИСПОЛЬЗОВАНИЕ ТЕПЛОМЕРА ДЛЯ ОПРЕДЕЛЕНИЯ ПЛОТНОСТИ ТЕПЛОВОГО ПОТОКА ПРИ КИПЕНИИ С НЕДОГРЕВОМ В ЭКСПЕРИМЕНТЕ ПО ОХЛАЖДЕНИЮ ЦИЛИНДРА

**Аннотация** — Описывается использование модифицированного гардоновского тепломера для измерения плотности теплового потока при кипении с недогревом у горизонтального сильно нагретого цилиндра большого диаметра в процессе его охлаждения в насыщенной или недогретой воде. Описана методика изготовления и калибровки прибора, а также дан подробный анализ температурного поля внутри тепломера и в окружающей его среде. Рассчитана приближенная зависимость плотности теплового потока от температуры по измеренной кривой охлаждения цилиндра в любой его точке. Показано, что эта кривая кипения хорошо согласуется с кривой, регистрируемой тепломером. Сделан вывод, что тепломер можно эффективно использовать для получения воспроизводимой кривой кипения в эксперименте по охлаждению.