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DNB IN LIQUID METAL HEATED FORCED CONVECTION BOILING

D. M. FRANCE

Components Technology Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439, U.S.A.

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Abstract—An experimental program was performed to investigate departure from nucleate boiling (DNB) in a flow boiling system heated by a liquid metal flow. The boiling fluid, freon 12, was circulated vertically upward and was heated by countercurrent flowing mercury. Magnitudes and trends of the heat flux and quality at DNB were compared to data obtained on a similar experimental facility employing uniform electrical heating of the test section wall. The results show that at a given quality, the magnitude of the DNB heat flux is larger in the case of uniform electrical heating. This result is not predicted by a DNB correlation based on data obtained from electrically heated test sections employing uniform and non-uniform axial heat flux distributions. It is demonstrated that the DNB phenomenon in a temperature controlled system (liquid metal heated) may not be well predicted from correlations based on data (uniformly or nonuniformly heated) obtained from heat flux controlled systems (electrically heated).

NOMENCLATURE

C, specific heat;
d, i.d. of copper tube;
d_1, o.d. of copper tube = i.d. of mercury annulus;
d_2, o.d. of mercury annulus;
ε, thermal eddy diffusivity;
G, mass velocity [lb_m/hft^2];
h_{fg}, heat of vaporization;
k, thermal conductivity;
m, mass flowrate [lb_m/s];
Pr, Prandtl number;
P, pressure;
Pe, Péclét number;
q, heat flux based on i.d. of the copper tube [Btu/hft^2];
$\bar{q}_{DNB}$, average heat flux from inception of boiling to location of DNB [Btu/hft^2];
ρ, density;
Re, Reynolds number;
r, radial coordinate;
T, temperature;
U, axial mercury velocity;
W, axial coordinate $= -Z$;
X, flow quality;
Z, axial coordinate;
Z_0, heated test section length;
Z^*, dimensionless axial coordinate $= Z/Z_0$.

Subscripts
B, bulk conditions;
DNB, location of DNB;
F, Freon;
Hg, Mercury;
I, fluid inlet;
O, fluid outlet;
R, reference;
W, outer annulus wall.

INTRODUCTION

SODIUM heated steam generators for application to liquid metal fast breeder reactors are of two general types. The "once through" type delivers superheated steam, and the evaporator of the recirculation type delivers a two-phase mixture. The transition from nucleate† to film type†

† These terms are borrowed from pool boiling experience and refer to boiling phenomena similar in some respects to the well-defined pool boiling situation.

boiling is always encountered in the former type and may be present in the latter type depending upon the particular design. The accurate prediction of the maximum heat flux in the system occurring prior to the transition which has been termed departure from nucleate boiling (DNB), critical heat flux, and burnout heat flux in the engineering literature is an important aspect in the thermal design of these steam generators.

Uncertainty in prediction of the DNB heat flux and quality necessitates the inclusion of extra heat transfer area in the design of a liquid metal heated steam generator. This extra area due solely to known inaccuracies in DNB prediction was estimated at 11–12 per cent in [1] for a 30 MW unit. Further data indicating the importance of accurate prediction of DNB were obtained in the performance testing of the ALCO/BLH 30 MW sodium heated steam generator [2] revealing poor performance at 40 per cent rated load. Various correlations available for the prediction of DNB in a forced circulation system were summarized by Clerici [3] and more recently by Tong [4]. Most of these correlations were developed from experimental data obtained by uniformly heating an experimental test section via electrically heating the test section walls. Direct application of such correlations to liquid metal heated steam generators may lead to substantial error due in part to the nonuniformity of the axial heat flux in a steam generator. For this reason, some of the correlations were extended to include data from non-uniform electrically heated systems. In all cases, however, the heat flux was imposed via electrical heating. Experiments of this type produced reliable data with relatively small scatter and did not require elaborate experimental apparatus. In most instances where DNB occurred at the test section exit difficulties in obtaining the required experimental measurements were minimized. The results were directly applicable to heat flux controlled systems such as water cooled nuclear reactor cores. However, in a liquid metal heated steam generator the local heat flux is not directly controlled. The purpose of this investigation was to determine the effect on DNB of a nonuniform heat flux temperature controlled system, liquid metal heated, in contrast to a heat flux controlled system. The successful application of presently available DNB correlations based on electrically heated test section data to liquid metal heated steam generators is dependent upon a favorable comparison between DNB data from the two systems.

There are several differences in the heat transfer characteristics of electrically heated and liquid metal heated systems which affect the acquisition of experimental data. In a heat flux controlled system DNB is generally approached in a quasi-steady manner by small increases in system power until DNB is reached. Upon reaching DNB, the rate of wall temperature rise is quite large, and it is usually necessary to decrease the test section power. This transient situation creates a problem in determining the axial location of the inception of DNB if it does not occur at the test section outlet as discussed by Lee and Obertelli [5]. Most heat flux controlled experiments including the uniformly heated case found DNB to occur first at the test section exit. In this situation, the location of DNB and the DNB heat flux were both known, and thus, the majority of available data were obtained from this least complicated arrangement.

In contrast, experiments in a liquid metal heated system were performed at steady state with DNB occurring in the central portion of the test section. The wall temperature rise associated with DNB was of course limited by the liquid metal temperature, and DNB was observed under steady state conditions. However, in this system, the local heat flux was not directly measureable and was deduced from the liquid metal axial temperature profile. The location of DNB in the test section was also determined in this manner. Obtainment of reliable data necessitated maximum accuracy in measurement of liquid metal axial temperature profiles, and was complicated by thermal oscillation in the region of DNB. (These oscillations are briefly discussed in [6] and [7] for electrically heated systems and will be discussed further for the liquid metal heated case.) Thus, experimental procedures for data acquisition and reduction were developed which, due to the nature of the system, are significantly more complex than previously necessary.

In order to obtain a comparison between electrically heated and liquid metal heated system data experiments were performed using freon 12 to simulate high pressure water; mercury was employed as the heating fluid. The results of these experiments were compared with DNB data obtained by Stevens *et al.* [8] in a freon 12 system employing a uniformly electrically heated test section wall.

EXPERIMENTAL FACILITY

The experimental facility shown schematically in Fig. 1 consisted of separate mercury and freon loops converging at the concentric double pipe test section, Fig. 2. The test section by-pass and condenser by-pass lines allowed minimum preheater power to be employed which enabled operation with minimum freon subcooling at the test section inlet. Visual verification of the subcooled state of inlet freon was provided by the test section inlet sight. Freon flowed vertically up the central tube of the test section; mercury flowed counter-current with respect to the freon in all tests.

Teflon inserts were employed in the test section to minimize entrance and exit flow effects on heat transfer. A total of 33 thermocouples were located on the outer tube wall. The axial thermal gradient in this tube was assumed to equal the axial thermal gradient in the liquid metal which is proportional to the local heat flux into the freon. An estimate of the data reduction error associated with this assumption is given in the Appendix.

The central test section tube was fabricated from copper in order to minimize the heat

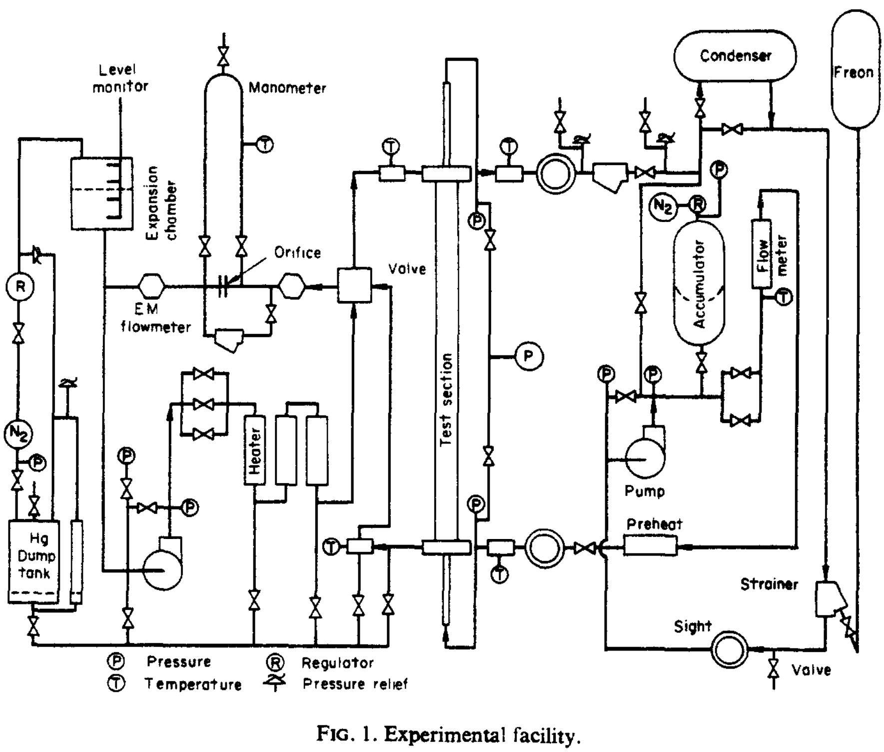

FIG. 1. Experimental facility.

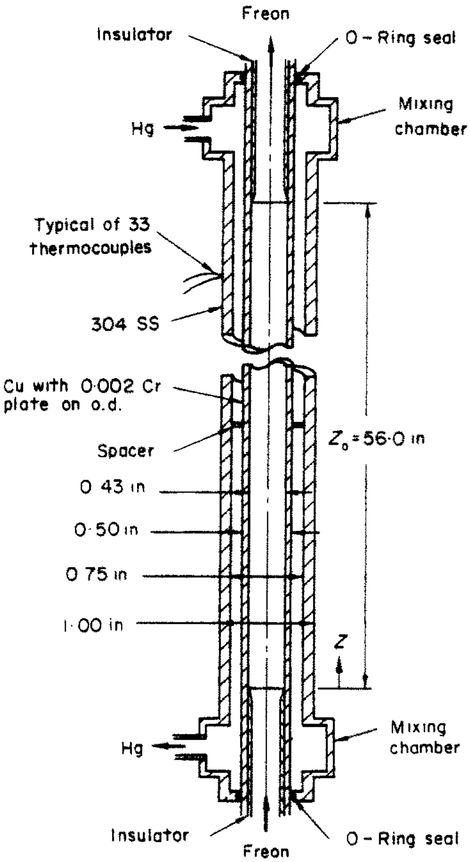

FIG. 2. Test section schematic.

transfer resistance of the tube wall relative to the heat transfer resistance of the boiling freon. Due to the problem of test section degradation from mercury–copper amalgamation, the exterior of the copper tube was crome plated. The mercury–crome thermal contact resistance due to the non-wetting effect was seen to be small such that the boiling freon heat transfer resistance was not masked.

It was determined during preliminary testing that small central tube displacement, as a result of tube bowing due to thermal stress, caused significant errors in the data. The problem was alleviated by using 0-ring slip seals at both ends of the central tube. The spacer shown in Fig. 2 was also added for this reason. The spacer was designed and positioned to minimize flow disturbance in the liquid metal. The spacer was seen to induce no measureable change in the heat transfer characteristics of the system.

EXPERIMENTAL TECHNIQUE

A typical test consisted of specifying the mercury mass flowrate. Then at a specified freon mass flowrate, pressure, and inlet subcooling the mercury inlet temperature was increased until DNB occurred in the test section. The system was maintained at steady state while data were taken. A typical scan of test section temperatures is shown in Fig. 3. The solid line

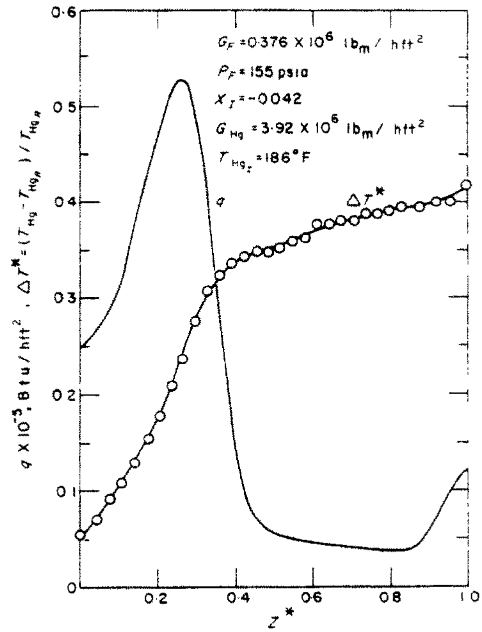

FIG. 3. Typical temperature and heat flux profiles.

drawn through the data is the result of a cubic spline function curve fit to the data. This curve fitting technique including data smoothing is especially desirable when the first derivative of the curve is sought. In all cases deviations between the spline function and the temperature data were required to be less than 1°F. The heat flux curve shown in Fig. 3 was obtained directly from the spline curve fit employing the relation

$$q = \frac{C_{Hg} m_{Hg}}{\pi d} \frac{dT_{Hg}}{dZ} \quad (1)$$

where radial symetry applies and $dT_{Hg}/dZ \simeq dT_W/dZ$. The maximum heat flux is by definition the point of DNB. The freon was slightly subcooled at the inlet in all cases and the exit quality was less than unity in most cases.

The temperature measurements shown in Fig. 3 were recorded in less than one second. Repeated scans of the test section thermocouples revealed temperature oscillations in the region of DNB. The envelope of the temperature fluctuations for the conditions of Fig. 3 is shown in Fig. 4. The maximum fluctuations occur in the region of maximum slope at approximately

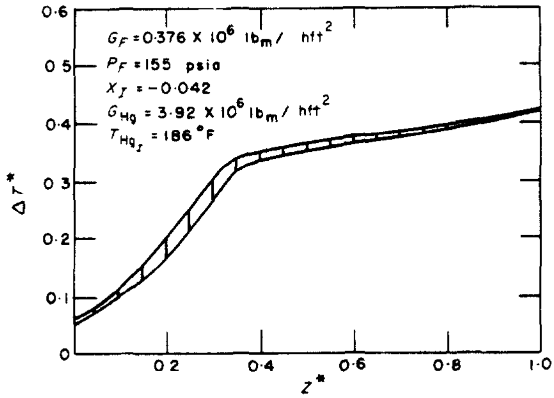

FIG. 4. Range of thermal oscillations in the region of DNB.

$Z^* = 0.27$. These temperature fluctuations are plotted in Fig. 5, as a function of time at the mercury inlet ($Z^* = 1.0$), the region of DNB ($Z^* = 0.27$), and the mercury exit ($Z^* = 0$). As in all tests, the mercury and freon inlet temperature fluctuations resulting from system characteristics were maintained less than $\pm 1°F$. This feature is seen in the relatively small amplitude mercury temperature variation at $Z^* = 1.0$ shown in Fig. 5. The mercury exit temperature fluctuations at $Z^* = 0$ are also small and within experimental error. Thermal oscillations in the DNB region, $Z^* = 0.27$, were sufficiently large to necessitate multiple temperature scanning during data acquisition. The duration of a single scan was less than one second, and scans were spaced at ten-second intervals. Data were recorded for 5–8 min.

The local value of DNB heat flux averaged over all scans was obtained in the following manner. For a given test, the smoothing parameter of the spline function curve fit was established to obtain the best fit to the temperature data under the constraint that the difference between any datum point and the curve not exceed $\pm 1°F$. The spline function curves were then fit separately to each scan of the test: a value for the local DNB heat flux was obtained for each, and the results were averaged over the total number of data scans. The results of a typical test of 35 scans are

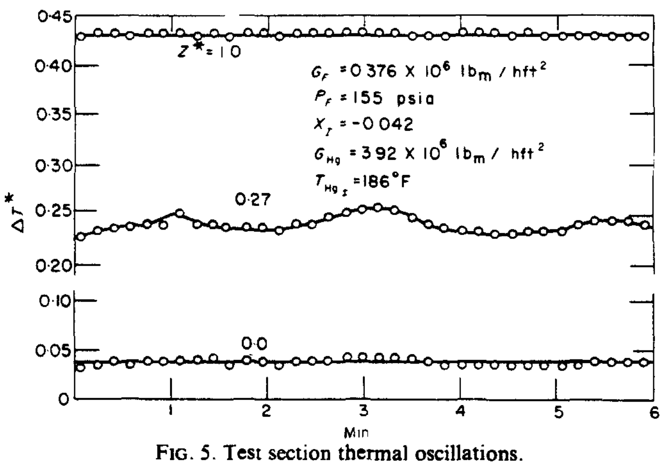

FIG. 5. Test section thermal oscillations.

shown in Fig. 6. Variations in q_{DNB} and X_{DNB} were small for the 35 scans considered. The quality at DNB, X_{DNB}, was calculated from a heat balance,

$$X_{DNB} = X_I + \frac{(mC)_{Hg}}{(mh_{fg})_F}\left(T_{Hg_{DNB}} - T_{Hg_O}\right) \quad (2)$$

for each scan and averaged over all scans. An alternate simpler approach would have been to average the temperature data of 35 scans and fit a single spline curve to the average data. The result of such a calculation is shown in Fig. 6 where it is seen that considerable error is introduced. This difference in prediction of q_{DNB} and X_{DNB} is a consequence of sufficiently large thermal fluctuations during a given test which caused the axial position of DNB to vary with time. As a result q_{DNB} calculated from averaged temperatures incorporated unreasonably large error: this technique was not employed.

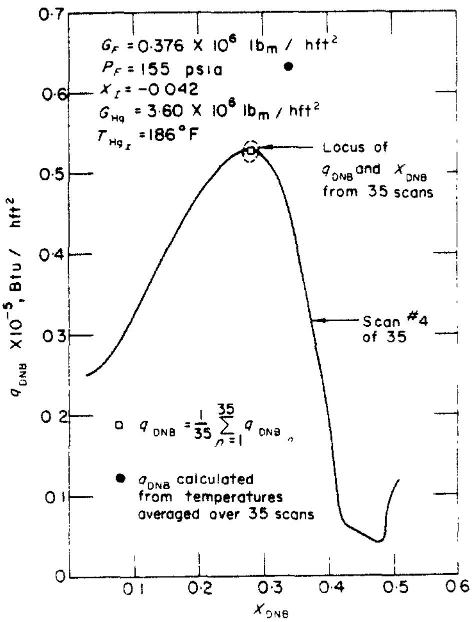

FIG. 6. Calculation of q_{DNB} from thermal profiles.

The task of data reduction by the first method discussed above was facilitated by use of a high speed computer data acquisition system. Temperature scans were recorded, changed to engineering units, printed, and stored on magnetic tape. Subsequent to testing, the stored data were read into the computer and reduced using a cubic spline curve fit routine. Some results were computer plotted as a data control.

RESULTS

A series of experimental tests were performed at a constant freon mass velocity of $G = 0{\cdot}376 \times 10^6$ lbm/hft^2 with a freon inlet pressure of 155 psia. This pressure was chosen for comparison with the electrically heated data of Stevens *et al.* [8] and corresponds to a ratio of liquid to vapor density of 20. This density ratio is characteristic of water at a pressure of 1000 psia. The DNB heat flux and quality results for these conditions are shown in Fig. 7 for both the liquid metal and electrically heated systems. The electrically heated data shown in Fig. 7 with its relative data scatter is the result of an interpolation of the data of [8]. This interpolation yielded in a minor deviation from the results of a particular electrically heated channel because of a small (5 per cent) difference in channel diameter between it and the present test section.

Conducting a test at a specified inlet subcooling with DNB occurring at the test section exit, a single datum point was obtained in the electrically heated case. Under the same subcooling condition in the liquid metal heated facility several data points were obtained by varying the mercury mass flowrate and/or mercury inlet temperature. This feature accounts for a large percentage of the scatter in the liquid metal heated data shown in Fig. 7 and is further discussed below. The range of data reproduceability as shown in Fig. 7 is larger for liquid metal heated data than for the electrically heated results. The difference is primarily attributed to the indirect measurement of DNB heat flux in the liquid metal heated system and is typical of this type of experiment. However, the range of

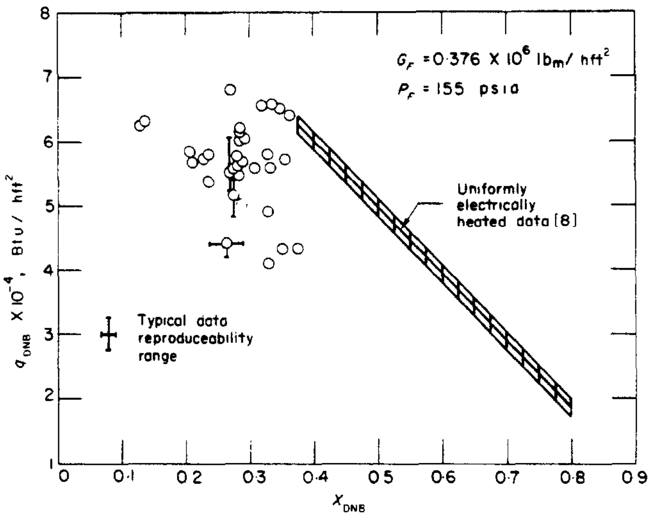

FIG. 7. Comparison of liquid metal and electrically heated DNB data.

reproduceability of the liquid metal heated data is not so large as to account for the seemingly random pattern of Fig. 7. An important feature of the data is the fact that at a given quality, the DNB heat flux is greater in the case of the electrically heated system. The same result is seen in Fig. 8 at a freon mass velocity of $0{\cdot}753 \times 10^6$ lb$_m$/hft^2. The inlet quality for all liquid metal heated data of Fig. 8 was $-0{\cdot}008$. Liquid metal heated data is also presented at a low mass velocity of $0{\cdot}188$ lb$_m$/hft^2. The liquid metal heated DNB heat flux is of smaller magnitude than the electrically heated data in the two cases shown. At all three freon mass velocities, the liquid metal heated data do not exhibit the distinctive trends found in the electrically heated cases. This result is a consequence of the fact that both mercury mass

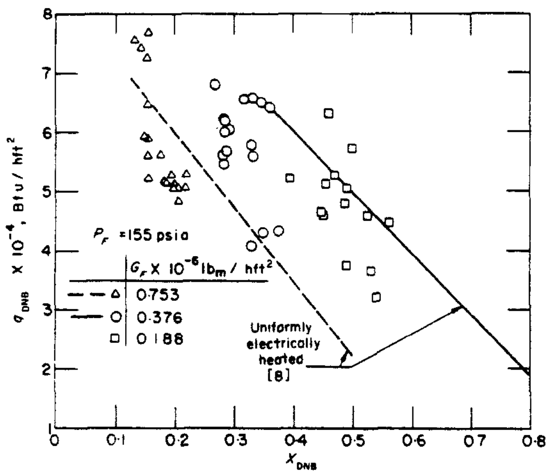

FIG. 8. Comparison of liquid metal and electrically heated DNB data.

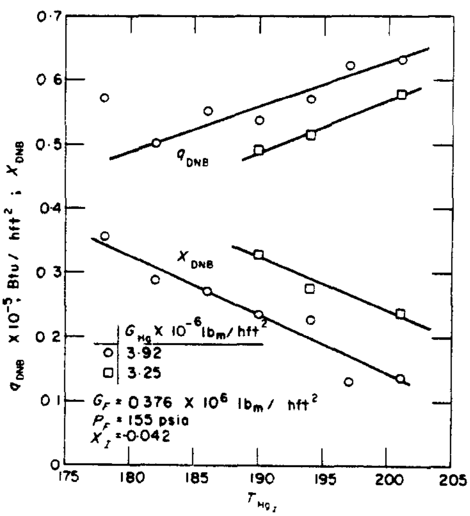

FIG. 9. Trends in liquid metal heated data.

velocity and inlet temperature were varied in obtaining the data of Figs. 7 and 8. If the mercury inlet temperature is varied at constant mercury mass velocity the DNB heat flux and quality exhibit distinct trends as shown in Fig. 9. The same result is obtained in Fig. 10 by varying the mercury mass velocity at fixed mercury inlet temperature.

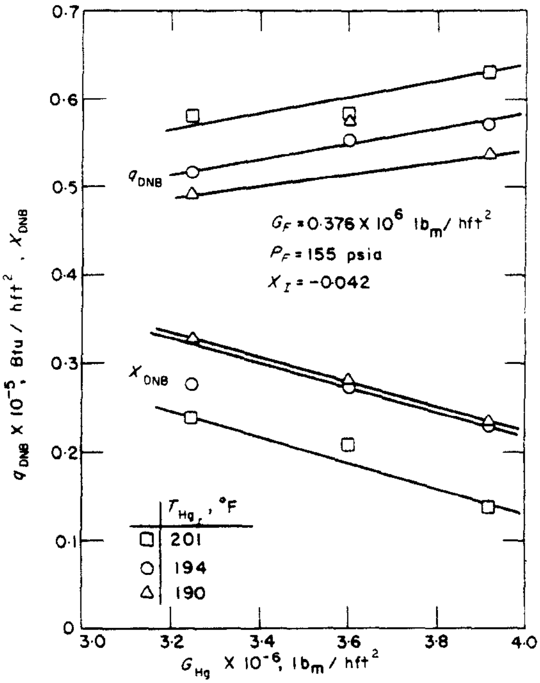

FIG. 10. Trends in liquid metal heated data.

It has been postulated that DNB occurring at higher qualities may be better correlated in terms of the average heat flux rather than the local value as employed thus far. In 1963, Tong [9] presented a DNB correlation for water in the quality region based on the average heat flux from inception of boiling to DNB. This feature was later incorporated into Tong's F factor correlation [10]. Thus, the liquid metal heated DNB data were replotted in Figs. 11 and 12 as a function of average heat flux, $\bar{q}$. Note that $\bar{q}$ is the heat flux spatially averaged from the location of DNB upstream with respect to the freon to the

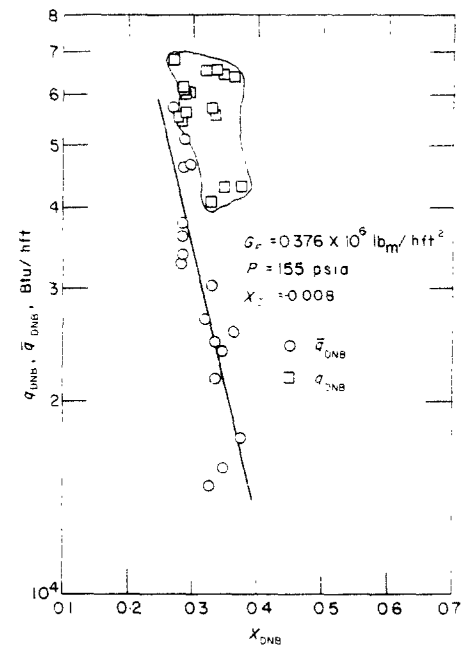

FIG. 11. Comparison of average and local DNB heat flux parameters.

point of boiling inception. Typical results shown in Fig. 11 indicate that the average heat flux is a better correlating parameter than the local value at DNB. Similar results are shown in Fig. 12 for the experimental range of freon mass velocities.

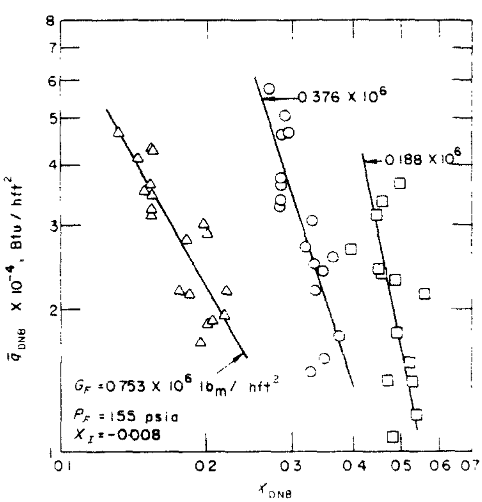

FIG. 12. Average heat flux correlating parameters.

DISCUSSION

Comparison of the two sets of data, liquid metal heated and uniformly electrically heated, of Figs. 7 and 8 indicate that a DNB correlation based on the latter data is not conservative when applied to the liquid metal heated system. At a given quality, the DNB heat flux predicted by the correlation is of larger magnitude than experimentally obtained in the liquid metal heated system. A similar nonconservative prediction in the thermal design of a liquid metal heated steam generator could result in the unit not meeting desired performance. There are two features of the heating methods employed in obtaining these two sets of data that influence the observed differences. The axial heat flux in the liquid metal heated experiments was nonuniform; the electrically heated data were obtained from a uniformly heated test section. The question then arises whether the effect of liquid metal heating can be predicted by correlations based on nonuniformly electrically heated data. If such prediction could be made then the effect of liquid metal heating on DNB would be only to alter the axial heat flux. However, the second heating feature of a temperature versus heat flux controlled system may influence the basic DNB mechanism complicating the liquid metal heating effect on DNB. The subject of nonuniformly electrically heated data will be discussed first.

Various investigators have reported significant effects of axial heat flux on DNB. These studies have been performed with a variety of fluids over various parametric ranges. For example, Bertoletti *et al.* [11] reported agreement among their data, Russian, and U.S.A. data showing no axial heat flux effect on DNB. Axial heat flux was shown to be significant in water by Tong *et al.* [10], in potassium by Alad'yev *et al.* [12] and in freon by Stevens *et al.* [13]. Tong's correlation of [4] and [10] predicts DNB heat flux in parametric ranges where the axial heat flux distribution is both significant and insignificant. This F factor correlation is based on nonuniformly electrically heated data. Because of its form, it can be applied to the present liquid metal heated freon data while other DNB correlations inherently related to other fluids, cannot be employed.

Consider a linear approximation of the liquid metal heated test section axial heat flux profile from the freon inlet to the location of DNB. The F factor correlation predicts that the heat flux at DNB will be equal to or greater than (depending on X_{DNB}) the DNB heat flux obtained in a uniformly heated case. The data of [12] for linearly increasing heat flux (electrically heated) in the direction of flow fall in the predicted range. The present data, liquid metal heated, do not.

At a given quality, the DNB heat flux from the liquid metal heated system was of a lesser magnitude than from the uniformly heated system. Although the F factor correlation is based on nonuniformly heated DNB data, these data were obtained from electrically heated systems, and the correlation does not predict the DNB heat flux under the nonuniform axial heat flux condition of the liquid metal heated system.

The F factor correlation incorporates the concept of two DNB regimes. At low and negative qualities, the local heat flux is dominant, and axial heat flux effect is minimal. In the quality regime, the average heat flux from initiation of boiling to the location of DNB is dominant. The liquid metal heated data as shown in Figs. 11 and 12 fall into the second regime. However, Todreas and Rohsenow [14] reported two DNB mechanisms occurring in annular flow boiling which may also be classified in the second regime. The mechanisms were nucleation and film dryout where nucleation was suppressed, and the limited data obtained under the latter DNB mechanism were not well correlated by local DNB heat flux.

Based on these results, it is reasonable to postulate that the DNB phenomenon observed in the liquid metal heated system was a consequence of film dryout. The failure of the factor correlation to predict the DNB heat flux may be a result of differences in the flow dynamics or in the DNB mechanism itself between the liquid metal and electrically heated systems. The F factor correlation is based on electrically heated data.

CONCLUDING REMARKS

The results of this investigation indicate that in the paramateric range of interest at a given quality, the magnitude of the DNB heat flux is greater in a uniformly electrically heated system than in a liquid metal heated system. The data were obtained at qualities pertinent to steam generator design. All data were obtained using freon 12 at a liquid to vapor density ratio of 20. Extending these results to the thermal design of a liquid metal heated steam generator would require additional tests in a sodium–water system. However, the indication of these results is that the thermal design of such a steam generator employing a DNB correlation based on electrically heated (uniformly or nonuniformly) data will be nonconservative.

The phenomenon of thermal oscillation in the region of DNB was observed and discussed. Little information concerning this effect is reported in the literature. These oscillations may be mechanically detrimental and also warrant further investigation.

ACKNOWLEDGEMENTS

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APPENDIX

Due to the spatial variation in axial heat flux in the liquid metal heated experiments error in the data reduction was introduced by the approximation

$$\frac{dT_W}{dZ} \simeq \frac{dT_{Hg}}{dZ}. \tag{A.1}$$

The following analysis of the system was performed as an estimate of that error.

Consider the axially symetric test section geometry of Fig. 2 with mercury flowing vertically downward in the annulus. Heat is transferred through the inner wall to the freon: the outer wall is insulated. The energy equation for the mercury may be written as

$$U\rho C\frac{\partial T}{\partial W} = \frac{1}{r}\frac{\partial}{\partial r}\left[r(k + \rho C\varepsilon)\frac{\partial T}{\partial r}\right] \quad (A.2)$$

where r, the radial coordinate, is measured from the center-line of the freon tube. All properties refer to the mercury, and the subscript Hg has been omitted.

The boundary conditions are

$$q(W) = -k\frac{\partial T}{\partial r}\bigg|_{r=d_1/2} \quad (A.3)$$

$$\frac{\partial T}{\partial r}\bigg|_{r=d_2/2} = 0 \quad (A.4)$$

$$T(W = 0, r) = T_I \quad (A.5)$$

where the initial condition of uniform temperature T_I, has been assumed. Chen and Yu [15] treated this problem under the conditions of fully developed turbulent flow for an arbitrary $q(W, r = d_1/2)$. Employing the method of separation of variables into entrance region and fully developed solutions the following results are obtained:

$$T_W(y) - T_B(y) = -\frac{4\delta}{kRe}\sum_{n=1}^{\infty} C_n Y_n(1)\beta_n^2 \int_0^y q(t)\exp\left[-4\beta_n^2 \times (y - t)/Re\right]\mathrm{d}t \quad (A.6)$$

and

$$T_B(y) = T_I + \frac{8\delta}{k(2 + R)Pe}\int_0^y q(t)\,\mathrm{d}t \quad (A.7)$$

where

$$\delta = (d_2 - d_1)/2$$

$$R = \frac{d_2}{d_1} - 1$$

$$y = \frac{W}{2\delta}.$$

The coefficients, C_n, eigenfunctions, Y_n, and eigenvalues, β_n, are tabulated in [16] for $n = 1$ to $n = 10$ for various values of Re, Pr and d_2/d_1. At $d_2/d_1 = 1{\cdot}5$ corresponding to the present test section, the results of Yu and Chen were utilized in equations (A.6) and (A.7). Values of $Re = 5 \times 10^4$ and $Pr = 0{\cdot}006$ approximated a typical liquid metal heated DNB test. The experimentally determined heat flux $q(W)$ was approximated by analytical functions and integrated in equations (A.6) and (A.7). At the axial location of DNB, the result was obtained that

$$\frac{\dfrac{\mathrm{d}T_W}{\mathrm{d}W} - \dfrac{\mathrm{d}T_B}{\mathrm{d}W}}{\dfrac{\mathrm{d}T_B}{\mathrm{d}W}} \simeq 8 \text{ per cent.}$$

This case was typical of all data taken and was considered sufficient justification for using the approximation of (A.1) in the data reduction.

NAISSANCE DE L'EBULLITION NUCLEEE EN CONVECTION FORCEE ET CHAUFFAGE PAR METAL LIQUIDE

Résumé—Un programme expérimental a été établi pour étudier la naissance de l'ébullition nucléée dans un fluide en ébullition chauffé par un écoulement de métal liquide. Ce fluide en ébullition qui est du fréon 12 circule verticalement vers le haut et est chauffé à contre-courant par un écoulement de mercure. La grandeur et la tendance des flux thermiques et la qualité au début de l'ébullition nucléée sont comparées aux résultats obtenus sur un montage semblable utilisant un chauffage électrique uniforme de la section de mesure. Les résultats montrent que pour une qualité donnée, la valeur du flux thermique est plus grande dans le cas du chauffage électrique uniforme. Ce résultat n'est pas prévu par une corrélation empirique basée sur les données obtenues à partir de sections d'éssais chauffées électriquement et employant des distributions axiales de flux uniformes ou non. On démontre que la naissance de l'ébullition nucléée dans un système à température contrôlée (chauffage par métal liquide) ne peut pas être estimée correctement à partir des corrélations établies sur les données (chauffage uniforme ou non) obtenue à partir de systèmes à flux contrôlés (chauffage électrique).

DIE KRITISCHE WÄRMESTROMDICHTE BEI SIEDEN IN ERZWUNGENER KONVEKTION UND BEHEIZUNG DURCH FLÜSSIGMETALL

Zusammenfassung—Zur Untersuchung der maximalen kritischen Wärmestromdichte (DNB) in einer mit Flüssigmetall beheizten Zweiphasenströmung wurde ein experimentelles Versuchsprogramm durchgeführt. Die siedende Flüssigkeit, Freon 12, strömt senkrecht nach oben und wurde im Gegenstrom mit Quecksilber beheizt. Grösse und Verlauf der Wärmestromdichte und der Dampfqualität am Burnout-

Punkt wurde mit Ergebnissen verglichen, die an einer ähnlichen Versuchsanlage mit elektrisch beheizter Teststrecke und konstanter Wärmestromdichte gewonnen wurden. Die Messergebnisse zeigen, dass bei einer bestimmten Dampfqualität die maximale kritische Wärmestromdichte grösser ist als im Falle der elektrischen Heizung mit konstanter Wärmestromdichte. Dieses Ergebnis wird von keiner Beziehung für die kritische Wärmestromdichte berücksichtigt, die aus Messergebnissen an elektrisch beheizten Teststrecken unter Anwendung konstanter oder veränderlicher axialer Verteilung der Wärmestromdichte gewonnen wurde. Es wird gezeigt, dass das Auftreten der maximalen Wärmestromdichte in temperaturgeregelten Systemen (Flüssigmetall-beheizt) nicht genügend genau mit Beziehungen vorausberechnet werden kann, die auf Messergebnissen (konstante oder veränderliche Wärmestromdichte) beruhen, welche an Systemen mit geregelter Wärmestromdichte erhalten wurden (elektrisch beheizt).

КРИЗИС КИПЕНИЯ В СИСТЕМАХ, НАГРЕВАЕМЫХ ЖИДКИМ МЕТАЛЛОМ ПРИ ВЫНУЖДЕННОЙ КОНВЕКЦИИ

Аннотация—Выполнена экспериментальная программа по исследованию кризиса кипения в текущих системах, нагреваемых жидким металлом. Кипящая жидкость (фреон 12) циркулировала вертикально вверх и нагревалась потоком ртути, циркулирующей в противоположном направлении. Величины и направление теплового потока и удельное паросодержание в критическом состоянии сравниваются с данными, полученными на аналогичной экспериментальной установке, в которой стенка рабочего участка равномерно нагревалась электрическим током. Результаты исследования показывают, что при заданном удельном паросодержании величина критического теплового потока больше в случае равномерного нагрева электрическим током. Расчет кризиса кипения с помощью соотношения, полученного на данных для рабочих участков с электронагревом при использовании равномерного и неравномерного распределения теплового потока на оси, не дал такого результата. Показано, что кризис в системах с с регулируемой температурой (нагрев жидким металлом) не может быть рассчитан правильно по соотношениям на основе данных при равномерном и неравномерном нагреве, полученных для систем с регулируемым тепловым потоком (электронагрев).