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MERCURY POOL BOILING UNDER THE INFLUENCE OF A HORIZONTAL MAGNETIC FIELD

LORRY Y. WAGNER and PAUL S. LYKOUDIS
School of Nuclear Engineering, Purdue University, West Lafayette, IN 47907, U.S.A.

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Abstract—Experimental results for the pool boiling of pure mercury and mercury plus wetting agents in the presence of a magnetic field are presented. The results indicate that a significant reduction in the heat-transfer coefficient occurs as the magnetic field is increased, the incipient boiling heat flux is lowered, and the transition to film boiling is encouraged. Data are presented for magnetic fields of 0.4, 0.8 and 1.26 T at the saturated pressures of 0.0066, 0.026 and 0.1 MPa.

NOMENCLATURE

B, magnetic field flux density [T];
q'', heat flux [kW/m^2];
T_B, liquid bulk temperature [°C];
T_w, wall temperature [°C];
T_{sat}, liquid saturation temperature [°C];
ΔT_{sat}, superheat temperature, $T_w - T_{sat}$ [°C];
P_{sat}, liquid saturation pressure [MPa].

INTRODUCTION

ONE OF the most effective ways to extract energy from fusion reactors is through the use of a lithium blanket surrounding the plasma core. This type of design would accommodate the high heat fluxes, while also providing the facility for neutron moderation and tritium breeding. However, with the high magnetic fields in magnetic confinement systems, one would like to avoid the large Magneto-Fluid-Mechanic (MFM) losses that would be incurred by circulating the lithium. Several two-phase designs have evolved that alleviate this problem. Fraas [1] has proposed an energy removal system of once through potassium boiler tubes to be installed in the lithium blanket. This design has the additional advantage of providing the capability for a topping cycle. A similar idea was suggested by Fujii-e *et al.* [2] where a two component two phase flow of lithium and another liquid metal would be used. Pendergrass *et al.* [3] have devised a scheme where the lithium in the blanket is used as the two phase medium. In each of these designs, the energy transfer through the boiling process allows a smaller flow than in the single phase system, leading to a decrease in the MFM losses.

It is well established, theoretically and experimentally [4–6], that in single phase flow the magnetic field inhibits convective heat transfer. The theoretical aspects of boiling in a magnetic field have been investigated by Lykoudis [7] and Wagner and Lykoudis [8]. Their results, using a simplified model, indicate a significant effect on bubble growth and overall heat transfer due to the magnetic field's presence. A semi-empirical correlation based on the theoretical results of [7] and [8] was successful in correlating all the data obtained in the present work. This correlation is reported by Wagner and Lykoudis in [9]. A more detailed theoretical model is now under development and will be reported in the future. However, the available experimental results for two-phase heat transfer (pool boiling) are in substantial disagreement with one another. In 1963, Lunardini [10] provided the first experimental results for liquid metal pool boiling in a horizontal magnetic field. Stable nucleate boiling was achieved with fractional amounts of magnesium and titanium added to pure mercury. The results of this work indicated that no significant variation of boiling heat transfer occurred due to the magnetic field's presence for fields up to 1.7 T. Faber and Hsu [11] studied the effect of a vertical magnetic field on the subcooled boiling of mercury plus wetting agents, on a horizontal surface. The results obtained from this work indicated that the magnetic field (6 T) retarded the heat transfer for natural convection and definitely encouraged the onset of nucleate boiling. For subcooled boiling, the magnetic field effects are less clear. The temperature difference between the heater surface and bulk liquid showed a definite decrease as the heat flux was increased for a given magnetic field. This would seem to indicate an enhancement of the heat transfer, however, due to the modest range of the subcooled data and none for saturated boiling, only limited conclusions can be made. Fraas *et al.* [12] conducted a study of the effects of a vertical magnetic field on the boiling of potassium from a vertical surface. The authors concluded that no discernible effect on the boiling heat transfer was present. In the investigation by Michiyoshi *et al.* [13], a horizontal cylinder was placed in a pool of pure mercury with a horizontal magnetic field perpendicular to the axis. The results of this work indicated a definite decrease in the heat transfer when the magnetic field was applied. For a field of 1 T, the ratio of the heat-transfer coefficient with the magnetic field over that without the field was 0.74. The experiments by Kawamura *et al.* [14], also show similar trends to those by Michiyoshi. In this case, a liquid sodium pool containing a vertical heater was placed in a vertical magnetic field. The presence of the field (1.5 T) promoted the onset of nucleate boiling but had little effect on the burnout heat flux. A visual study of boiling mercury was conducted by Sanokawa *et al.* [15]. In this case, the horizontal surface was covered with 2–3 mm of mercury and placed in a vertical magnetic field. The photographic results revealed that boiling is facilitated with the application of a magnetic field.

The most recent work on this subject, by Takahashi *et al.* [16], studied the effect of a vertical magnetic field (0.9 T) on the pool boiling of pure mercury on a horizontal surface. The results of their experiment verified much of the work of Faber and Hsu [11]: the onset of nucleate boiling was promoted; the natural convection heat-transfer coefficient decreased as the field increased; in the low heat flux boiling regime the heat-transfer coefficient increased. Surprisingly, no mention of this work was made in the paper of Takahashi *et al.*, even though their literature review was fairly complete. Much of the data from this latest work was in the film boiling regime, which provided evidence of the magnetic fields encouragement of the transition to film boiling. Due to the poor wetting of the mercury on stainless steel in their experiment, the boiling data appear to be in the natural convection-nucleate boiling transition regime [17] or, at the higher heat fluxes, in the film boiling regime. This makes it difficult to determine the effect of a magnetic field on stable nucleate boiling, which they never seemed to have obtained.

The results of all of these experiments when taken together, make it difficult to draw any conclusions about the fundamental mechanisms that are involved. A more definitive set of experiments must be carried out to try and resolve the inconsistencies and also provide more information on the nucleate boiling heat-transfer variation. This paper presents the results of an experiment in which reproducible nucleate boiling occurs in mercury from a horizontal surface in the presence of a horizontal magnetic field.

THE EXPERIMENT

The boiling system that was used in this investigation is similar in its basic design to those used for several of the original liquid metal studies [18–21]. A simple one-dimensional geometry was chosen because a large amount of non-magnetic horizontal flat plate boiling data is available for comparison. Any effect that the magnetic field had on the boiling process would be readily apparent.

A schematic of the experimental system is shown in Fig. 1(a). High purity nitrogen was used for a cover gas with the regulation being provided by a vacuum pump, cold trap, pressure reservoir (50 times the boiler volume) and MKS pressure transducer. This system enabled the saturated pressure to be controlled to ± 2.0 Pa over the experimental range of 0.0066–0.1 MPa. The boiler fill system consisted of a sealed plexiglass reservoir (64 mm ID $\times$ 46 mm long) and a 7 μ in-line filter connected in series to the boiler with stainless steel tubing. The boiler, shown in Fig. 1(b), was comprised of a vertical stainless steel 316 tube (60 mm ID $\times$ 910 mm long) with a horizontal heater surface at the bottom and a water cooled condenser region at the top. The central boiler tube was surrounded by an insulation jacket fabricated from a stainless steel 304 cylinder (95 mm ID $\times$ 610 mm long). Insulation was provided by a free flowing silicon oxide powder (Eccospheres SI) with very low conductivity (0.07 W/m°C) and excellent temperature stability (to 1000°C).

The heater plate was designed to give a uniform surface temperature and heat flux. According to Leidenfrost [22], with a uniformly distributed heat source and a plate thickness of four times the depth of the heater channels, the temperature fluctuations at the heater surface will be of a 100 000 fold smaller amplitude than the fluctuations at the heating element boundary. These conditions were accomplished with the design shown in Fig. 2. The heater plate was machined from stainless steel 316 and the heater coil

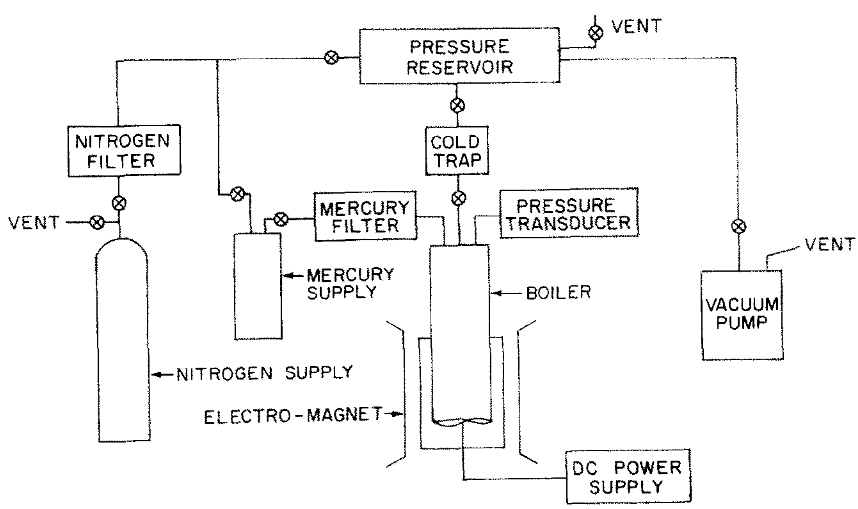

FIG. 1(a). Schematic of the boiling system.

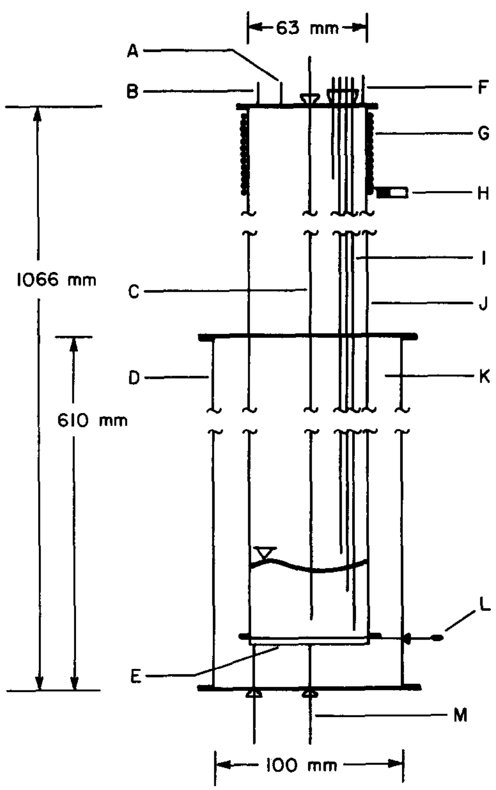

FIG. 1(b). Mercury boiler: A, nitrogen reservoir; B, mercury reservoir; C, traversing platinum resistance thermometer; D, insulation jacket; E, heater; F, pressure transducer; G, water cooling coils; H, acoustic transducer; I, iron–Constantan thermocouples; J, boiling vessel; K, SiO_2 insulation; L, surface platinum resistance thermometer; M, copper electrodes.

was nickel brazed to the underside. In order to assure uniform contact before and during brazing, a spiral honeycomb was used to hold the coil into the plate recess. This heated region was 60 mm in diameter and allowed a maximum power input of 1000 W. The power to this heater was controlled by a D.C. power supply that was stable to $\pm 0.2\%$. The boiling surface was machined flat and then polished to a mirror finish on a diamond wheel to remove any surface imperfections. Before the plate was sealed to the boiler, it was then carefully sandblasted with 400 μ sand to give a very rough surface with a uniform and reproducible distribution of nucleation sites. The boiler seal was a metal V-Seal with gold and platinum coatings on an Inconel 718 base. This provided the capability for periodic boiler disassembly without damaging the boiler surface.

The temperature sensors were the most critical components of the whole system, therefore it was essential that they be able to provide data of high precision. The surface temperature was measured by a 1.2 mm platinum resistance thermometer imbedded in the boiler plate 0.6 mm below the surface. It was been shown by Leidenfrost [22], that for a method similar to this, the surface temperature can be accurately determined to ± 0.001°C. This method of determining the surface temperature eliminates the need for multiple plate temperature measurements by thermocouples and subsequent extrapolation. However, the primary advantage is that the resistance thermometer will yield an average surface temperature from an infinite number of points along its length, where as a thermocouple determines the temperature at only one point. Another platinum resistance thermometer was used for the bulk temperature measurement. This probe was able to traverse the entire depth of the liquid mercury so that any bulk temperature variations could be measured. Several fixed thermocouples were also used to verify the liquid temperature. Additional thermocouples were located in the condenser and insulation regions.

An acoustic transducer was used as a supplemental tool to help delineate which boiling process was occurring. A steady signal on the oscilloscope indicated that natural convection was present, while any subsequent noise above that level indicated the presence of boiling. These acoustic signals correlated very well with the surface temperature fluctuations and gave an accurate account of the heat-transfer phenomena. This transducer was mounted on the boiler tube.

The magnetic field was provided by a water-cooled D.C. electromagnet powered by a 150 kW D.C. motor-generator set. It was possible to maintain the field to $\pm 0.5\%$ of the set field. For this experiment the pole faces were 305 × 305 mm with a gap of 102 mm and a maximum field of 1.26 T.

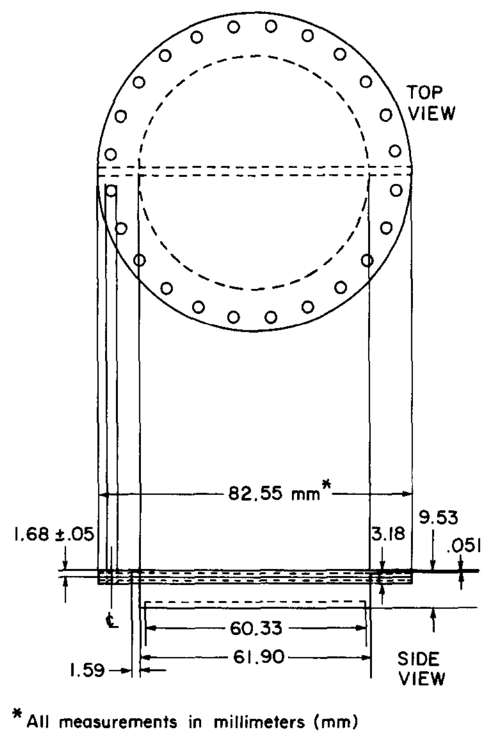

FIG. 2. Heater cross-section.

The system was initially prepared by cleaning all the stainless steel components in an acid bath and then flushing with distilled water. The boiling surface was then prepared and the apparatus assembled. At this point, the system was flushed with trichloroethylene and then flushed again with distilled water. The calibration procedure for the heat losses was performed and then the system was pressure and vacuum tested. The boiler was now ready for the initial boiling tests with water. Several runs were made to check the surface characteristics and provide experience with the apparatus and instrumentation. When the water tests were finished, the boiler was again filled with trichloroethylene and flushed with distilled water. This completed the preliminary tests and the system was ready for the boiling mercury runs. The boiler was filled with quadruple distilled mercury to a level of 40 mm and pressure and vacuum tested again.

During the course of the experiment a standard procedure was used to take the data. A saturated pressure was established in the system and then the heat flux woud be varied from zero to the maximum with the system stabilized at each power level for 20–30 min. The magnetic field was then set and the procedure was repeated. This was done for each magnetic field setting (0.4, 0.8 and 1.26 T) and then the zero field data were repeated. The final check of the data consisted of picking several heat fluxes and then varying the magnetic field from zero to 1.26 T and back to zero. The results of this process indicated that the data were very repeatable and that the nucleate boiling in the system was stable. For each system pressure, a traverse of the entire fluid depth was made at 3 heat flux levels in the nucleate boiling regime. The results of these measurements indicated that the temperature variation in the pool was less than 1°C for 0.1 MPa and as great as 4°C for a saturated pressure of 0.0066 MPa. For the bulk temperature measurements, the probe was located at 20 mm above the boiling surface.

After the data were established with pure mercury, 10 ppm titanium and 200 ppm magnesium were added to the liquid as wetting agents. The same data acquisition procedure was used and the experiment repeated.

A schematic of the instrumentation is shown in Fig. 3. The PDP 11/03 minicomputer was programmed to read the signals over a selected time interval, take an average, display the voltage readings, and then reduce the data to engineering values (pressure, temperature, etc.). This system enabled the experiment to be monitored continuously, while also providing a current analysis of the data.

The heat flux through the surface was the only parameter that was not directly measured. The total heat input was known from the heater voltage and current readings, however, the losses through the insulation had to be determined. Two methods were used to do this. The first way was to calibrate the energy loss with the heater temperature. At a given power input with the boiler empty and evacuated, the energy loss through the insulation is the total power minus the surface radiation. Therefore, at this heater temperature, the insulation loss is known. When the boiler is filled with mercury, it is estimated that the same energy is lost through the insulation when the heater reaches the calibrated temperature. In this way the heater temperature can be used to calibrate the energy losses in the system. The second way, employed the direct calculation of the heat transfer through the insulation. The temperature field of the boiler assembly was calculated by a relaxation method [23] with the thermocouple temperatures in the insulation used as input. The calibration technique was used in the on-line data analysis, while the more accurate heat-transfer calculation was used for the final data analysis. For a heat flux of 35 kW/m^2 the maximum loss was

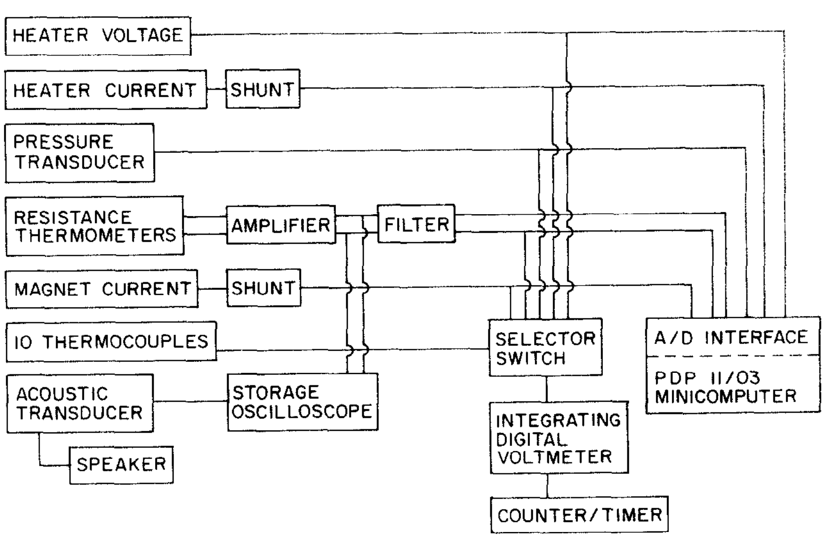

FIG. 3. Data acquisition system schematic.

15% and at the maximum flux of 310 kW/m^2 the heat loss was 5%. Further details are available in [24].

THE RESULTS

The first nucleate boiling data were obtained with water at a saturated pressure of 0.1 MPa. The data can be seen in Fig. 4 along with the water results from several other liquid metal boilers [19, 25, 26]. The heat-transfer rates from this experiment are seen to be in agreement with those obtained by the other investigators.

The initial experiments in mercury indicated that film boiling was present. (This type of non-wetting film boiling has been reported in the literature [17, 18, 26].) Due to the poor wetting conditions that existed between the mercury and stainless steel, it was relatively easy to form a vapor blanket. In the first 60 s of heating at 46 kW/m^2, the surface temperature rose to 100°C above the saturation temperature (356.6°C) before the power was reduced to protect the system. After approximately 20 h of continuous operation, nucleate boiling began to appear. This regime was stable up to a heat flux of 82 kW/m^2, at which point film boiling reappeared. As the wetting improved over the next 10 h of operation, the nucleate boiling regime was stable at progressively higher heat fluxes (up to 310 kW/m^2), and film boiling did not reappear. The nucleate boiling results obtained at this time represent the "pre-aged" data.

As the surface "aged" over the first two months of operation, there was a gradual increase in the superheat for a given heat flux. This is shown by the translation of the data to the right. After this time, the system remained unchanged and the temperature data were repeatable to within ±2.5%. The results of stable nucleate boiling for the pre-aged and aged states are presented in Fig. 5. Bonilla *et al* [18], Michiyoshi *et al.* [13], Takahashi *et al.* [16], and Lyon *et al.* [26] also boiled pure mercury on stainless steel, however, only the first two systems were able to achieve stable nucleate boiling. This data is presented in Fig. 6 along with the present work. The agreement at 0.1 MPa is reasonable, while at 0.0066 MPa the similarity is remarkable considering the differences in surface preparation.

When a magnetic field is applied, the data indicate that a significant reduction in the heat-transfer coefficient occurs. The results in pure mercury for the saturated pressures of 0.1 MPa (760 mmHg), 0.26 MPa (200 mmHg), and 0.0066 MPa (50 mmHg) are presented in Figs. 7, 8 and 9 respectively. For a given superheat, a magnetic field of 0.4 T will reduce the heat-transfer coefficient by 20% while at 1.26 T the reduction is on the order of 55%. The results of Takahashi *et al.* [16] are also included in Fig. 9 as a comparison. While trends in the heat-transfer re-

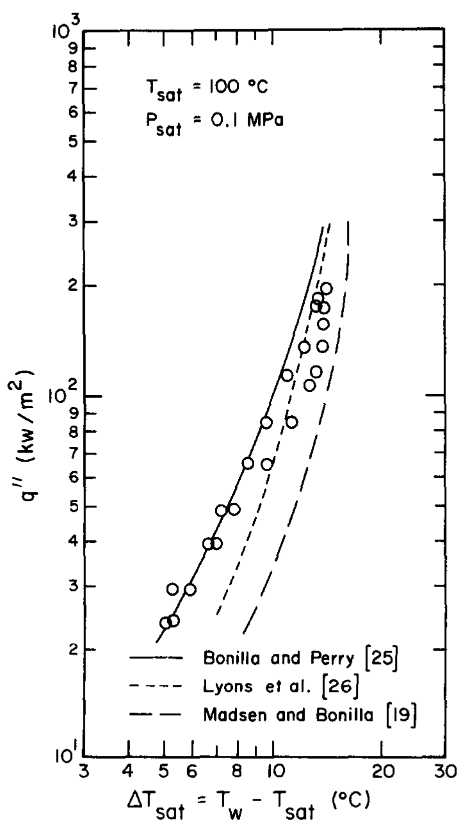

FIG. 4. Heat flux vs superheat for boiling water.

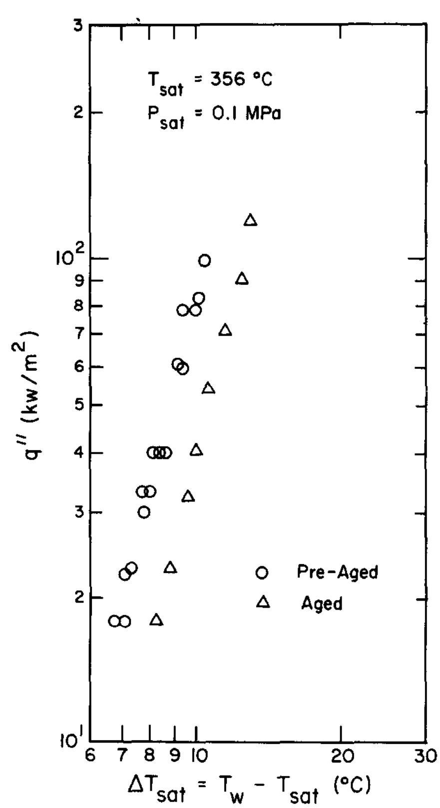

FIG. 5. Heat flux vs superheat for the pre-aged and aged data in pure mercury.

duction are similar as the magnetic field increases, the previous work does not maintain stable nucleate boiling but proceeds to film boiling as the heat flux increases above the natural convection regime. This is characteristic of non-wetting systems as described earlier and in [17].

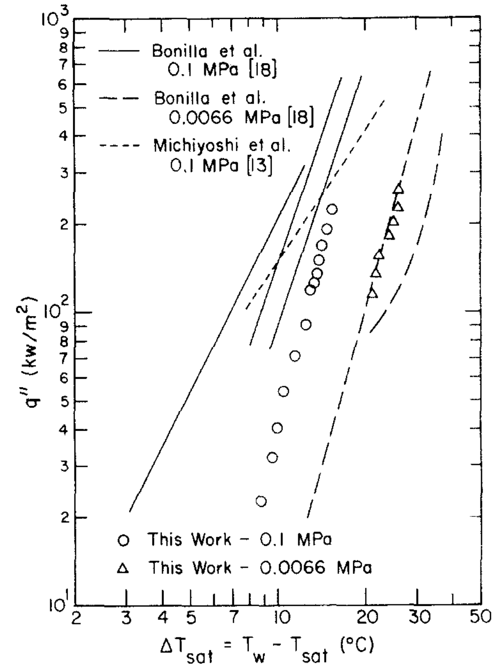

FIG. 6. Heat flux vs superheat for pure mercury.

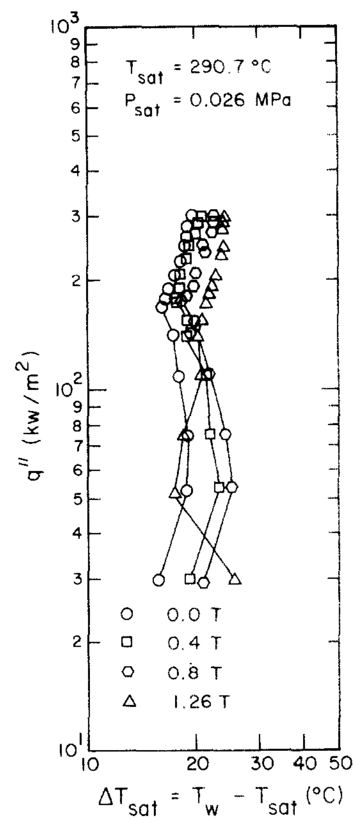

FIG. 8. Heat flux vs superheat for pure mercury in the presence of a magnetic field.

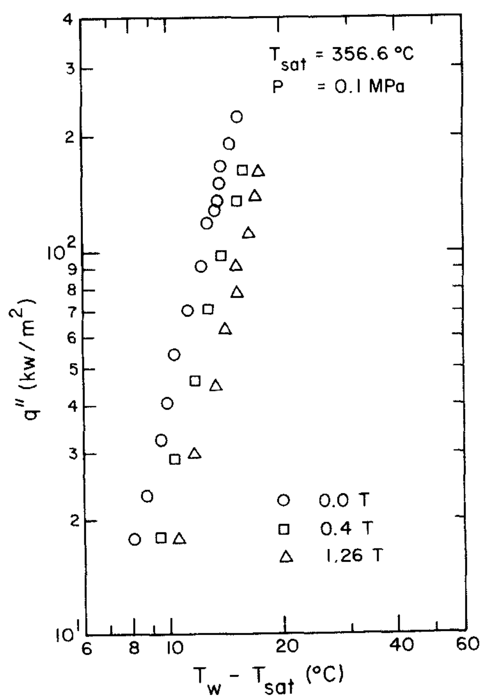

FIG. 7. Heat flux vs superheat for pure mercury in the presence of a magnetic field.

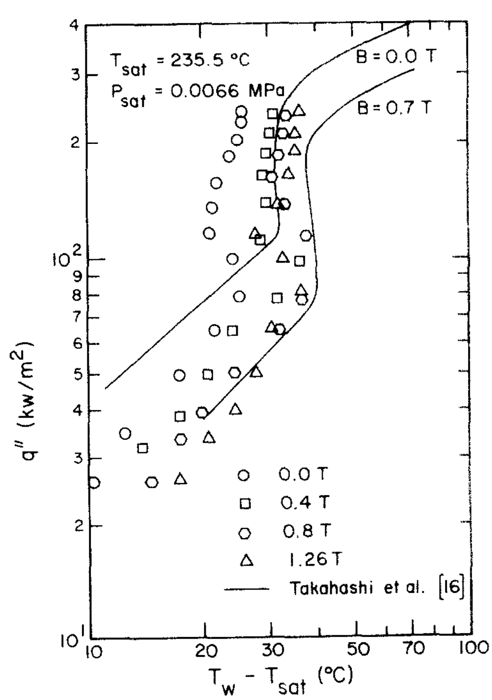

FIG. 9. Heat flux vs superheat for pure mercury in the presence of a magnetic field.

The phenomena of natural convection-nucleate boiling bumping is also illustrated in Figs. 8 and 9. The heat-transfer mode did not make a smooth transition from natural convection to nucleate boiling. As the heat flux was increased during natural convection, a point was eventually reached where this heat-transfer regime was not sufficient to remove all the energy. At the same time, the heat flux was not great enough to support stable nucleate boiling. The surface temperature would gradually increase above the liquid saturation temperature until a boiling burst occurred. At this point the temperature dropped rapidly and the process was repeated. The bulk temperature also followed the same pattern. It would superheat and then after the burst, drop to the saturation level. The lower portion of the curve represents the bumping regime, whereas the upper part describes stable nucleate boiling. This phenomena was reported in the literature for other liquid metal systems [17, 21]. When the transition from bumping to stable boiling occurs, the temperature driving force actually decreased. This forms the basis of the characteristic S-shaped curves as reported by Orell [27]. As the heat flux is raised, the frequency of bursts increases, and eventually a point is reached where stable nucleate boiling can be sustained. At this time the surface temperature actually drops with an increase in heat flux (above 80 kW/m^2). A large number of nucleation sites have become available and the heat-transfer process is more efficient. In order to maintain the heat-transfer rates at a given heat flux, the superheat must decrease. Ultimately, a heat flux is reached where any subsequent increase is accompanied by an increase in superheat and stable nucleate boiling follows. The presence of a magnetic field reduces the overall heat-transfer coefficients but the phenomenon remains the same.

In any liquid metal system, the heat transfer rates are dependent upon how well the liquid wets the surface. In the mercury–stainless steel system, the wetting can be improved by adding fractional amounts of titanium (10 ppm) and magnesium (200 ppm) to the mercury. When these agents were added to the boiler, the heat-transfer rates improved immediately as evidenced by the lower super heats from the same heat flux levels. The effect of a magnetic field on this well-wetted system can be seen in Fig. 10. These results were very stable over time and are not much different from the aged system with pure mercury. The only noticeable difference is that the "S" phenomena is more pronounced and even occurs in the stable nucleate boiling regime.

The effect of a magnetic field on the incipient boiling heat flux can be seen in Fig. 11. As the magnetic field increases, boiling bursts occur at a lower heat flux than in the absence of a magnetic field. During the natural convection regime, an increase in the magnetic field inhibits the natural circulation, which leads to a decrease in the heat-transfer rates and higher surface temperatures. This provides the mechanism for boiling to occur at a lower heat flux. The results shown here are similar to those of Takahashi [16] and Kawamura [14]. Even though the geometries of each of these systems are different, the fundamental process is the same.

The pre-aged data for pure mercury at 0.0066 MPa clearly show the effect a magnetic field has on initiating film boiling. During the first experimental runs at this pressure, nucleate boiling was established at each point for 15 min and then the data were recorded. However, when the heat flux reached 220 kW/m^2, a new phenomenon occurred that was distinctly different from all previous results. Initially, nucleate boiling was established without the magnetic field, but when it was applied an abrupt transition in the boiling process resulted. The surface temperature rose from 270.1°C to

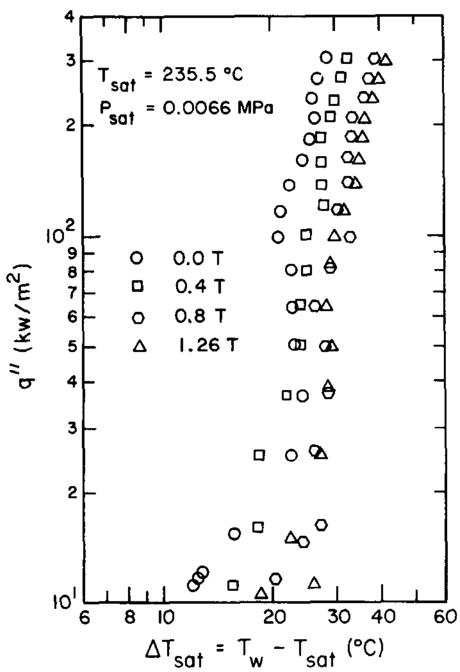

FIG. 10. Heat flux vs superheat for mercury plus 10 ppm titanium and 200 ppm magnesium in the presence of a magnetic field.

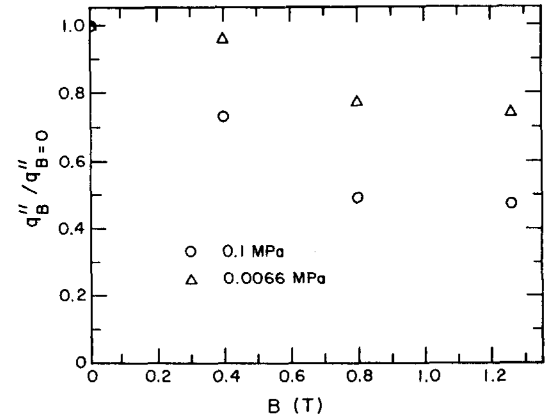

FIG. 11. The effect of a magnetic field on the incipient boiling heat flux.

over 495°C in 5 min, indicating that film boiling was present. If nucleate boiling had existed with only the normal reduction in heat transfer due to the magnetic field, the surface temperature would have been approximately 285°C. Since the surface temperature in film boiling at this heat flux could be several hundred degrees higher [16, 18] the decision was made to terminate the experiment at this point. Therefore, the data in Fig. 12 for film boiling do not represent a stable value, but only a transition point into the film boiling regime. Nevertheless, it is clear from these experiments that the magnetic field caused film boiling to occur when stable nucleate boiling previously existed.

CONCLUSIONS

An experiment has been performed that clearly shows the effect of a horizontal magnetic field on nucleate boiling heat-transfer rates. Pure mercury and mercury plus wetting agents were boiled on a horizontal surface in a reflux-type boiler at saturated pressures of 0.0066, 0.026 and 0.1 MPa under magnetic fields of 0.4, 0.8 and 1.26 T. Data were presented that showed the magnitude of the heat-transfer reduction in nucleate boiling was as much as 55% at a field of 1.26 T. Additional data were provided that showed the incipient boiling heat flux was reduced as the magnetic field increased. This reduction is on the order of 50% when compared to the zero field case. The presence of a magnetic field also causes the transition to film boiling to occur when nucleate boiling was initially present.

A description of the aging process in this experiment was presented that showed how the heat-transfer regimes change over time. For the initially non-wetted system, film boiling was predominant, however, as the system aged, stable nucleate boiling appeared at

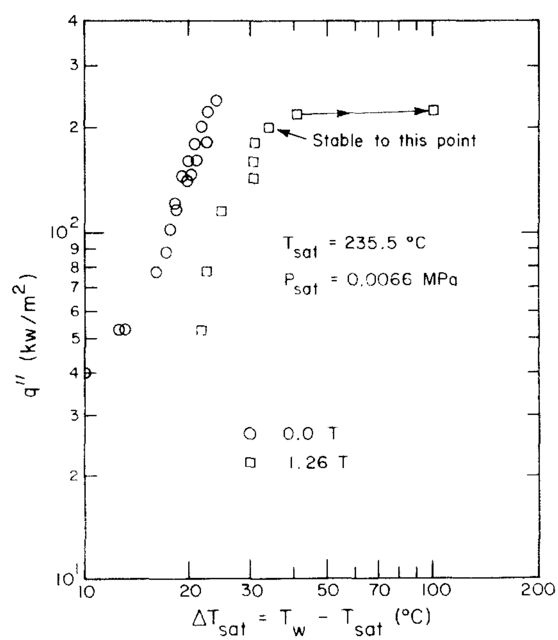

FIG. 12. Heat flux vs superheat for pure mercury—the transition to film boiling.

progressively higher heat fluxes. After a period of two months, the system was completely aged and the data remained unchanged. It is believed that the large number of nucleation sites promoted stable nucleate boiling after only 30 h, whereas in the case of previous work, several weeks were necessary before this occurred. While the exact relation between surface roughness and wetting is not discernible, it appears that a rough surface promotes early nucleate boiling with pure mercury.

The data from all of the experimental runs clearly indicated the complexity of the boiling process in liquid metals. The key factor that determined the existence of any given heat transfer mode was the wettability of the liquid–surface combination. At a given heat flux and superheat any one of the three heat-transfer regimes (bumping, stable boiling or film boiling) could have been present, depending upon the wetted or aged state of the system. It was also shown that the stable boiling attained in an aged system could be readily obtained in a fresh system by providing additives (magnesium and titanium) to the mercury. When the magnetic field was turned on, the main effect was one of reducing the heat-transfer coefficient. However, at certain points in the natural convection and film boiling regimes, it was possible to promote the onset of nucleate boiling and film boiling, respectively. Further work is required in order to define the conditions that lead to the transition of one heat-transfer mode to another, whether it be by aging, wetting or the application of magnetic field.

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EBULLITION DU MERCURE EN RESERVOIR SOUS L'INFLUENCE D'UN CHAMP MAGNETIQUE HORIZONTAL

Résumé—On présente des résultats expérimentaux sur l'ébullition en réservoir du mercure pur et du mercure avec des agents mouillants en présence d'un champ magnétique. Les résultats montrent qu'une réduction sensible du coefficient de transfert thermique so produit lorsque le champ magnétique augemente, le flux de début d'ébullition est diminué et la transition à l'ébullition en film est favorisée. Des données sont présentées pour des champs magnétiques de 0,4, 0,8 et 1,26 T aux pressions de saturation de 0,0066, 0,026 et 0,1 MPa.

BEHÄLTERSIEDEN VON QUECKSILBER UNTER DEM EINFLUSS EINES WAAGERECHTEN MAGNETISCHEN FELDES

Zusammenfassung—Es wird der Einfluß eines waagerechten magnetischen Feldes auf das Behältersieden von reinem Quecksilber und Gemischen aus Quecksilber und oberflächenaktiven Stoffen untersucht. Wie die Versuchsergebnisse zeigen, nimmt der Wärmeübergangskoeffizient stark ab, wenn die Stärke des magnetischen Feldes zunimmt: Die anfängliche Wärmestromdichte beim Sieden wird kleiner, und der Übergang zum Filmsieden wird gefördert. Versuchsergebnisse werden für magnetische Felder von 0,4; 0,8 und 1,26 T und für Dampfdrücke von 0,0066; 0,026 und 0,1 MPa mitgeteilt.

КИПЕНИЕ РТУТИ В БОЛЬШОМ ОБЪЕМЕ ПРИ ВОЗДЕЙСТВИИ ГОРИЗОНТАЛЬНОГО МАГНИТНОГО ПОЛЯ

Аннотация — Представлены экспериментальные данные по кипению очищенной ртути и ртути с примесью смачиваемых агентов при воздействии магнитного поля. Результаты показывают, что по мере усиления магнитного поля происходит значительное снижение коэффициента теплопереноса, а величина теплового потока, характерная для возникновения кипения, понижается, что способствует переходу к пленочному режиму кипения. Данные представлены для магнитных полей интенсивностью в 0,4; 0,8 и 1,26 Т и давлений насыщения, равных 0,0066; 0,026 и 0,1 МПа.