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NATURAL CONVECTION HEAT TRANSFER FROM A HORIZONTAL CYLINDER TO MERCURY UNDER MAGNETIC FIELD*

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Abstract—This paper presents the experimental data of natural convection heat transfer from a horizontal cylindrical heater immersed in mercury pool under the two applied magnetic fields of which directions are perpendicular and parallel to the direction of gravity, respectively. The presence of both magnetic fields causes increase in heater surface temperature and liquid temperature surrounding the heater and also increase in thermal boundary layer thickness, at the fixed surface heat flux. From these results, it is expected that the magnetic field affects the inception of boiling. Variation of local heat-transfer coefficient along the periphery of the heater is also discussed.

NOMENCLATURE

- B, magnetic flux density [T];
- $B \perp g$, magnetic field direction is perpendicular to gravity direction (Fig. 1a);
- $B \parallel g$, magnetic field direction is parallel to gravity direction (Fig. 1b);
- C_p, specific heat at constant pressure [J/(kg·K)];
- d, O.D. of heater [m];
- g, acceleration of gravity [m/s²];
- Gr, Grashof number, $d^3 g\beta(T_w - T_\infty)/\nu^2$;
- M, Hartmann number, $Bd(\sigma/\mu)^{1/2}$;
- Nu, Nusselt number, $d\alpha/\lambda$;
- Pr, Prandtl number, $C_p\mu/\lambda$;
- q, surface heat flux [W/m²];
- T, temperature [°C];
- T_l, liquid temperature [°C];
- T_w, surface temperature [°C];
- T_∞, ambient temperature [°C].

Greek symbols

- α, heat-transfer coefficient [W/(m²·K)];
- α_θ, heat-transfer coefficient at θ [W/(m²·K)];
- β, expansion coefficient [1/K];
- ΔT_1, temperature difference, $T_w - T_\infty$ [K];
- θ, angle from lower stagnation point, (Fig. 1) [rad];
- λ, thermal conductivity [W/(m·K)];
- μ, dynamic viscosity [kg/(m·s)];
- ν, kinematic viscosity [m²/s];
- σ, electrical conductivity [S/m].

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INTRODUCTION

IN GENERAL, the characteristic of pool boiling heat transfer is much dependent on the motion of liquid and bubbles adjacent to the heating surface. Such a motion of liquid is affected by the Lorentz force, if the electrically conducting liquid, for example liquid metal, moves under an applied magnetic field. Therefore, it is expected that the magnetic field affects the natural convection heat transfer and also the inception of boiling of the liquid metals. The inception of boiling is situated at the transition from the natural convection to the nucleate boiling region. In order to find out the effect of magnetic field on the inception of boiling and the boiling heat transfer on a horizontal cylinder immersed in the liquid metal, it is very important to study, in the first place, the natural convection around the horizontal cylinder.

This paper presents the experimental data of natural convection heat transfer from a horizontal cylindrical heater in mercury pool under the two applied magnetic fields of which directions are perpendicular and parallel to the direction of gravity. Particular attention was paid to the temperature distributions on the heater surface and in liquid mercury in this study, because such distributions have not yet been clarified as will be seen in the following literature survey.

LITERATURE SURVEY

Analyses of natural convection heat transfer from vertical plane surface under the magnetic field of which direction is perpendicular to the direction of gravity were dealt with by Mori [1], Sparrow and Cess [2], Lykoudis [3], Sun [4], and Cramer [5]. They showed that the heat-transfer coefficient decreased with increasing the intensity of magnetic field. The same conclusion was theoretically given to the natural convection heat transfer from horizontal plate under the magnetic field vertical to the plate by Gupta [6], and Singh and Cremers [7, 8]. Magnetic field effects on the convective heat transfer from cylindrical hot-film probe in mercury were experimentally studied by Malcolm [9] and Dunn and Lykoudis [10]. Their results indicated a reduction in heat transfer from the probe. Lunardini [11] studied the nucleate boiling of mercury on a horizontal plane surface under the magnetic field perpendicular to the gravity. He reported that the heat transfer was not affected by the presence of magnetic field (maximum intensity: 1.7 T) for the heat flux above 110.2 kW/m^2 but was slightly affected for the heat flux less than 78.8 kW/m^2. Faber and Hsu [12] presented the data of natural convection and subcooled nucleate boiling heat transfer for mercury on a horizontal plane surface under the magnetic field (maximum intensity: 6 T) parallel to the gravity. They concluded that the magnetic field exerted a strong retarding effect upon the natural convection heat transfer and subcooled nucleate boiling heat transfer. Experimental studies on heat transfer by natural convection and pool boiling of sodium on a vertical cylindrical heater pin under the magnetic field (maximum intensity: 1.5 T) parallel to the gravity were conducted by Kawamura *et al.* [13]. Their results indicated that a sharp rise of the heater surface temperature in the case of natural convection under the magnetic field was always observed at a certain point when the heat flux was gradually increased, following which, severe temperature oscillations were set off, and that the heat flux and the superheat at boiling incipience were both distinctly lowered by the presence of magnetic field. Since they utilized a grounded-type heater pin, the electrical current flowed through the sodium from the heater pin to the busbar connected to the sodium tank. It is not clear in their paper how much interaction effects of such current with the magnetic field were assessed upon the heat transfer.

To the authors' knowledge, the effect of magnetic field on the natural convection around a horizontal cylinder and the temperature distributions on the cylinder surface and in liquid mercury still remain to be solved.

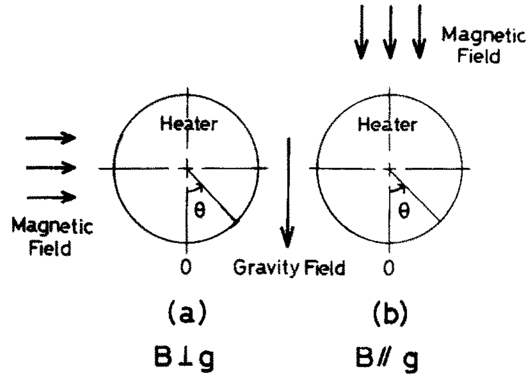

FIG. 1. Coordinate systems.

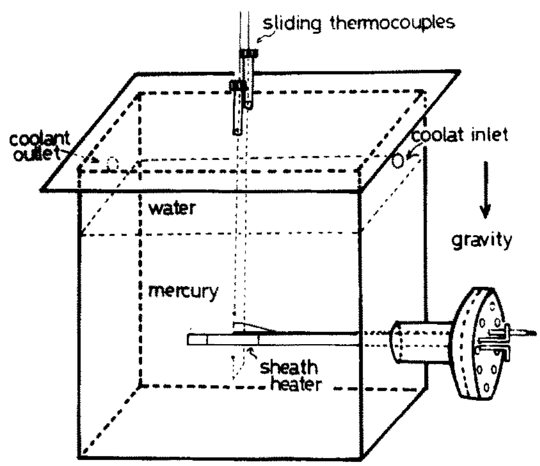

FIG. 2. Experimental apparatus.

EXPERIMENTAL APPARATUS AND PROCEDURES

Experiments of natural convection around a horizontal cylinder were conducted under the two applied magnetic fields of which directions were perpendicular and parallel to the direction of gravity as shown in Figs. 1(a) ($B \perp g$) and 1(b) ($B \parallel g$), respectively.

Distilled mercury is filled in a type 304 stainless steel tank having rectangular cross section as shown in Fig. 2. The cylindrical heater of unground type sheathed with type 316 stainless steel of 0.55 mm thickness, of which outer diameter is 6.5 mm and effective heating length is 39 mm as shown in Fig. 3, is immersed horizontally in the mercury pool. This heater is heated by supplying DC current. The heat flux is up to 6.4×10^5 W/m^2 at the heater surface.

The heater surface temperature is measured by stainless steel sheathed alumel–chromel thermocouple of 0.3 mm O.D. which is welded on the heater surface. The liquid mercury temperature distribution near the heater is measured by four stainless steel sheathed alumel–chromel thermocouples of 0.65 mm O.D. as shown in Fig. 3. Since the heater is fixed to the flange having eight holes for bolts, the temperature distribution along the periphery of the heater and that of liquid mercury surrounding the heater can be measured by rotating the flange every 45° angle. In this case, particular attention is paid to keep the same heating condition. Moreover, two sliding thermocouples (stainless steel sheathed alumel–chromel thermocouples of 0.25 mm O.D.) are utilized to measure the vertical temperature distributions of liquid mercury just above and below the heater.

The experiments are carried out in the following manner. Temperature of mercury is kept at about 25°C at the position of 25 mm just below the heater surface by circulating the cooling water along the mercury free surface under the atmospheric pressure. After the feed of cooling water is turned off, the heater surface temperature is measured under quasi-steady state at any settled heat input.

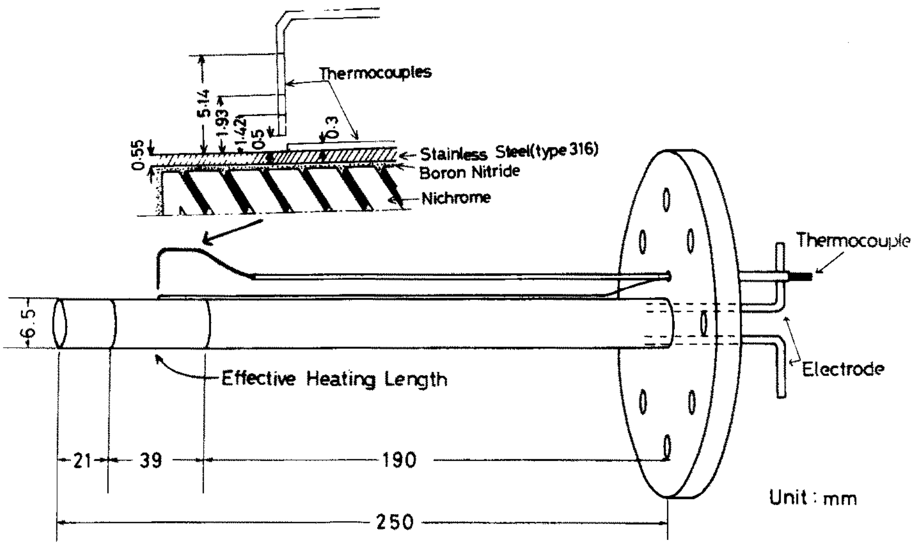

FIG. 3. Test heater.

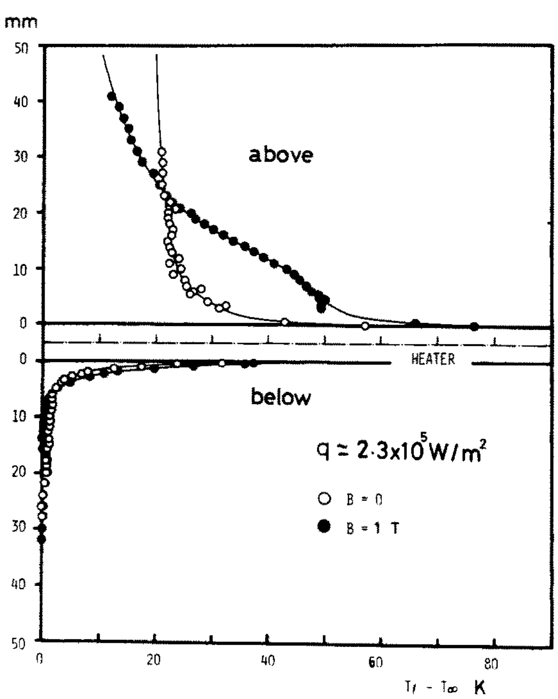

FIG. 4(a). Vertical distribution of liquid mercury temperature near the heater surface ($B \perp g$).

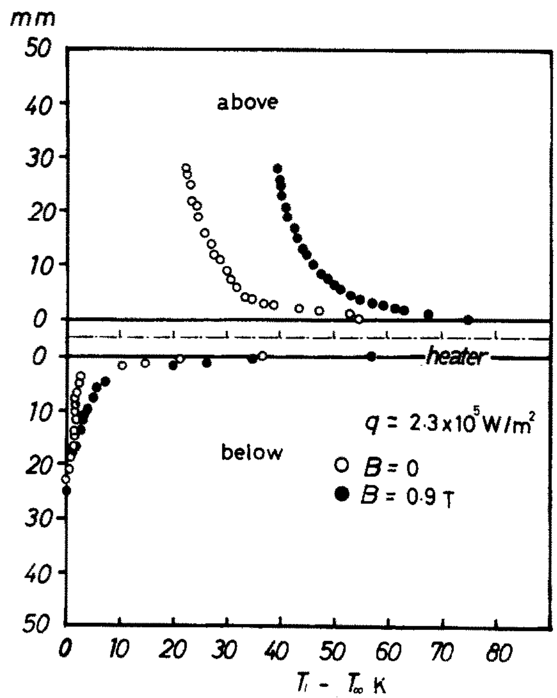

FIG. 4(b). Vertical distribution of liquid mercury temperature near the heater surface ($B \parallel g$).

In the case of $B \perp g$ (Fig. 2), the mercury tank is 45 × 340 mm inner cross section and 350 mm high. Depth of mercury is 280 mm and the level of mercury is 150 mm just above the center of the heater. Diameter of magnetic pole-piece is 300 mm and the maximum intensity of magnetic field of 1.1 T can be obtained between the pole-piece gap of 55 mm wide. This is the electromagnet for NMR test use. Besides sheathed heater shown in Fig. 3, a type 304 stainless steel sheathed heater, of which outer diameter is 4.8 mm and effective heating length is 50 mm, is utilized to obtain the experimental data indicated in Fig. 10(a) alone.

In the case of $B \parallel g$ (Fig. 2), the mercury tank is 190 × 290 mm inner cross section and 125 mm high. Depth of mercury is 105 mm and the level of mercury is 60 mm just above the center of the heater. Dimension of magnetic pole-piece is 200 × 1000 mm and the maximum intensity of magnetic field of 0.9 T can be obtained between the pole-piece gap of 150 mm wide. This is the electromagnet for MHD power generation test use.

RESULTS AND DISCUSSION

Figures 4(a) ($B \perp g$) and 4(b) ($B \parallel g$) show the vertical distributions of liquid temperature T_l just above and below the heater surface which were obtained by using the sliding thermocouples mentioned before, at the surface heat flux of 2.3×10^5 W/m^2. In these figures T_∞ means the liquid temperature which is not affected by

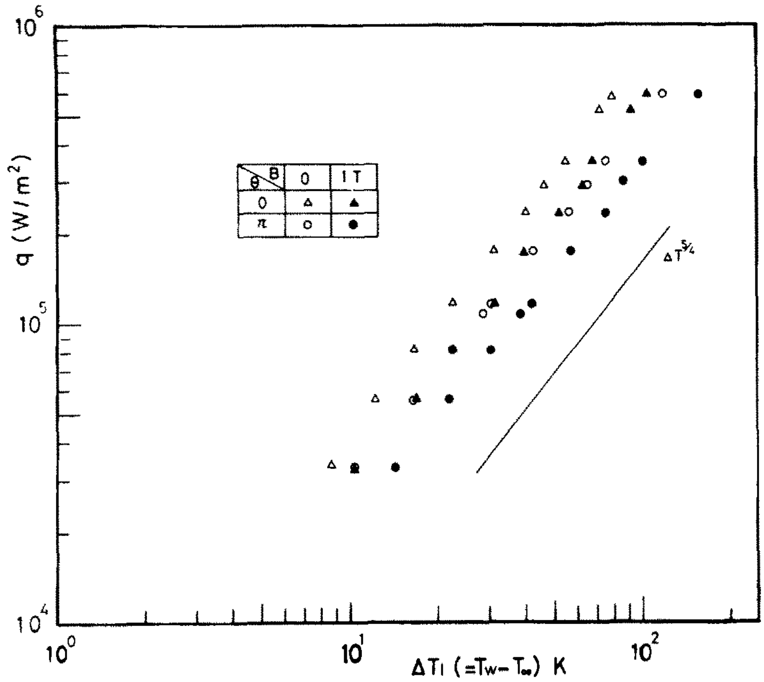

FIG. 5(a). Correlation of surface heat flux q with temperature difference $\Delta T_l (B \perp g)$.

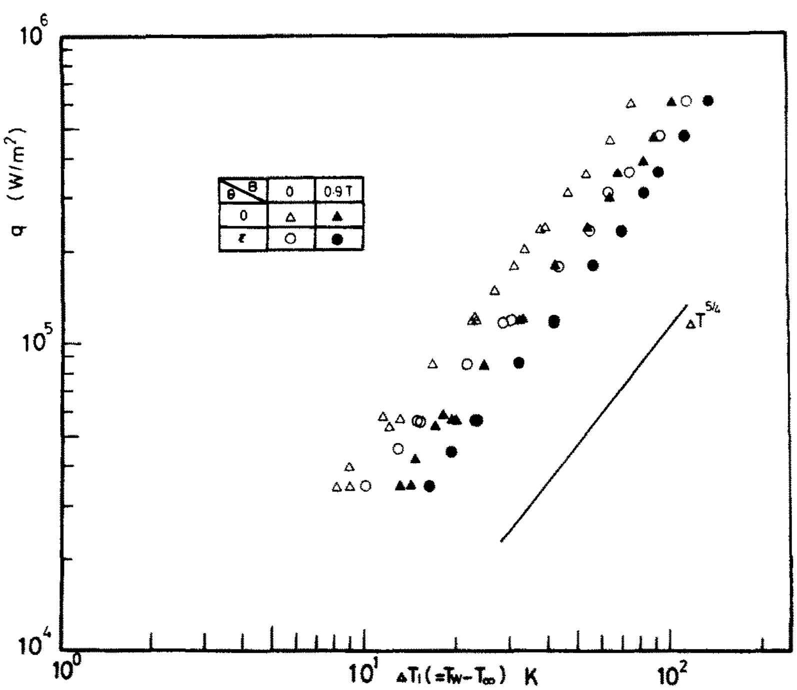

FIG. 5(b). Correlation of surface heat flux q with temperature difference $\Delta T_l (B \parallel g)$.

natural convection and is not varied vertically just below the heater surface and T_∞ is attainable at the position of about 20 mm below the heater surface. Therefore, the ambient temperature T_∞ of mercury is measured at the fixed position of 25 mm just below the heater surface throughout the present study.

In the case of both $B \perp g$ and $B \parallel g$, the liquid temperature near the heater surface as well as the surface temperature is higher than that in the case of $B = 0$. This is due to the suppression of natural convection flow by the Lorentz force. While the liquid flows along the periphery of heater under the magnetic field, its temperature rises much more than the case of $B = 0$.

The range of Grashof number is between 3×10^6 and 8×10^7 in this experiment, and hence the natural convection seems to be laminar (see [14]). Accordingly, the surface heat flux is proportional to $\Delta T_1^{5/4}$. This is supported by the present experimental data. From Figs. 5(a) and 5(b), it is expected that the magnetic field affects the inception of boiling, because the heater surface temperature under the magnetic field is higher than that observed in the case of $B = 0$ at the same heat flux and it passes faster the saturation temperature of liquid as the heat flux is increased.

Figure 6 ($B \parallel g$) shows the local heat-transfer coefficient α_θ against the surface heat flux q, where α_θ is

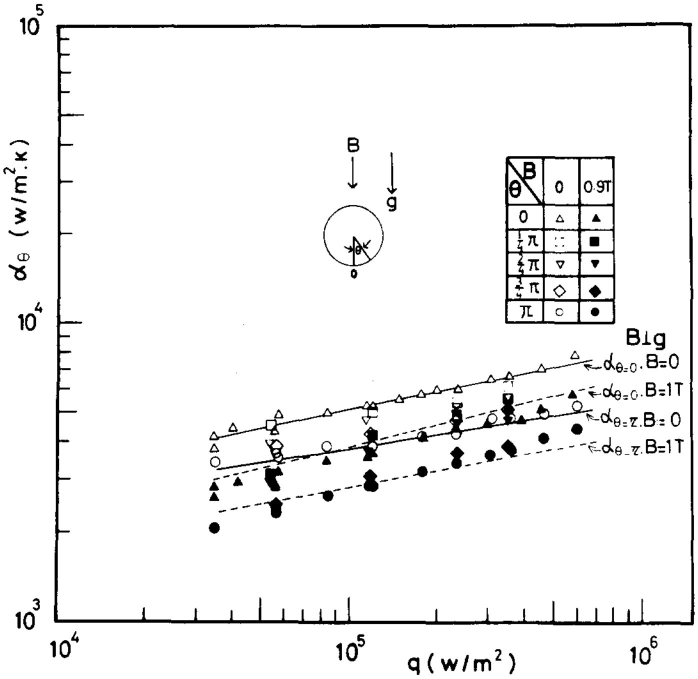

FIG. 6. Correlation of local heat-transfer coefficient α_θ with surface heat flux q ($B \parallel g$).

For $B \perp g$ (Fig. 4a), the upward vertical flow just above the heater surface is suppressed by the Lorentz force and hence the temperature of liquid is higher near the surface but is lower above the position of about 22 mm than that for $B = 0$. On the other hand, for $B \parallel g$ (Fig. 4b), the upward vertical flow is not affected by the Lorentz force, and the liquid temperature just above the heater surface becomes higher than that for $B = 0$ even at the position of 30 mm.

Relation between the surface heat flux q and the temperature difference $\Delta T_1 = T_w - T_\infty$ is shown in Figs. 5(a) ($B \perp g$) and 5(b) ($B \parallel g$), where T_w indicates the heater surface temperature at the two positions of $\theta = 0$ and $\theta = \pi$. The surface heat flux q is defined by the heat input into the heater divided by the heating surface area. Strictly speaking, the local heat flux varies along the periphery of the heater. However, since the temperature of the center of heater is so high and the heater surface temperature is low and not so much varied locally as will be seen in Figs. 8(a) and 8(b), it is not necessary to take into account the local heat flux.

defined as $q/\Delta T_1$ at any position of heater surface. In the case of $B = 0$, the experimental data indicate that $\alpha_{\theta=0} > \alpha_{\theta=\pi}$ at the fixed heat flux q. This tendency has been already analyzed by Hermann [15] for isothermal horizontal cylinder and Koh [16, 17] for nonisothermal horizontal cylinder. When the magnetic field is applied, the experimental data also show $\alpha_{\theta=0} > \alpha_{\theta=\pi}$. The solid lines and the broken lines indicate the data of $\alpha_{\theta=0}$ and $\alpha_{\theta=\pi}$ for $B = 0$ and $B = 1$ T, respectively, in the case of $B \perp g$. Regardless of the dimension of mercury tank and the depth of mercury, $\alpha_{\theta=0}$ and $\alpha_{\theta=\pi}$ of both cases are almost identical.

However, the variation of α_θ with θ is different in both cases as shown in Figs. 7(a) ($B \perp g$) and 7(b) ($B \parallel g$). These figures indicate $\alpha_\theta/\alpha_{\theta=0(B=0)}$. It is noticed that α_θ for $B = 0$ decreases with increasing θ and it becomes about 70% of $\alpha_{\theta=0}$ at $\theta = \pi$. The value of $\alpha_\theta/\alpha_{\theta=0}$ is inconsistent with Hermann's theory for $\theta > \pi/2$. It is also noticed that α_θ for $B \perp g$ ($B = 1$ T) is about 75–70% of α_θ for $B = 0$ at any θ, while α_θ for $B \parallel g$ at $\theta = \pi/4$ and $\pi/2$ is higher than that at $\theta = 0$.

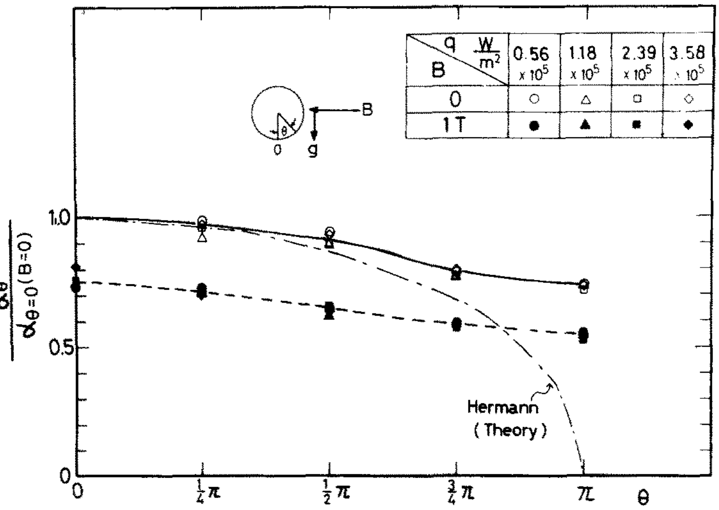

FIG. 7(a). Variation of local heat-transfer coefficient α_θ with θ ($B \perp g$).

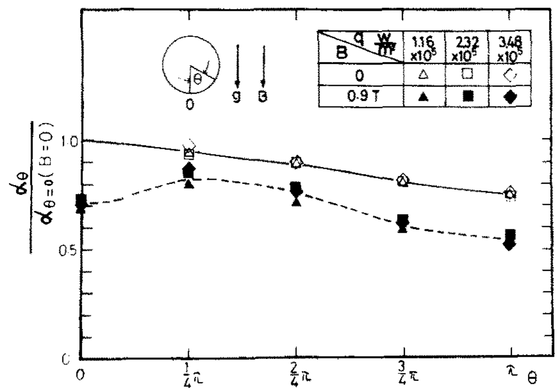

FIG. 7(b). Variation of local heat-transfer coefficient α_θ with θ ($B \parallel g$).

In this connection, we should refer to Figs. 8(a) ($B \perp g$) and 8(b) ($B \parallel g$) which illustrate the isothermal lines of liquid mercury around a horizontal heater and also the heater surface temperature shown within the center circle. It is clearly seen that the heater surface temperature is lowest at $\theta \simeq \pi/4$ in the case of $B \parallel g$. This tendency is different from the cases of $B = 0$ and $B \perp g$ where the surface temperature is lowest at $\theta = 0$. These results are caused by the complex flow of natural convection affected by the Lorentz force. From Figs. 8(a) and 8(b), it can be seen that, in general, the presence of magnetic field increases thermal boundary layer thickness as compared with the case of $B = 0$ at the fixed surface heat flux.

Local Nusselt number Nu at $\theta = 0$ and $\theta = \pi$ is shown against $Gr \cdot Pr^2$ in Figs. 9(a) ($B \perp g$) and 9(b) ($B \parallel g$), where the characteristic length of Nu and Gr is the outer diameter of heater and the physical properties of mercury corresponds to those at film temperature $[= (T_w + T_\infty)/2]$. In these figures, the empirical equation of average Nusselt number for $B = 0$ [18],

$$Nu = 0.53(Gr \cdot Pr^2)^{1/4}$$

is also shown for comparison. Although the empirical

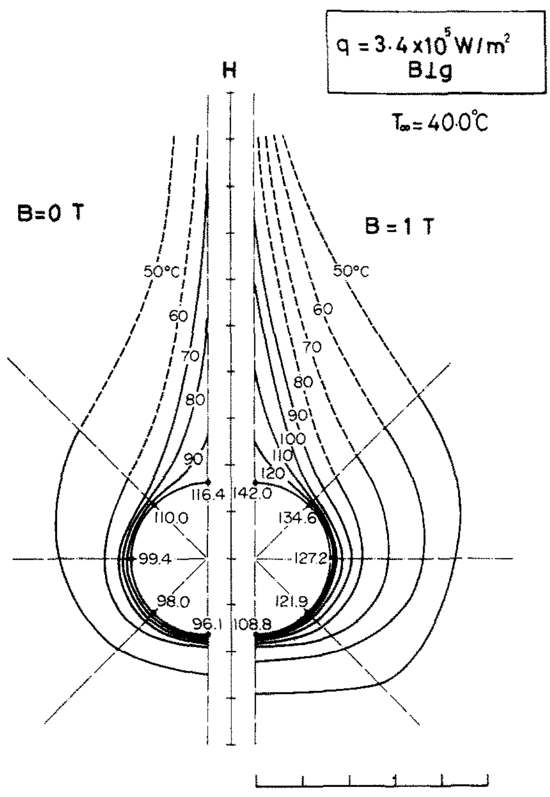

FIG. 8(a). Comparison of isotherms around a horizontal heater between the case of $B = 0$ (left) and $B \neq 0$ (right)—the heater surface temperature is shown within the center circle.

$B \perp g$, $q = 3.4 \times 10^5$ W/m², $T_\infty = 40.0$°C.

equation is concerned with the average Nusselt number, the present experimental data are a little below the equation. This might be due to which temperature of liquid was determined as the ambient temperature T_∞, as mentioned before.

In Figs. 10(a) ($B \perp g$) and 10(b) ($B \parallel g$), local Nusselt number Nu at $\theta = 0$ and $\theta = \pi$ is shown against

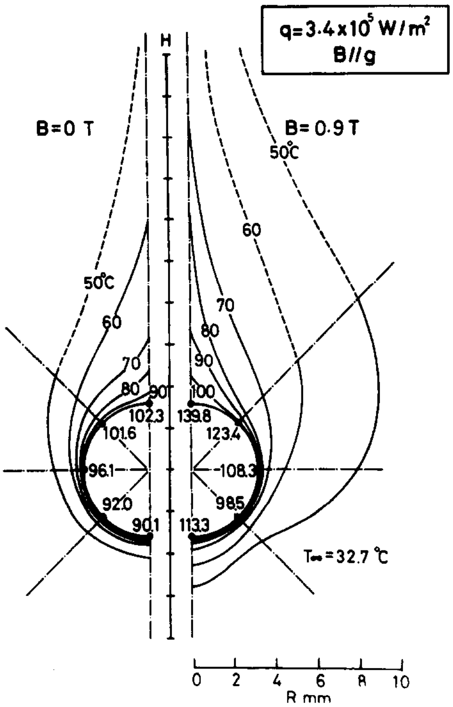

FIG. 8(b). Comparison of isotherms around a horizontal heater between the case of $B = 0$ (left) and $B \neq 0$ (right)—the heater surface temperature is shown within the center circle. $B \parallel g$, $q = 3.4 \times 10^5$ W/m^2, $T_\infty = 32.7$°C.

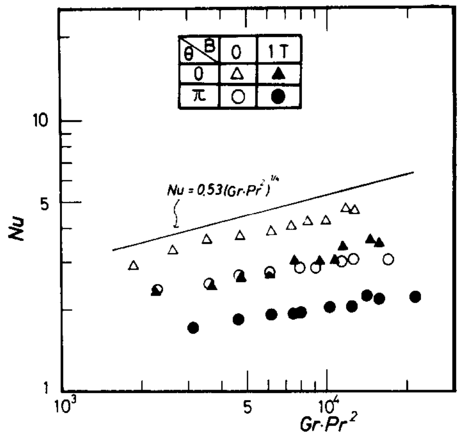

FIG. 9(a). Correlation of local Nusselt number Nu with $Gr \cdot Pr^2$ ($B \perp g$).

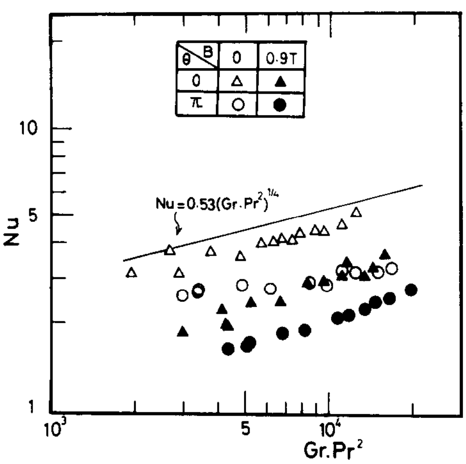

FIG. 9(b). Correlation of local Nusselt number Nu with $Gr \cdot Pr^2$ ($B \parallel g$).

Hartmann number M, where the characteristic length of M is the outer diameter of heater. The decrease of Nu is gradually leveling off at high Hartmann numbers. This tendency is the same as Sun's theory [4] for the vertical plane surface under the magnetic field of $B \perp g$.

Figure 11 shows a change in temperature after turning off the magnetic field of which intensity was 0.9 T and direction was parallel to the direction of gravity. The surface heat flux remains constant, 3.4×10^5 W/m^2. The magnetic field intensity becomes zero after about 6 s. The heater surface temperature at $\theta = 0$ and $\theta = \pi$ begins to decrease after about 2 s and the liquid temperature at the position of 10 mm just above the heater

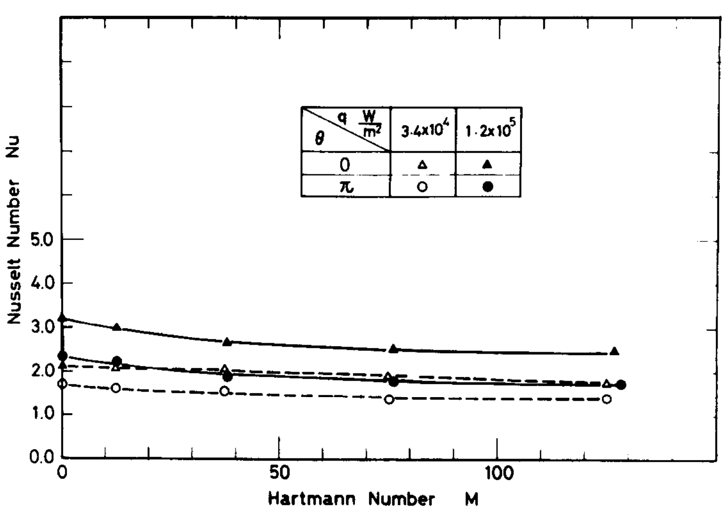

FIG. 10(a). Correlation of local Nusselt number Nu with Hartmann number M ($B \perp g$).

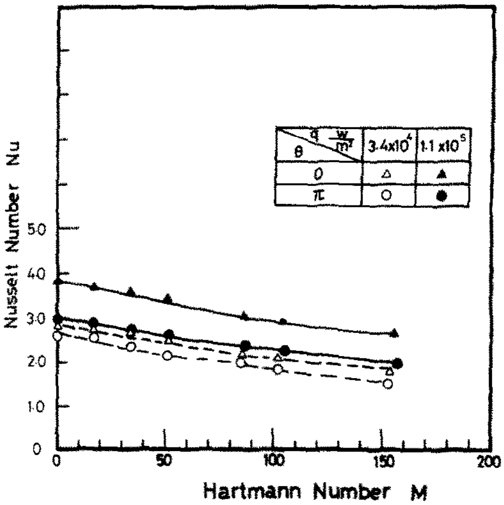

FIG. 10(b). Correlation of local Nusselt number Nu with Hartmann number M ($B \parallel g$).

applied magnetic fields of $B \perp g$ and $B \parallel g$ by virtue of the action of Lorentz force. The local Nusselt number decreases with increasing the Hartmann number, but the reduction is gradually leveling off at high Hartmann numbers.

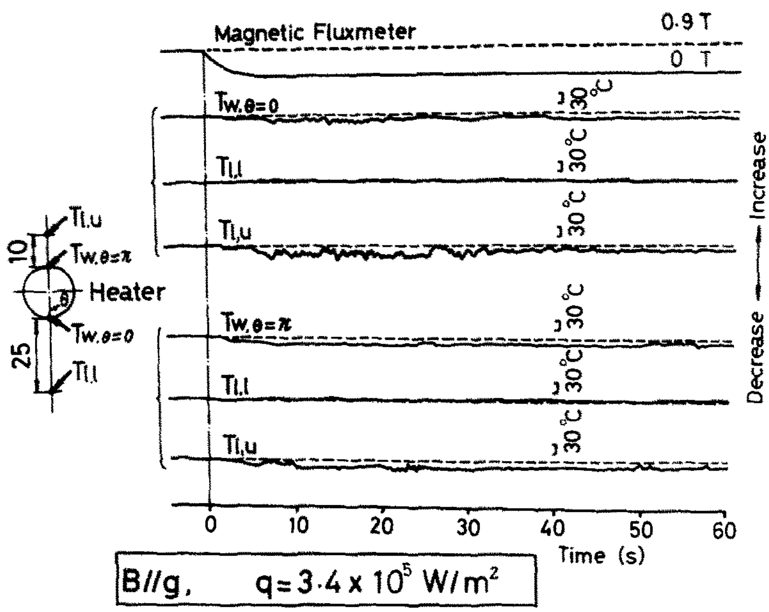

FIG. 11. Temperature traces after a sudden decrease in magnetic field strength.

surface also begins to decrease, but the liquid temperature at the position of 25 mm just below the heater surface begins to increase a little. These results indicate that the suppressed natural convection flow becomes free after turning off the magnetic field.

CONCLUSIONS

Natural convection heat transfer was experimentally studied on a horizontal cylindrical heater immersed in mercury pool under the two applied magnetic fields of $B \perp g$ and $B \parallel g$. The presence of both magnetic fields causes increase in heater surface temperature and liquid temperature surrounding the heater and also increase in thermal boundary-layer thickness, at the fixed surface heat flux. From these results, it is expected that the magnetic field affects the inception of boiling. Variations of local heat-transfer coefficient along the periphery of the heater are different under the two

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TRANSFERT DE CHALEUR PAR CONVECTION NATURELLE AUTOUR D'UN CYLINDRE HORIZONTAL PLONGE DANS DU MERCURE SOUMIS A UN CHAMP MAGNETIQUE

Résumé—L'article présente une étude expérimentale du transfert de chaleur par convection naturelle autour d'un cylindre horizontal chauffé, plongé dans du mercure et soumis à deux champs magnétiques appliqués perpendiculairement et parallèlement au champ de gravité. La présence des deux champs magnétiques provoque une augmentation de la température de surface du cylindre chauffant et de celle du fluide environnant, ainsi qu'un épaississement de la couche limite thermique, à flux pariétal constant. Ces résultats laissent penser que le champ magnétique doit affecter la naissance de l'ébullition. Sont également discutées les variations du coefficient local de transfert thermique sur la périphérie.

DER WÄRMEÜBERGANG BEI NATÜRLICHER KONVEKTION VON EINEM HORIZONTALEN ZYLINDER AN QUECKSILBER UNTER EINWIRKUNG VON MAGNETFELDERN

Zusammenfassung—Es werden Versuchsergebnisse angegeben für den Wärmeübergang bei freier Konvektion von einem in ein Quecksilberbad eingetauchten horizontalen, zylindrischen Heizkörper unter Einwirkung von zwei Magnetfeldern, deren Feldlinien senkrecht bzw. parallel zur Schwerkraftsrichtung verlaufen. Die Anwesenheit von zwei Magnetfeldern verursacht eine Zunahme der Temperatur der Heizfläche und der sie umgebenden Flüssigkeit sowie eine Zunahme der Dicke der Temperaturgrenzschicht bei konstanter Wärmestromdichte. Aus den Ergebnissen kann geschlossen werden, daß das Magnetfeld den Beginn der Blasenbildung beeinflußt. Die Veränderung des örtlichen Wärmeübergangskoeffizienten über den Umfang des Heizrohres wird ebenfalls diskutiert.

СВОБОДНО-КОНВЕКТИВНЫЙ ПЕРЕНОС ТЕПЛА ОТ ГОРИЗОНТАЛЬНОГО ЦИЛИНДРА К РТУТИ В МАГНИТНОМ ПОЛЕ

Аннотация — В статье приводятся экспериментальные данные по теплообмену при естественной конвекции от горизонтального цилиндрического нагревателя, погруженного в ванну с ртутью при воздействии двух магнитных полей, одно из которых расположено перпендикулярно, а другое параллельно направлению силу тяжести. Оба магнитных поля повышают температуру поверхности нагревателя и температуру окружающей его жидкости, а также увеличивают толщину пограничного слоя при фиксированном тепловом потоке на поверхности. По полученным результатам можно предположить, что магнитное поле влияет на начало кипения. Кроме того, обсуждается изменение локального коэффициента теплообмена на внешней стороне нагревателя.