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Natural heat transfer in a mercury bath and the effect of introduced partitions

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Abstract—The heat transfer in a half cylindrical bath filled with mercury and heated from above is investigated experimentally. Partitions were introduced into the bath in order to weaken the natural convection effect. Six different cases were considered: no partitions, 2, 6, 10, 16 and 44 partitions. The temperature field of each case and its heating power were measured. The change from a dominant natural convection regime, for the case of no partitions, to conduction, for the case of 44 partitions, was clearly noted. This last case fitted to the numerical solution obtained from the calculation that considered conduction only. A plot of Nusselt number as a function of the mean distance between the partitions has been derived.

INTRODUCTION

HEATING the upper surface of a liquid in a container, the bottom of which is cooled, causes heat transfer by conduction only. When the container walls are also cooled, the hot liquid near the cold walls becomes cooler and more dense, and sinks. A circulatory motion thus arises which is typical of natural heat transfer in a liquid within a closed container.

Such a geometry is interesting when local heating is used, such as arc melting of metals.

Few studies have been published on the natural heat transfer of liquid metals in enclosures heated from above. The closest geometry to the one employed in the present study was discussed by Tenchine [1], who investigated the case of a rectangular enclosure heated from above and cooled on its sides. However, as was noted by Stewart and Weinberg [2], natural heat transfer depends strongly on the geometry, and quantitative results for one geometry cannot be derived from another.

Heat transfer within enclosures containing partitions or baffles has been addressed in only a few investigations. Most of the studies dealt with the heat transfer in a rectangular enclosure, with a temperature gradient between its side walls. The fluid was usually air [3–5], water [6, 7] or liquids having large Prandtl numbers [8, 9].

In the present study, experiments are described in which a half cylindrical bath filled with mercury ($Pr = 0.02$), was heated with a heating element from above (see Fig. 1). Partitions were introduced into the bath and the reduction in the heat transfer was studied for five different configurations.

THEORETICAL CONSIDERATIONS

The cylindrical bath used for both calculations and experiments is shown schematically in Fig. 1.

A crude estimate of the distance between partitions which is required to stop heat convection can be derived as follows. According to Holman [10] and Gilly *et al.* [11], the heat transfer in a closed rectangular cavity, heated on one side and cooled on the other, is mainly conductive as long as $Ra < 10^3$. Considering $Ra = 10^3$ as a criterion for the onset of significant convection, we calculate

$$Ra = Gr\,Pr = \frac{X^3 g\beta\Delta T\,Pr}{\nu^2}.$$

Hence

$$X^3 = \frac{6\times10^{-7}}{\Delta T}$$

where ΔT is the temperature difference between neighbouring partitions. We assume as an approximation a linear distribution of the temperature between the heating element and the side wall. Then $\Delta T = 110X/5.5$ (for an overall ΔT^* of 110°C), yielding $X = 0.42$ cm.

EXPERIMENTAL

The experiment was conducted in a water-cooled stainless steel semi-cylindrical bath containing mercury. An overall view of the setup is given in Fig. 2. The heat source was a heating element along the cylinder axis.

The bath was a 10 cm long half cylinder with an inner radius of 5.5 cm. Cooling water flowed between double walls. The flow rate of the cooling water was sufficient to permit its temperature to be considered constant. The heating element was a 9.4 mm diameter 'Bent firerod cartridge' manufactured by Watlow (St. Louis, Missouri). It was positioned along the axis of the cylinder, 3 mm below the mercury surface. The heating element had a thermocouple in its centre to

NOMENCLATURE

- A mean area, 7.96×10^{-3} m^2
- g acceleration of gravity
- Gr Grashof number
- k heat conductance of mercury
- Pr Prandtl number
- Q power of the heating element
- Ra Rayleigh number
- T_C temperature of the cooling water
- T_H hottest temperature measured in the mercury
- ΔT temperature difference
- X distance from the hot side to the cold side
- X_b distance from the heating element to the side wall.

Greek symbols

- β volumetric expansion coefficient
- ν kinematic viscosity.

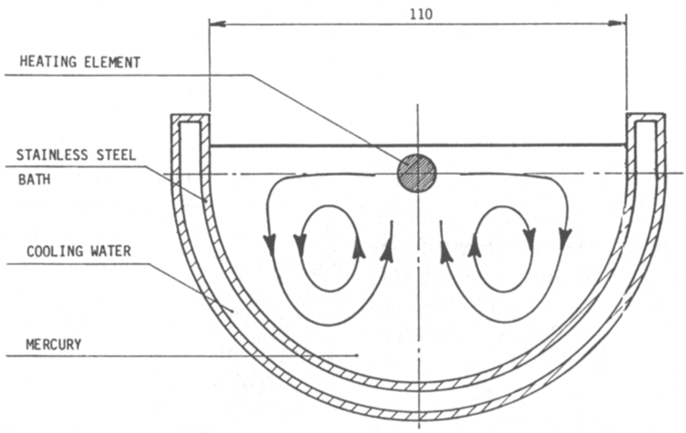


FIG. 1. Schematic cross-section of the bath. The arrows indicate the direction of convection.

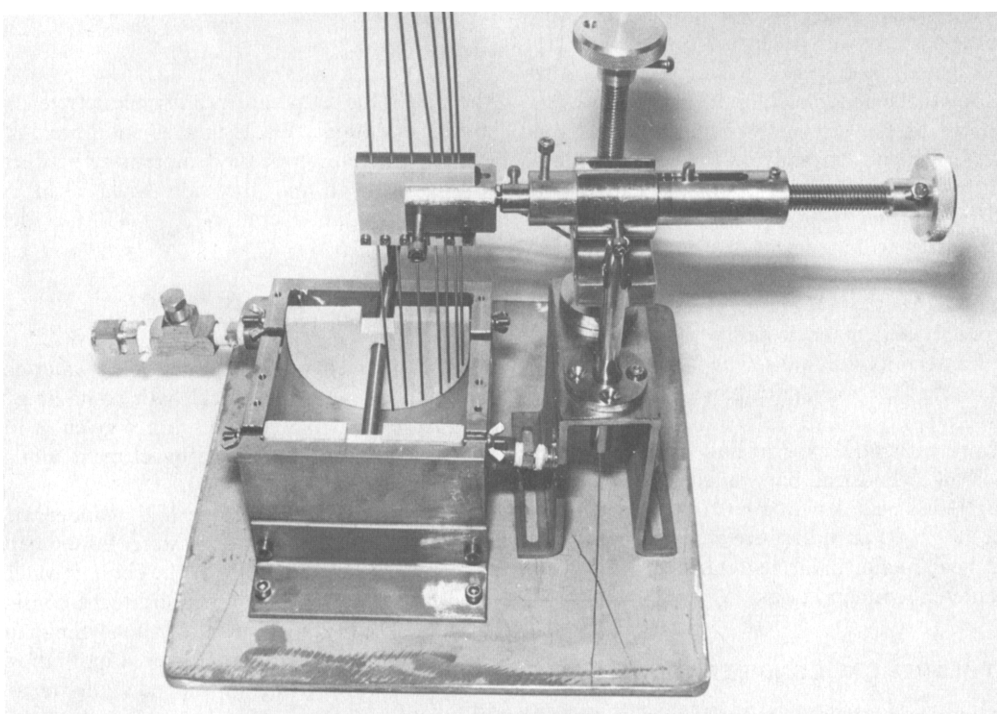


FIG. 2. The experimental setup.

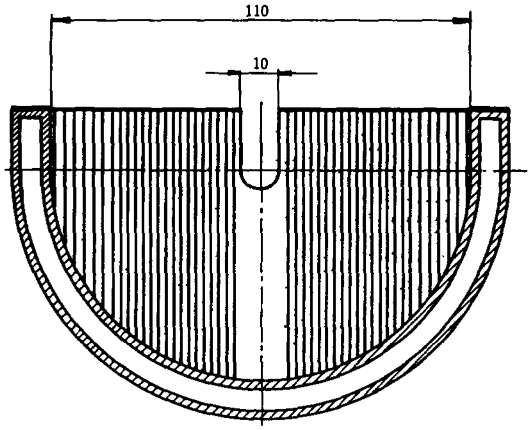


FIG. 3. Cross-section of the bath with the partitions in place.

enable stabilization of its temperature using a suitable controller. Machinable ceramic insulators were placed on each side of the bath, restricting heat transfer to the radial direction. The effective length of the bath was 76 mm. The temperature field inside the mercury was measured using seven chromel–alumel thermocouples, 0.8 mm thick, held together in a comblike catch. A two axes moving apparatus enabled accurate lowering and raising of the thermocouples.

To stop convection 0.2 mm thick tantalum partitions were used. They were positioned parallel to the bath axis (see Fig. 3), in order to cut the flow of the mercury. Stainless steel walls were placed on both ends of the cylinder (on the inner side of the insulators). These walls had slots to hold the partitions in place while permitting removal of any partition. The bath, with the partitions in place, was covered with a stainless steel cover with a slot for inserting the thermocouples.

In order to avoid mercury poisoning of the operator, the whole setup was enclosed in a plastic box placed in a fume chamber. The box was filled with argon to avoid oxidation of the mercury.

MEASURING PROCEDURE

After inserting the partitions in place, the bath was covered and the thermocouples were lowered to the lowest position. The box was then flushed with argon to complete five changes of the gas. The argon flow was then stopped and the power to the controller was turned on. The temperature measurements were taken 30 min later, which was more than twice the time needed to attain a steady state. The temperature was measured in steps of 5 mm, in the vertical direction. Six different cases were considered: no partitions, 2, 6, 10, 16 and 44 partitions. The power of the heating element was also recorded.

RESULTS AND DISCUSSION

The results of the temperature measurements for the different cases are shown in Figs. 4(a)–(f). A linear distribution of temperatures was used to draw isotherms of 10°C intervals. In Table 1 the parameters of each case are given. In Fig. 5(a) the isotherms are stratified with a large temperature gradient in the upper layer, as expected when natural heat transfer is dominant. As the partitions are introduced into the bath (Figs. 4(b)–(f)), the isotherms become gradually concave until they are almost radial in the last case, an indication that convection has been stopped altogether (except in the heating element region which had no partitions).

To assess the results we have calculated the Nusselt number (Nu) for each case. We define Nu as

$$Nu = \frac{hX_b}{k}$$

where

$$h = \frac{Q}{A(T_H - T_C)}.$$

The plot of the calculated Nu as a function of the mean distance between the partitions is given in Fig. 5. The line was fitted to the experimental points using the mean least squares. The correlation coefficient of the line has been calculated to be 0.99, which is a good fit.

A numerical analysis of pure heat conduction in mercury in the same bath was carried out using the finite element technique. The calculation was carried out in a two-dimensional plane. The usual numerical analysis of heat conduction in solids was used. The baffles were not included in this calculation. But since the mercury was stationary and the baffles occupied only 6% of the bath's volume, their influence was minor. The isotherms plotted by computer, together with the element mesh, are given in Fig. 6. The power calculated to get the same temperature difference

Table 1. Parameters of the cases measured and the calculated Nu

Case No.	No. of partitions	Dp (cm)	T_H (°C)	T_C (°C)	Heating power (W)	Nu
1	0	5.0	113	9	555	3.56
2	2	2.5	113	9	415	2.66
3	6	1.3	115	11	289	1.85
4	10	1.0	117	12	284	1.81
5	16	0.6	116	9	230	1.43
6	44	0.2	113	10	197	1.28

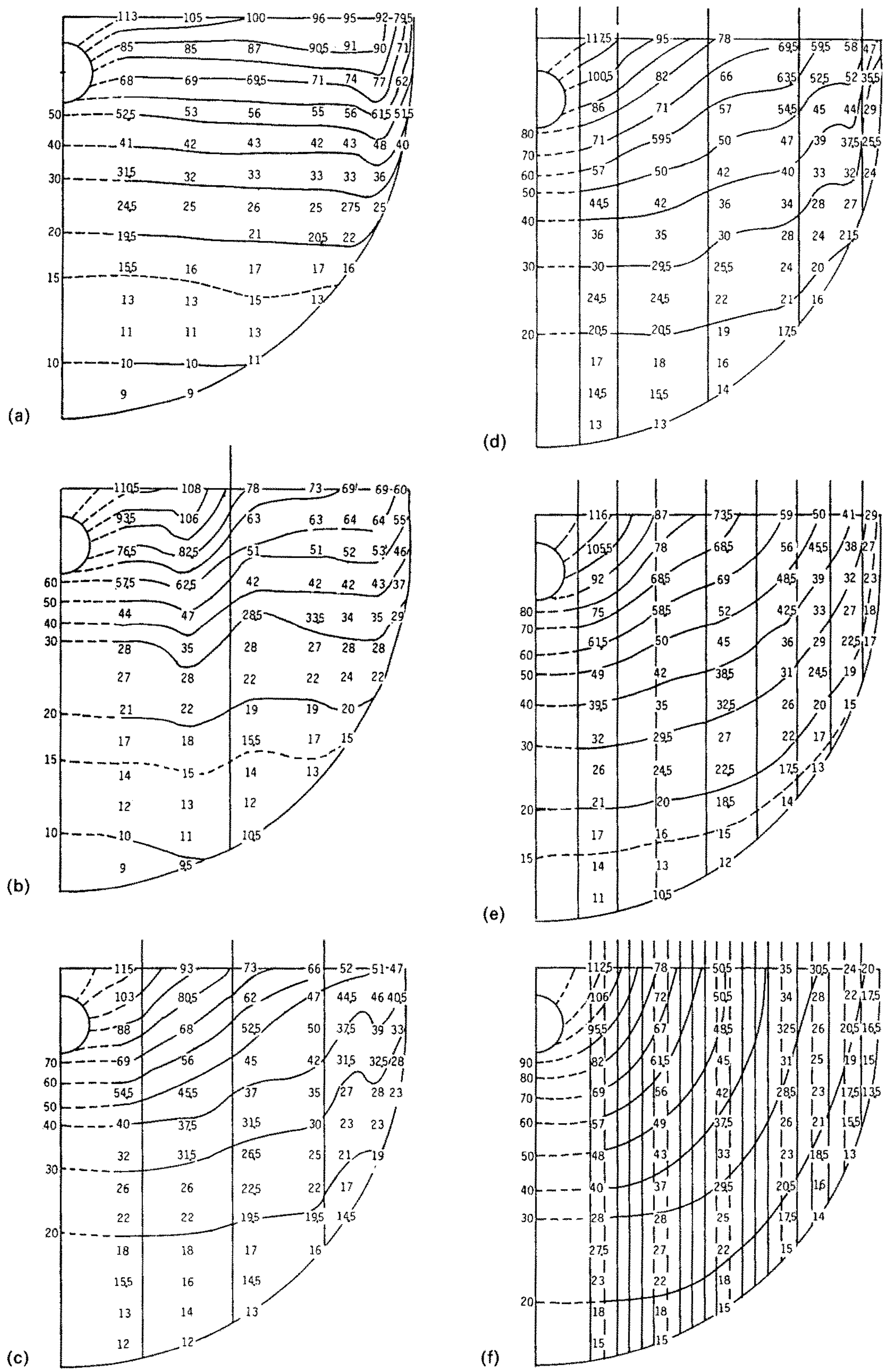


FIG. 4. The temperature profiles measured (only half of the bath is shown): (a) case 1, no partitions; (b) case 2, 2 partitions; (c) case 3, 6 partitions; (d) case 4, 10 partitions; (e) case 5, 16 partitions; (f) case 6, 44 partitions.

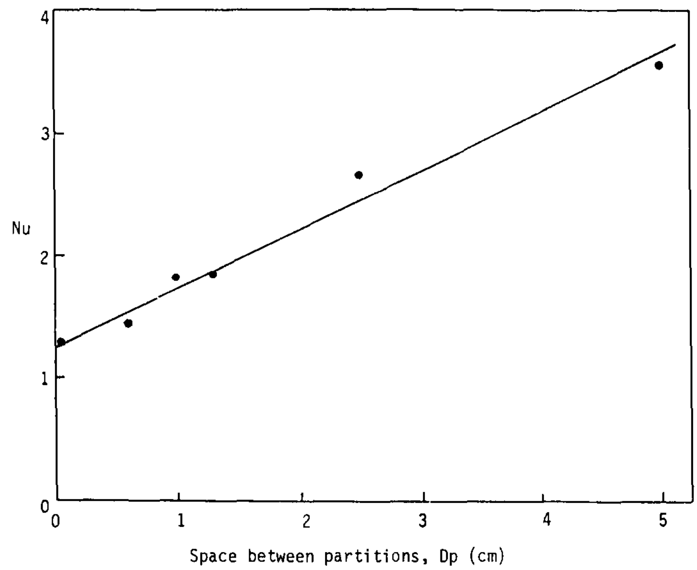
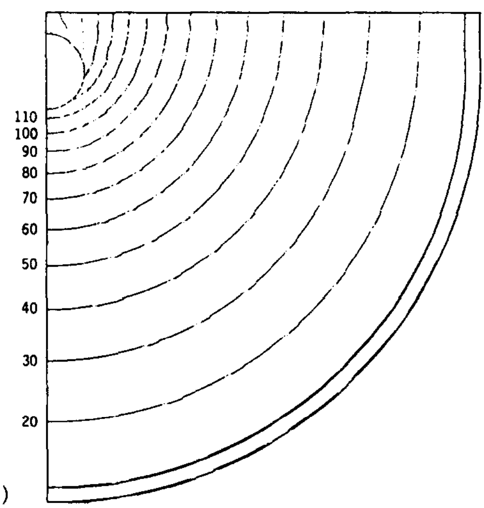
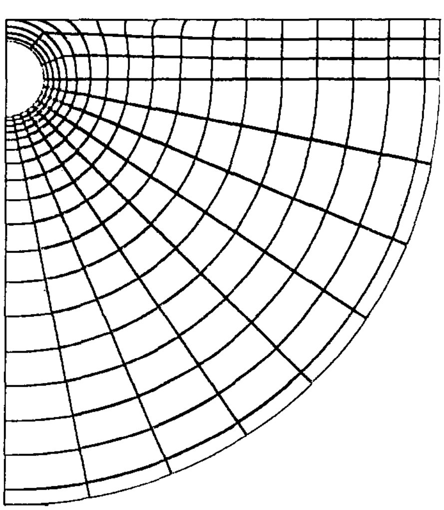


FIG. 5. Plot of Nu calculated as a function of the distance between partitions.



(a)



(b)

FIG. 6. (a) The temperature profile for pure heat conduction, plotted by computer. (b) The element mesh used.

$(T_H - T_C)$ was 167 W, which is in good agreement with the power of 183 W, derived from Fig. 5 for $Nu = 1.19$ $(Dp = 0)$; the stainless steel side walls were taken into consideration. The temperature profile in Fig. 4(f) is close to the profile obtained by the numerical analysis. Hence dividing the bath into 2 mm wide cells, stopped the natural heat transfer almost entirely. In fact we conclude from Table 1 that there is little advantage in making the cells smaller than 6 mm, which requires only 16 partitions. This result agrees well with the estimate discussed above. Comparing Fig. 4(f) and Fig. 6 we note that there is a tendency for the isotherms to rise near the centre plane of the bath. This deviation and the difference in the power can be explained by the fact that no partitions were placed in the heating element region, allowing development of some convection there.

CONCLUSIONS

Although the heat conductance of a liquid metal is high and a bath 11 cm in diameter is small, the natural heat transfer in many cases is more significant than the conduction heat transfer. Heat convection can be stopped by dividing the bath into cells smaller than 0.5 cm. For a liquid metal with high thermal conductivity, the heat transferred is reduced by a factor of 3, in comparison with non-metallic liquids where a reduction by a factor of 10 or more can be realized.

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CONVECTION THERMIQUE NATURELLE DANS UN BAIN DE MERCURE ET EFFET DES PARTITIONS INTRODUITES

Résumé—Le transfert thermique dans un bain semi-cylindrique rempli de mercure et chauffé par le bas est étudié expérimentalement. Des partitions sont introduites dans le bain de façon à affaiblir la convection naturelle. Six cas différents sont considérés: pas de partition, 2, 6, 10, 16 et 44 partitions. On mesure dans chaque cas le champ de température et la puissance de chauffage. On note clairement le changement depuis le régime dominant de convection naturelle pour le cas sans partition, jusqu'à la conduction dans le cas des 44 partitions. Ce dernier cas est en accord avec la solution numérique obtenue en considérant la conduction suele. On en déduit une relation entre le nombre de Nusselt et la distance moyenne entre les partitions.

WÄRMEÜBERGANG IN EINEM QUECKSILBERBAD UND DIE AUSWIRKUNG VON EINGESETZTEN TRENNWÄNDEN

Zusammenfassung—Der Wärmeübergang in einem halbzylindrischen, mit Quecksilber gefüllten Bad, welches von oben beheizt wird, ist experimentell untersucht worden. In das Bad wurden Trennwände eingesetzt, um die natürliche Konvektion abzuschwächen. Sechs verschiedene Fälle wurden untersucht: keine Trennwände, 2, 6, 10, 16 und 44 Trennwände. Temperaturfeld und zugehörige Heizleistung wurden für jeden Fall gemessen. Der Übergang von überwiegend freier Konvektion im Fall ohne Trennwände zur Wärmeleitung im Fall der 44 Trennwände wurde deutlich registriert. Dieser letzte Fall paßte zur numerischen Lösung, die aus der Berechnung der reinen Wärmeleitung ermittelt wurde. Die Nusselt-Zahl wurde in Abhängigkeit vom Hauptabstand zwischen den Trennwänden aufgetragen.

СВОБОДНОКОНВЕКТИВНЫЙ ТЕПЛООБМЕН В РТУТНОЙ ВАННЕ С ПЕРЕГОРОДКАМИ

Аннотация—Экспериментально исследован теплообмен в нагреваемой сверху полуцилиндрической ртутной ванне. Для ослабления свободной конвекции в ванне установлены перегородки. Рассмотрены шесть случаев: перегородки отсутствуют, имеется 2, 6, 10, 16 и 44 перегородки. Во всех случаях измерены температурное поле и мощность, затрачиваемая на нагрев. Отмечается четкий переход от доминирующего режима естественной конвекции в случае без перегородок к режиму подачи тепла теплопроводностью при использовании 44 перегородок. Этому последнему случаю соответствует численное решение, полученное для режима теплообмена только теплопроводностью. Построена зависимость числа Нуссельта от среднего расстояния между перегородками.