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Natural convection measurements in a mercury-filled rectangular plenum

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Abstract—Experiments have been carried out using a rectangular plenum containing mercury, heated at the roof and one wall and cooled at the floor. The interaction between the internal stratification and the natural convection at the wall of the plenum has been measured for several different boundary conditions. Nusselt numbers at the plenum floor, when a uniform wall heat flux was applied, were found to be nearly 2; whereas a value of approximately 5 was observed for the uniform wall temperature case, indicating strong internal convection. The results confirm earlier water tests which showed strong unidimensional behaviour of the plenum temperature. Measured Nusselt numbers were found to agree well with predictions from a 1-D analysis.

1. INTRODUCTION

THE CURRENT U.K. design of a fast reactor, CDFR (commercial design fast reactor), is of the pool type, i.e. the main components such as the core, primary pumps and intermediate heat exchangers are situated in a large pool of liquid sodium coolant. It incorporates a novel feature, the intermediate plenum [1], which is an annular vessel containing sodium and is of rectangular cross-section (Fig. 1). The intermediate plenum separates the hot (540°C) sodium pool from the cold (370°C) pool of the reactor primary circuit. The hot pool is situated directly above the cold pool, separated by a pressure boundary; it is necessary to insulate the pressure boundary to prevent excessive thermal stressing in the steady state. The function of the intermediate plenum is to trap a stagnant layer of sodium between the two pools; if the sodium is stratified in an approximately uniform manner then adequate insulation is provided for the reactor structure in the steady state.

One situation which would prevent the intermediate plenum from achieving its optimum performance would be if there was a significant radial heat flux through the inner wall adjacent to the reactor core. This would produce natural convection flows inside the plenum, possibly disrupting the stratification. This paper describes model experiments to measure the interaction between the wall heat transfer and the stratification within the plenum, and to quantify the resulting deterioration in the insulation performance of the reactor component.

The main objective of the tests was to obtain steady-state heat transfer data, using mercury as a simulant fluid, to aid the development and validation of theoretical models and computer codes which will be used to predict the performance of the reactor intermediate plenum. Additionally, the qualitative features of the natural convection flows and heat transfer in the plenum, which were observed in previous water tests [1], have been confirmed in a low Prandtl number fluid.

2. MERCURY AS A SIMULANT FLUID

Mercury is a useful simulant fluid for natural convection flows in sodium, since the engineering complexity and costs are much less than for sodium. Mercury rigs can be operated at ambient temperatures, have the potential for velocity measurements using hot film anemometry, and can produce high Rayleigh and Grashof number conditions in small-scale models. The Prandtl number of mercury is typically 0.026 at ambient temperatures, compared with that of sodium of 0.0055 at 325°C.

It is well known that in natural convection the momentum and energy equations are inextricably linked; that is, the temperature field determines the velocity field and vice versa. Thus to model natural convection both the Grashof number, which appears in the momentum equation, and the Boussinesq number, which appears in the energy equation, must be similar. But the relationship between the two, $Bo = Gr\,Pr^2$, means that the Prandtl numbers must also be the same in the reactor and the model. Since there is no other fluid with the same Prandtl number as sodium, the implication at first sight is that only sodium experiments would be valid. However, this is not necessarily the case as an examination of their physical significance will show.

The Boussinesq number appears in the energy equation, and relates the relative transport of heat by natural convection and conduction, and therefore is a prime factor in determining the temperature field. This is particularly so for low Prandtl number fluids, where the penetration of the temperature field from a boundary wall is large. A consequence of this is that the velocity approaches the buoyancy velocity, $(g\gamma H\Delta T)^{1/2}$, and is independent of viscosity.

NOMENCLATURE

A	surface area [m^2]
c	fluid specific heat [$J\ kg^{-1}\ K^{-1}$]
g	acceleration due to gravity [$m\ s^{-2}$]
H	height of plenum vessel [m]
k	fluid thermal conductivity [$W\ m^{-1}\ K^{-1}$]
L	length of plenum vessel [m]
m	mass flow rate [$kg\ m^{-3}$]
q_w	vertical wall heat flux [$W\ m^{-2}$]
q	derived vertical wall heat flux, Q_F/A_w [$W\ m^{-2}$]
Q	heat transferred through floor [W]
Q_0	heat transferred by conduction alone [W]
T	temperature [K]
T^*	dimensionless temperature, $(T-T_c)/(T_H-T_c)$
ΔT	temperature difference [K]
x, y	coordinates, see Fig. A1 [m].

Greek symbols

α	fluid thermal diffusivity [$m^2\ s^{-1}$]
γ	coefficient of volumetric expansion [K^{-1}]
ν	kinematic viscosity [$m^2\ s^{-1}$].

Subscripts

F	floor
R	roof
w	vertical wall.

Superscripts

*	dimensionless quantity.

Dimensionless groups

Bo^*	modified Boussinesq number, $g\gamma qH^4/k\alpha^2$
Nu	Nusselt number, $Q/Q_0 = dT^*/dx^*$.

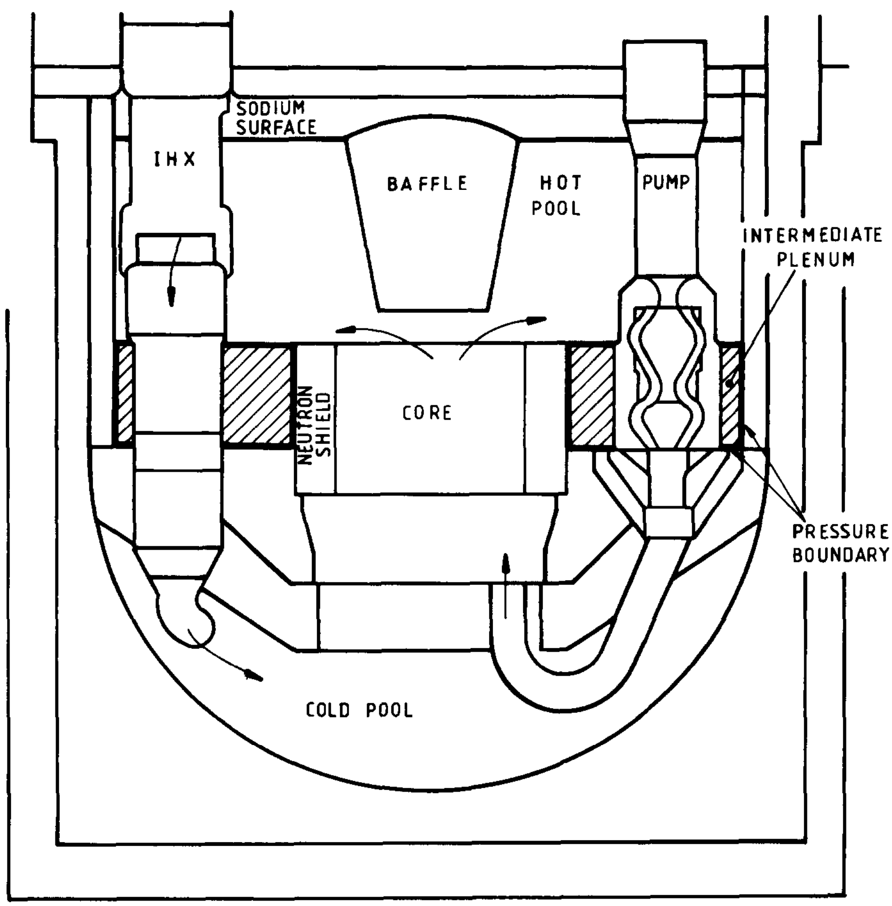

Fig. 1. Reactor arrangement.

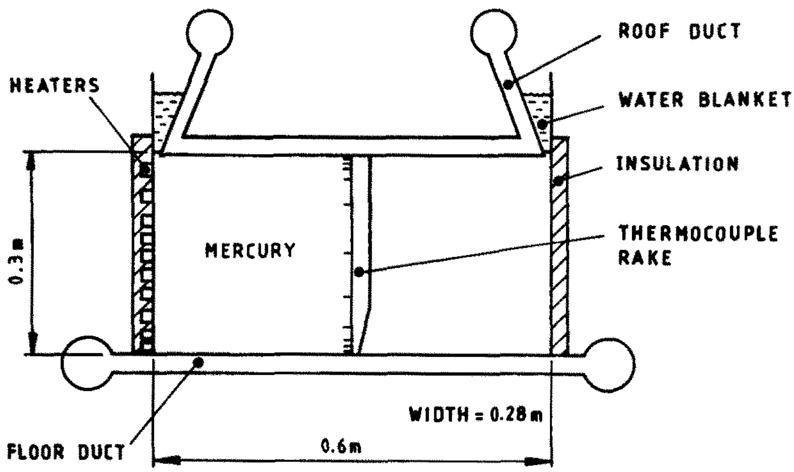

FIG. 2. Schematic section through the mercury rig.

Obtaining Boussinesq similarity, as is done in the mercury tests, with a fluid other than sodium implies that Grashof number similarity is not respected. The Grashof number indicates the relative strengths of gravitational and viscous forces in the flow. It is generally accepted as the group which determines the main changes in the flow structure, e.g. transition from laminar to turbulent flow. It is therefore possible that Grashof similarity need not be respected provided it is sufficient to obtain the correct flow regime. A simulant fluid which has a larger value of the important property parameter $(g\gamma/\nu^2)$ than sodium, such as mercury, is useful for attaining high values of the Grashof number in small-scale models, or with smaller temperature differences than the reactor case.

The turbulent contribution to heat transport is small compared with the molecular transport in liquid metals, except for highly turbulent forced flow conditions. It is not considered necessary to model this term in the energy equation for natural convection flow, and a sufficiently high Grashof number to ensure a turbulent flow distribution should suffice. The latter is important for the validation of the turbulent models used in the codes.

3. EXPERIMENTAL APPARATUS AND METHODS

The mercury test rig consists of a rectangular tank, which is a simplified 2-D representation of the CDFR intermediate plenum. The test-section has dimensions 0.6 m long × 0.28 m wide × 0.45 m high, with an operating depth of mercury of 0.3 m. The walls of the vessel are made from 6 mm stainless steel, and the horizontal boundaries are formed by water-carrying ducts; the roof duct is removable, with a 5 mm gap between it and the vessel walls. The rig is shown schematically in Fig. 2.

Heated water is pumped through the roof duct, and a water-glycol mixture through the floor duct, producing approximately isothermal boundary conditions to within 0.5°C. The normal operating temperatures are of the order of 50°C at the roof and 0°C at the floor. The hot roof represents the boundary in the CDFR between the intermediate plenum and the hot sodium pool, and the cooled floor the pressure boundary above the cold pool. It is possible to isolate the roof from the hot water system and insulate it sufficiently to produce an adiabatic roof boundary condition.

One of the smaller walls is fitted with ten individually controlled electrical heater elements, clamped to the outer surface of the wall. Both isothermal and uniform heat flux boundary conditions can be produced with this system. The heated wall represents the inner wall of the plenum annulus through which a radial heat flux would pass in the CDFR. The three remaining walls are insulated with polyurethane foam to provide approximately adiabatic conditions.

Temperatures within the rig are measured using 1 mm diameter stainless steel sheathed chromel/alumel thermocouples. Twenty-five of these are located in a moveable rake for measuring the mercury temperature distribution at different points, while others are embedded within the heated wall and the vessel floor. Thus both fluid and wall vertical temperature profiles can be recorded. The data is logged and analysed on a dedicated computer logger. The mercury free surface in the vessel around the edge of the roof is covered by a water blanket to prevent the emission of mercury vapour.

When operating the rig the roof temperature was set first and the rig allowed to reach thermal equilibrium, so that a linear temperature gradient was set up in the mercury; this gave a check on the instrumentation and thermal performance of the rig. The wall heating was then applied and the rig left for about 24 h. Once equilibrium had been reached, six sets of data were recorded over a 30 min period and these were averaged for analysis. Care was taken in the heated roof tests to ensure that a positive amount of heat was always being transferred from the roof to the mercury; this was necessary because it was possible for the flow through the roof to remove heat from the test section if the wall heating was too great, which would be an unrepresentative boundary condition. A heat balance for each test showed that losses and measurement errors amounted to less than 8% for all experiments.

An electronic three-term controller maintained the roof temperature at a value 60°C above that of the vessel floor during the heated roof tests. For the isothermal wall experiments the ten electrical heater strips which covered the wall were set individually; an initial estimate of the power distribution was applied to the rig, and the temperatures allowed to settle for 10 min. Using the signals from the thermocouples embedded in the heated wall the local surface temperature of the wall was calculated for each heater segment. The powers were then adjusted to bring the wall surface temperatures to within 0.5°C of that required in a series of iterative steps.

4. RESULTS AND DISCUSSION

Three sets of experiments were carried out using the mercury-filled plenum. The boundary conditions applied were as follows:

(a) uniform heat flux at the wall, together with a hot roof and cooled floor;

(b) uniform heat flux at the wall, with an adiabatic roof and a cooled floor;

(c) isothermal heated wall at the same temperature as the heated roof, with a cooled floor.

The Boussinesq number is an indication of the relative magnitudes of the convective and diffusive heat transfer in a given flow. For these experiments the height of the plenum and the wall heat flux were used in the evaluation of the modified Boussinesq number. For direct comparison of the results from the uniform flux and isothermal wall tests, the modified Boussinesq number was calculated for the isothermal wall case using the mean heat flux.

The Nusselt number is defined for the intermediate plenum as the ratio of the total heat transferred to the heat that would be transferred through the plenum by conduction alone, and is calculated from measurements of the local temperature gradient in the mercury

$$Nu_F = Q/Q_0 = \left(kA\frac{dT}{dy}\right)_F \Big/ (kA(T_R - T_F)/H)$$

$$Nu_F = \frac{H}{T_R - T_F}\left(\frac{dT}{dy}\right)_F = \left(\frac{dT^*}{dy^*}\right)_F$$

i.e. the Nusselt number is equal to the local normalized temperature gradient. (The asterisk indicates a dimensionless variable.) The local value of the thermal conductivity was used in the evaluation of the Nusselt number, and a mean value when calculating the Boussinesq number.

The results from all the mercury rig tests are summarized in Fig. 3. The uniform wall heat flux tests, in the case when the roof was heated also, gave Nusselt numbers in the range 1–2. As the wall heat flux was increased from values small compared with the vertical conduction heat load through the plenum ($Nu \sim 1$), the Nusselt number increased systematically until a point was reached when the wall temperature exceeded the plenum roof temperature, and the experiment became invalid ($Nu \sim 2$).

The adiabatic roof tests with uniform heat flux on the heated wall resulted in an almost constant value of the Nusselt number over the range of Boussinesq numbers examined. In these experiments the only heat entering the mercury came from the electrically-heated wall, which is finally transferred out through the vessel floor. With all other boundaries adiabatic, the only degree of freedom was the equilibrium temperature of the plenum roof, which determines the Nusselt number by definition. For this particular boundary condition a very simple analysis has been made on the basis of a boundary layer and a uniform downward drift velocity in the bulk fluid, with no heat exchange laterally between the two regions; a value of 2.0 for the Nusselt number was obtained, as shown in the Appendix. This is in remarkably good agreement with the experimental values.

As expected, the isothermal heated wall condition yielded the highest overall Nusselt numbers; the large temperature differences and high heat transfer coefficients at the base of the hot wall caused high heat fluxes in this region. Only a weak dependence of the Nusselt number on the modified Boussinesq number was observed, namely approximately $(Bo^*)^{0.14}$, which is a smaller exponent than in the usual natural convection correlations; this is a consequence of the only heat sink of the system being at the plenum floor, which does not favour an easy circulation path for the heated fluid passing through the boundary layer on the heated wall.

A more complex and detailed analysis has been successfully used to predict all three different boundary conditions in the mercury rig. This method combines a 1-D approximation to the energy equation for the bulk fluid with a laminar integral analysis of the heated wall boundary layer. This suggests that the stratification continues to dominate over the buoyancy-driven circulation, even at relatively high Boussinesq numbers, so that the isotherms remain approximately horizontal. This unidimensional temperature behaviour, having been seen in the earlier water tests, has now been confirmed in a liquid metal. Even so, a greater variation in the heat transfer across the plenum floor was detected. A systematic decrease in the Nusselt number of about 20% was measured from the heated to the adiabatic walls; no variation was detected normal to the long axis of the vessel.

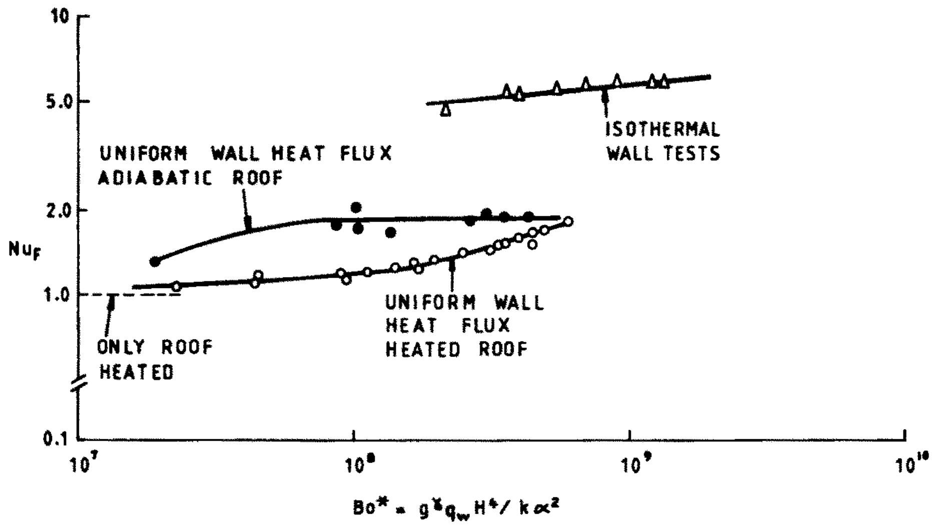

FIG. 3. Summary of mercury rig heat transfer results.

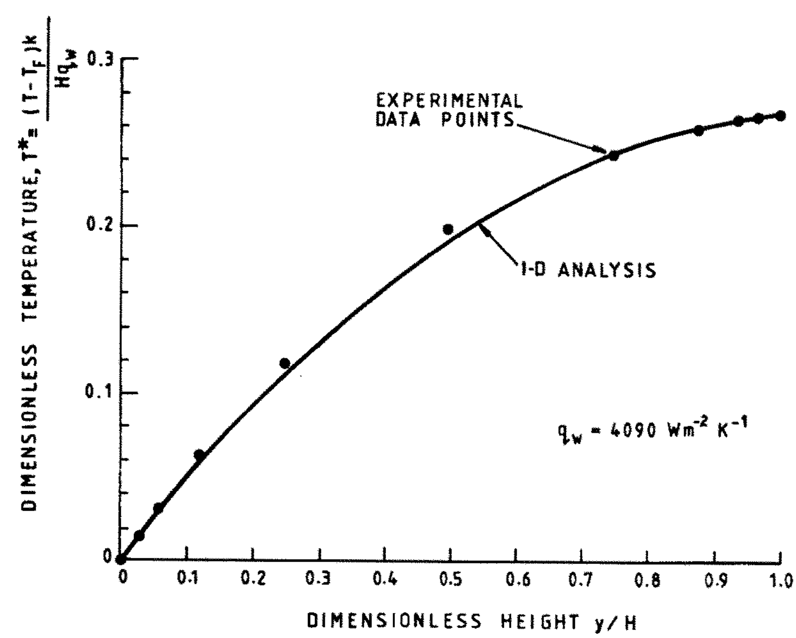

FIG. 4. Measured vertical temperature profile for adiabatic roof tests.

A typical vertical temperature profile through the mercury at the centre of the rig is shown in Fig. 4, together with the predictions of the 1-D analysis. The curvature of the profile, caused by the y-component of the convective circulation, is greatest near the plenum roof, where the bulk mass flow must balance the point of maximum flow in the wall boundary layer.

5. CONCLUSIONS

(1) With a uniform heat flux applied to the vertical wall, and with an adiabatic roof, the Nusselt number at the plenum floor of the mercury rig was ~2.0, indicating that natural convection was doubling the heat transfer rate from the fluid to the base plate compared with conduction alone. This is in contrast with the much higher values obtained with a uniform wall temperature.

(2) Nusselt numbers and vertical temperature profiles have been accurately predicted by the engineering analytical method currently used for design purposes.

(3) A simplified analysis (see Appendix) has been developed to bring out the physical significance of the plenum heat transfer processes to aid design optimization of the CDFR intermediate plenum.

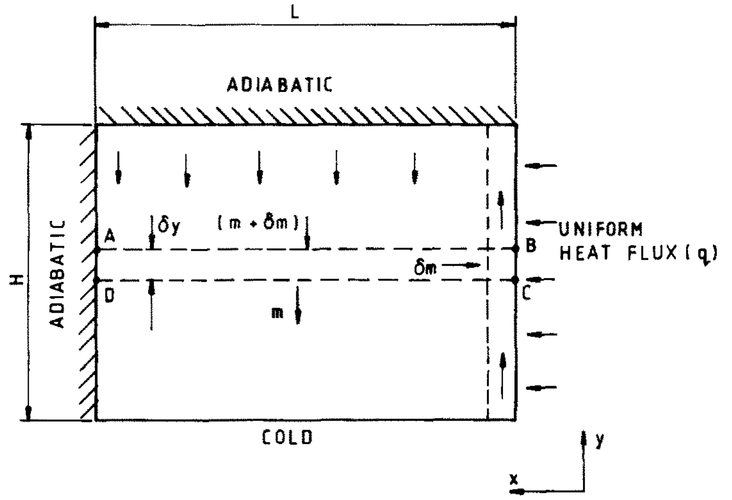

FIG. A1. Model used in the simplified analysis.

Acknowledgements—We are grateful to Mr J. Davidson, National Nuclear Corporation, U.K., for the 1-D analytical method by which the predictions of the mercury rig data were obtained.

REFERENCE

1. G. Kenworthy, G. L. Quarini, K. H. Winters, N. Sheriff and D. A. Booth, Study of natural convection phenomena in the LMFBR intermediate plenum. In *BNES Conference on Liquid Metal Engineering and Technology*, Oxford, U.K., Vol. 1, pp. 179–185 (April 1984).

APPENDIX

Analysis of plenum with uniform wall heat flux

From flow visualization in water tests, the flow pattern in the plenum can be simplified as illustrated in Fig. A1. A relatively thin boundary layer flow travels up the heated wall, with the balanced return flow spread across the plenum width. Apart from the cold floor of the plenum, all the other boundaries are assumed adiabatic.

The following assumptions have been made in the analysis:

(a) the temperature in the core is a function of the vertical coordinate, y, only;

(b) the vertical temperature gradient in the core region is locally the same as in the boundary layer region;

(c) the wall–fluid temperature difference is small compared to the overall plenum temperature difference;

(d) the boundary layer thickness is much smaller than the length of the plenum, L.

At each horizontal plane the mass flow rate in the boundary layer, $m(y)$, must be equal and opposite to the mean mass flow rate in the core. Taking the control volume ABCD (Fig. A1), of unit width in the z-direction, the development of the boundary layer flow involves a transport of fluid (δm) from the core to the boundary layer over the small height (δy). In formulating the heat balance equation it is necessary to allow for the small temperature excess (δT) in the boundary layer compared to the core, at any vertical height. The heat balance is given by

Heat in through AB and BC = Heat out through DC

$$q_w \delta y + kL\left(\frac{dT}{dy} + \frac{d^2T}{dy^2}\delta y\right) - (m+\delta m)\delta Tc = kL\frac{dT}{dy} - m\delta Tc \tag{A1}$$

$$q_w \delta y + kL\frac{d^2T}{dy^2}\delta y = \delta m \delta Tc$$

$$kL\frac{d^2T}{dy^2} = -q_w + \frac{\delta m \delta Tc}{\delta y}.$$

It seems reasonable to assume that for a liquid metal δT, the excess temperature in the boundary layer, will be small. As such it will be much smaller than the overall cavity temperature difference $(T_R - T_F)$, and the second term on the right-hand side can then be neglected compared to q. Equation (A1) thus reduces to

$$\frac{d^2T}{dy^2} = -\frac{q_w}{kL}. \tag{A2}$$

Using the following boundary conditions:

$$\frac{dT}{dy} = \frac{q_w H}{kL} \quad \text{at} \quad y = 0$$

and

$$T = T_R \quad \text{at} \quad y = H.$$

The solution of equation (A2) is

$$T = T_R - \frac{q_w}{2kL}(H^2 + y^2) + \frac{qH}{kL}y.$$

Noting that at $y = 0$, $T = T_F$

$$(T_R - T_F) = \frac{q_w}{kL}\frac{H^2}{2}.$$

Since

$$Nu = \frac{\text{Total heat removed}}{\text{Heat removed by conduction alone}}$$

$$= \frac{q_w H}{kL(T_R - T_F)/H}$$

$$= \frac{q_w H}{q_w H/2}$$

$$\therefore \underline{\underline{Nu = 2.0}}.$$

MESURE DE LA CONVECTION NATURELLE DANS UNE ENCEINTE RECTANGULAIRE EMPLIE DE MERCURE

Résumé—Des expériences ont été faites avec une enceinte contenant du mercure, chauffée au plafond et refroidie au plancher. L'interaction entre la stratification interne et la convection naturelle à la paroi de cette chambre a été mesurée pour différentes conditions aux limites. Les résultats confirment des essais antérieurs sur l'eau qui avaient montré un comportement fortement unidimensionnel de la température de la chambre. Les nombres de Nusselt mesurés s'accordent bien avec les prédictions d'une analyse unidimensionnelle.

MESSUNGEN BEI NATÜRLICHER KONVEKTION IN EINEM QUECKSILBERGEFÜLLTEN RECHTECKIGEN PLENUM

Zusammenfassung—Es wurden Experimente mit einem rechteckigen, quecksilbergefüllten Plenum durchgeführt, wobei die Oberseite und eine Wand beheizt, die Unterseite gekühlt wurden. Die Wechselwirkung zwischen der Schichtung im Inneren und der natürlichen Konvektion an der Wand des Plenums wurde bei verschiedenen Randbedingungen gemessen. Bei aufgeprägter Wärmestromdichte betrug die Nusselt-Zahl etwa 2, wohingegen ein Wert von etwa 5 bei isothermer Wand festgestellt wurde, was auf starke Konvektion im Inneren hinweist. Die Ergebnisse bestätigen frühere Versuche mit Wasser, welche eine streng eindimensionale Temperaturverteilung zeigten. Die gemessenen Nusselt-Zahlen stimmen gut mit den Berechnungen nach der 1-D-Analyse überein.

ИССЛЕДОВАНИЕ ЕСТЕСТВЕННОЙ КОНВЕКЦИИ В ПРЯМОУГОЛЬНОЙ ПОЛОСТИ, ЗАПОЛНЕННОЙ РТУТЬЮ

Аннотация—Проведены эксперименты в прямоугольной полости, заполненной ртутью, нагреваемой сверху и со стороны боковой стенки и охлаждаемой снизу. Влияние внутренней стратификации на естественную конвекцию в полости определено для различных граничных условий. Найдено, что числа Нуссельта на дне полости при нагреве стенки однородным тепловым потоком приблизительно равны 2, в то время как для случая однородной температуры это значение составляло примерно 5, что свидетельствует об интенсивной внутренней конвекции. Эти результаты подтверждают ранее проведенные эксперименты с водой, которые показали строго одномерный характер поля температуры в полости. Измеренные числа Нуссельта хорошо согласуются с расчетными, полученными из одномерного анализа.