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Magneto-fluid-mechanic pipe flow in a transverse magnetic field
Part 2. Heat transfer

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The present paper, part 2, consists of an experimental investigation of the influence of a transverse magnetic field on the heat transfer of a conducting fluid (mercury) flowing in an electrically insulated pipe subjected to a uniform heat flux at the wall. Mean temperature profiles and heat transfer data are presented which demonstrate that the magnetic field inhibits the convective mechanism of heat transfer through its damping of the turbulent velocity fluctuations.

1. Introduction

The convective mechanism of heat transfer plays an important role in the transport of thermal energy in a turbulent flow. Even for the case of liquid metals, it is the convective mechanism that is responsible for the heat transfer for Reynolds numbers above the 'slug flow' range. In the preceding paper (Gardner & Lykoudis 1971) the authors presented an experimental investigation of the influence of a transverse magnetic field on isothermal, turbulent, magneto-fluid-mechanic (MFM) pipe flow. It was shown that the magnetic field damps turbulent velocity fluctuations and imposes an angular dependence on the mean velocity and turbulence intensity profiles. A direct consequence of this damping of the turbulent fluctuations is the inhibition of the convective mechanism of heat transfer; this results in a decrease in heat flux or an increase in wall temperature depending on whether the boundary condition is constant temperature or constant heat flux.

For many years researchers have been studying the influence of magnetic fields on heat transfer in laminar flows from an analytical point of view. In general, laminar MFM forced convection heat transfer increases due to the Hartmann flattening of the velocity profile. (This is opposite the effect one expects for the case of turbulent MFM flow because the turbulent convective mechanism is absent.) Semi-empirical heat transfer analyses of turbulent MFM flows have been discouraged by the difficult nature of turbulence and the lack of experimental data.

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It is only in the past few years that some data have become available. Krasil'nikov (1965) and Gardner, Uherka & Lykoudis (1966) showed that transverse magnetic fields inhibit heat transfer in channel flows and Kovner, Krasil'nikov & Panevin (1966) showed a similar inhibition of heat transfer with an axial magnetic field. Blum (1967) also attempted experiments using an electrolyte as the fluid, but did not get a large interaction due to his fluid's relatively low electrical conductivity.

It is the purpose of this paper to present a more complete picture of the influence of a transverse magnetic field on local and average heat transfer for the flow of mercury through an electrically insulated circular pipe with a constant radial heat flux at the wall.

Reynolds number	10^4–10^6
Mean velocity	$\frac{1}{10}$–10 ft/sec
Entrance section	
Length	43·9 in.
Diameter	1·427 in.
L/d	31
Heat transfer test section	
Total length	79·0 in.
Heated length	76·8 in.
Diameter	1·431 in.
Heated L/d	53
Magnetic L/d	35
Temperature	75 °F

TABLE 1. Characteristic parameters

2. Experimental apparatus

The experimental MFM facility described by the authors in the preceding paper, part 1, was also used for the heat transfer experiments of the present paper. A set of general operating characteristics for the heat transfer investigation is given in table 1.

A heat transfer test section, shown in figure 1, was constructed in two units: an entrance section and a heated section. The entrance section was made from welded 316 stainless-steel tubing. Flanges were welded on both ends and the inside was then reamed and polished. The heated section was made from the same kind of pipe. After the flanges were welded to the ends, the inside of the pipe was reamed, polished, and then coated with 0·001 in. of FEP Teflon in order to insulate electrically the pipe from the flow. Except for a scratch line from the pipe weld (probably about 0·001 to 0·002 in. deep), the inside of the pipe was a smooth round surface.

Thirty-eight thermocouples were spot-welded to the exterior of the pipe in circular grooves at eight axial stations and four angles from the vertical magnetic field (0°, 30°, 60°, and 90°). A 0·050 in. layer of ceramic cement electrically insulated the pipe from the heating coil, a Nichrome V ribbon wound in the form of a helix. The thermocouple wires were led around the grooves and out through the open spaces between the windings. Then the assembly was wrapped with asbestos and fibreglass thermal insulation. Additional insulation was filled in the magnet's air gap when the heat transfer experiments were being conducted.

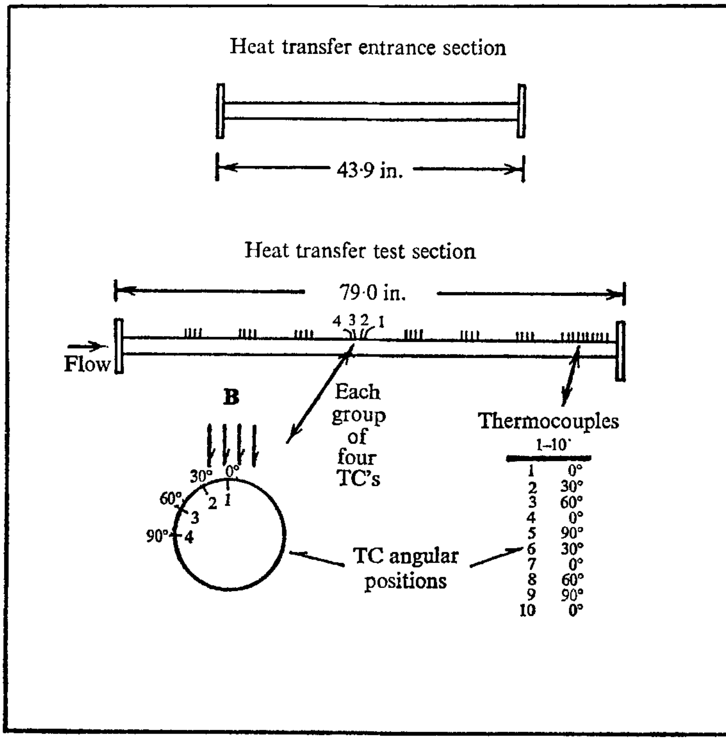

FIGURE 1. Entrance and heat transfer test sections.

(It was estimated from later experiments that about 94 % of the heat generated in the heating coil went into the mercury.) All thermocouples were connected to a selector switch which led to a common ice bath. A Vidar 520 integrating digital voltmeter was used for the acquisition of the thermocouple data.

A probe traversing mechanism was constructed at the exit of the test section in order to make mean temperature profile measurements.

Energy was supplied to the test section by a d.c. power supply capable of 0–50 amps and 0–500 volts with an additional control resistor for fine adjustment of the output.

A complete description of the MFM facility is given in the preceding paper.

3. Heat transfer measurements

Heat transfer measurements were made at four angles (0°, 30°, 60°, and 90°) from the vertical diameter in the upper half of the horizontal test section. The local Nusselt number which characterizes the local heat transfer as a function of the angular co-ordinate was determined from the relation

$$Nu(\theta) = hd/k = qd/k[T_w(\theta) - T_m], \tag{1}$$

where h, d, k, q, $T_w(\theta)$, and T_m are the heat transfer coefficient, pipe diameter, thermal conductivity, wall heat flux, inside wall temperature, and bulk mixing-cup temperature, respectively. T_m was calculated from the inlet and outlet mixing-cup temperatures and $T_w(\theta)$ was calculated by using the heat flux to extrapolate inward from the outside wall temperatures measured by the 38 thermocouples welded in the grooves. The zero-field Nusselt number results are compared to the data of other experiments in figure 2.

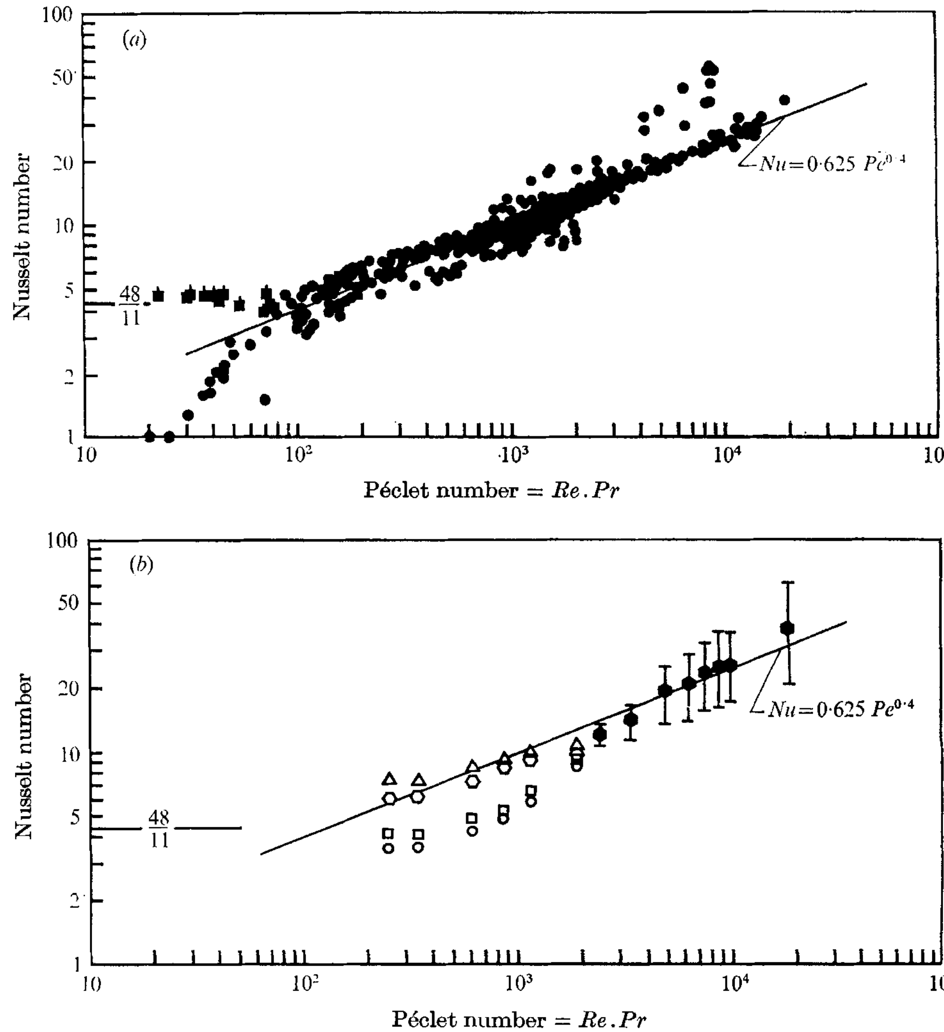

FIGURE 2. Zero-field heat transfer data. (*a*) ●, Lubarsky & Kaufman (1955); ▮, Emery & Bailey (1967). (*b*) Present work. Angle from top of pipe: △, 90°; ⬡, 60°; □, 30°; ○, 0°; ⬢, average, high *Pe* data; I, scatter, high *Pe* data.

The scatter of the zero-field data increases as the Péclet number increases because the heat flux was adjusted in such a way that the difference between the inlet and outlet mixing-cup temperatures was always about 10 °F. (The heat input varied from 400 watts to 16 000 watts over the range of Reynolds numbers investigated.) The increase in radial temperature gradient magnifies the uncertainty in the exact position of the thermocouples and probably caused much of the scatter in the data.

For low Péclet numbers, the Nusselt number data show an angular dependence due to the natural convection pattern that develops in the flow at low flow rates. The scatter in these data is no larger than the size of the individual data symbols. It should be noted that these low Péclet number data lie both above and below the laminar limit of 48/11.

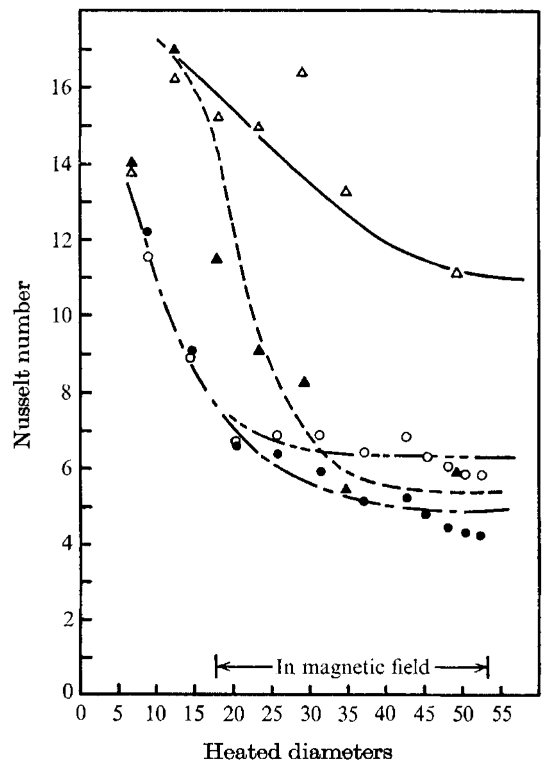

FIGURE 3. Entrance MFM heat transfer, $Re = 52\,600$. Angle and field: ○, 0°, 0 gauss; △, 90°, 0 gauss; ●, 0°, 3900 gauss; ▲, 90°, 3900 gauss.

Buhr, Carr & Balzhiser (1968) investigated the influence of natural convection on forced convection heat transfer and were able to correlate the available data with the parameter:†

$$Z = Ra(d/L)/Re, \tag{2}$$

where $Ra = Gr \times Pr$ = Rayleigh number, $Re = \rho U_m d/\mu$ = Reynolds number, $Gr = d^4\rho^2\beta g(dT/dx)/\mu^2$ = Grashof number, and U_m, L, dT/dx are the average velocity, heated length, and axial temperature gradient respectively. For $Z < 20 \times 10^{-4}$ they found that natural convection was not significant, and for

† The majority of the data used to make this correlation was from experiments in vertical test sections. In the present work the test section was horizontal, and the free convection, when present, is more pronounced.

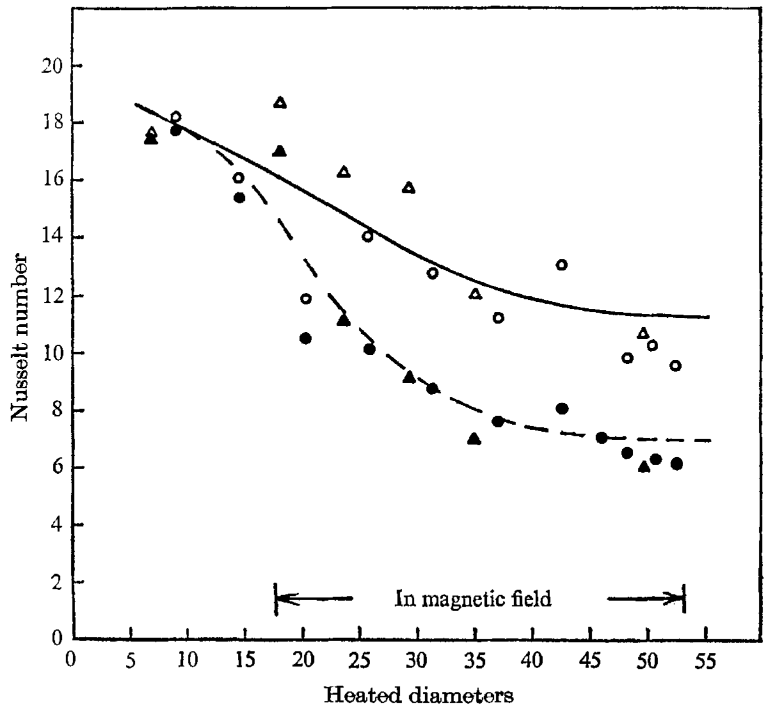

FIGURE 4. Entrance MFM heat transfer, $Re = 106000$. See figure 3 for symbols.

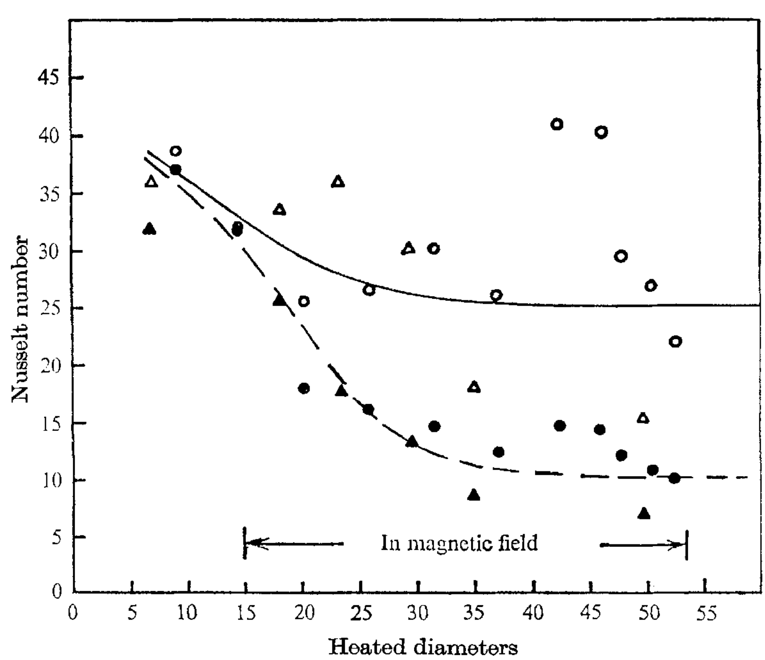

FIGURE 5. Entrance MFM heat transfer, $Re = 387000$. ○, △, see figure 3.
●, 0°, 13000 gauss; ▲, 90°, 13000 gauss.

$Z > 20 \times 10^{-4}$ natural convection affects the flow and heat transfer. In figure 2 the angular dependence disappears for $Pe > 3400$ (which corresponds to $Z \approx 24 \times 10^{-4}$): so the present experiment seems to agree with their conclusions. Temperature profiles, however, indicate that the natural convection is present to values as low as $Z \approx 12 \times 10^{-4}$. Temperature profiles will be discussed in the next section.

Figures 3, 4, and 5 show the development of the MFM heat transfer as the fluid travels through the heated test section and region under the magnetic field. As the flow moves downstream, the wall temperature increases and the Nusselt number decreases, reflecting the development of the temperature profile. The data of the lowest Reynolds number, figure 3, show that the magnetic field inhibits the natural convection pattern by the strong decrease in the $\theta = 90°$ data when the field is turned on. There is no angular dependence in the data for the higher Reynolds numbers.

It was found that the influence of the uncertainty in the exact position of the wall thermocouples could be eliminated in the study of MFM heat transfer if the data were referenced to the zero-field data. An equation was derived (Gardner 1969) which relates $Nu_{B\neq 0}$ to $Nu_{B=0}$ with the thermocouple's measurements for field on and field off cases as parameters:

$$Nu_{B\neq 0} = Nu_{B=0}/[1 + (Nu_{B=0})\, C\delta T], \tag{3}$$

where $\delta T = (T_u^* - T_0^*)(q/q^*) + (T_0 - T_u)$, T_0 = outlet mixing-cup temperature, T_u = temperature measured by thermocouple at unknown radial position, $C = k/(qd)$. An asterisk as a superscript denotes a measurement with the field turned on. The inlet temperature was the same for both field on and field off cases.

Figures 6 and 7 show the MFM heat transfer data calculated from (3). The zero-field data used in calculating the MFM Nusselt numbers were the same as those of figure 2. For large values of the Péclet number the average value was used. The MFM data show little scatter compared with those of figure 2. This gives support to the statement that the uncertainty in the thermocouple's position contributes significantly to the large scatter at high heat fluxes rather than the experimental error that comes from adjusting the flow rate, heat flux, etc.

Two regions of interest are apparent in figures 6 and 7.

For Reynolds numbers less than 50 000, an angular dependence appears. At 0° from the field, in figure 6, the curves cross over and the heat transfer increases with the magnetic field. This change is in the same direction that was predicted from the analytical solution of the laminar MFM pipe flow problem (Gardner 1968). In this solution the increase in Nusselt number was due to the Harmann flattening of the velocity profile. At 90° from the field, figure 7, there is a decrease in the Nusselt number indicating that the magnetic field also inhibits the natural convection heat transfer. It should be understood, then, that both the inhibition of the natural convection and the flattening of the velocity profile contribute to the crossover at 0°. MFM temperature profiles in the next section also show that the natural convection is being inhibited by the magnetic field for flow at low Reynolds numbers.

Above $Re = 50\,000$, the flow is vigorously turbulent and a significant amount of heat is being transfered by the turbulent convective mechanism of heat transfer. The influence of the magnetic field is to inhibit the convective mechanism through the damping of the velocity fluctuations. The data for a constant magnetic field approach the zero-field data as the Reynolds number increases because the ratio of the magnetic forces to the inertia forces is decreasing and the magnetic field has less influence on the flow.

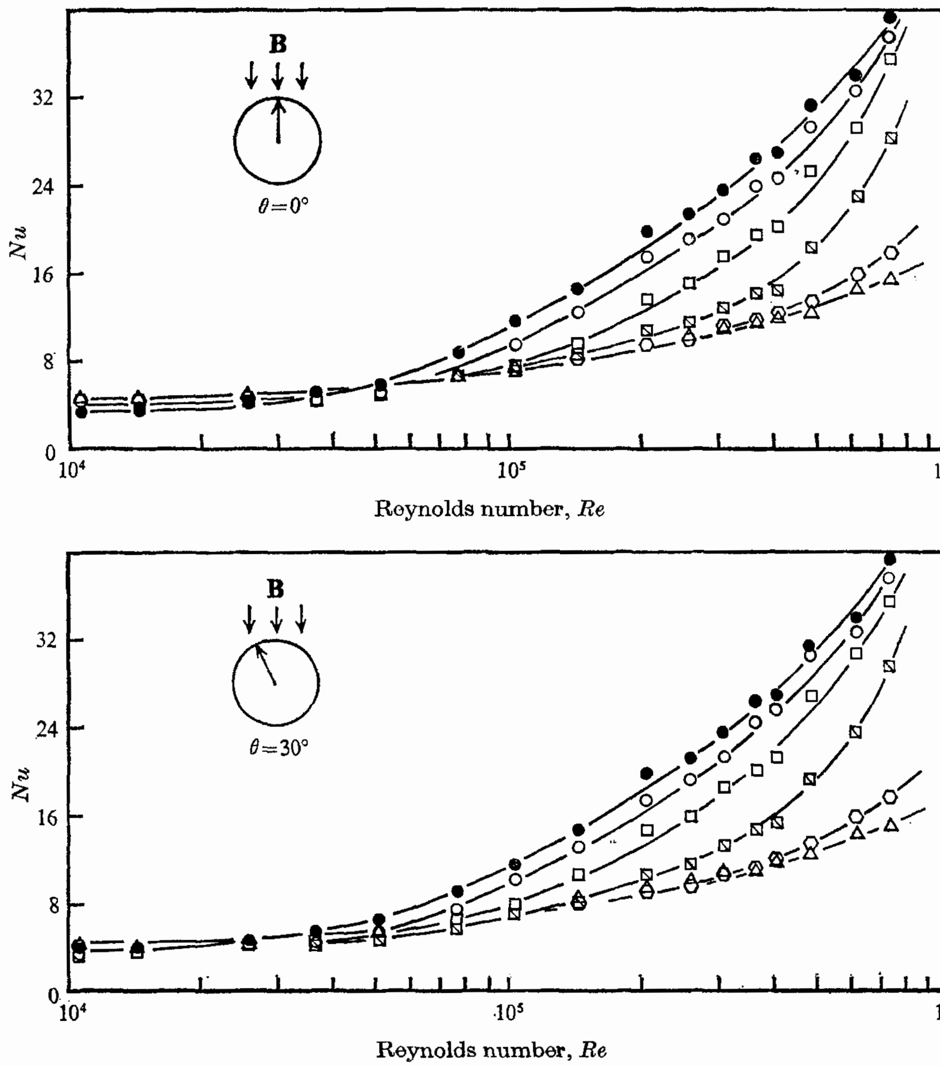

FIGURE 6. Local turbulent MFM heat transfer, 0° and 30° from magnetic field. Values of B (gauss); ●, 0; ○, 1000; □, 2000; ⧄, 4000; ⬭, 8000; △, 13000.

During the heat transfer investigation several attempts were made to detect the presence of either viscous or joulean heating in the flow. The inlet and outlet mixing-cup thermocouples were monitored for Reynolds numbers up to 330000 with the magnetic field at the maximum value of 13000 gauss and zero applied heat flux. No difference in the two temperatures was observed indicating that the viscous and/or joulean heating was negligibly small compared to the uniform wall heat flux imposed on the flow in the heat transfer experiments.

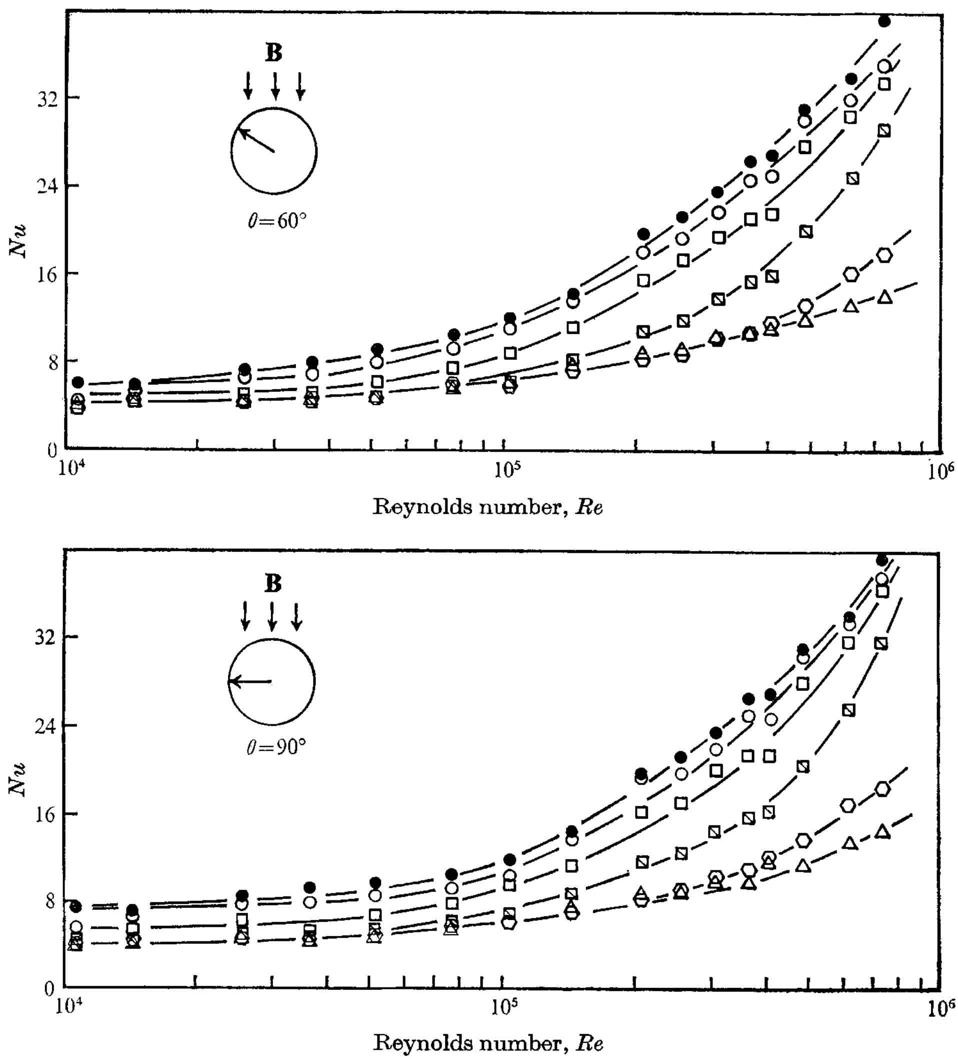

FIGURE 7. Local turbulent MFM heat transfer, 60° and 90° from magnetic field. See figure 6 for symbols.

4. Temperature profiles

Temperature profiles were measured at four Reynolds numbers from 10500 to 315000 with a thermocouple probe of 0·032 in. diameter. The signal from the probe was fed into a Vidar 520 voltmeter and integrated for a period of 10–15 seconds. Profiles were measured across the diameter of the pipe for angles of 0°, 45°, and 90° from the field. Figures 8 and 9 contain representative sets of profiles at two Reynolds numbers. The temperature decreases in the centre and increases

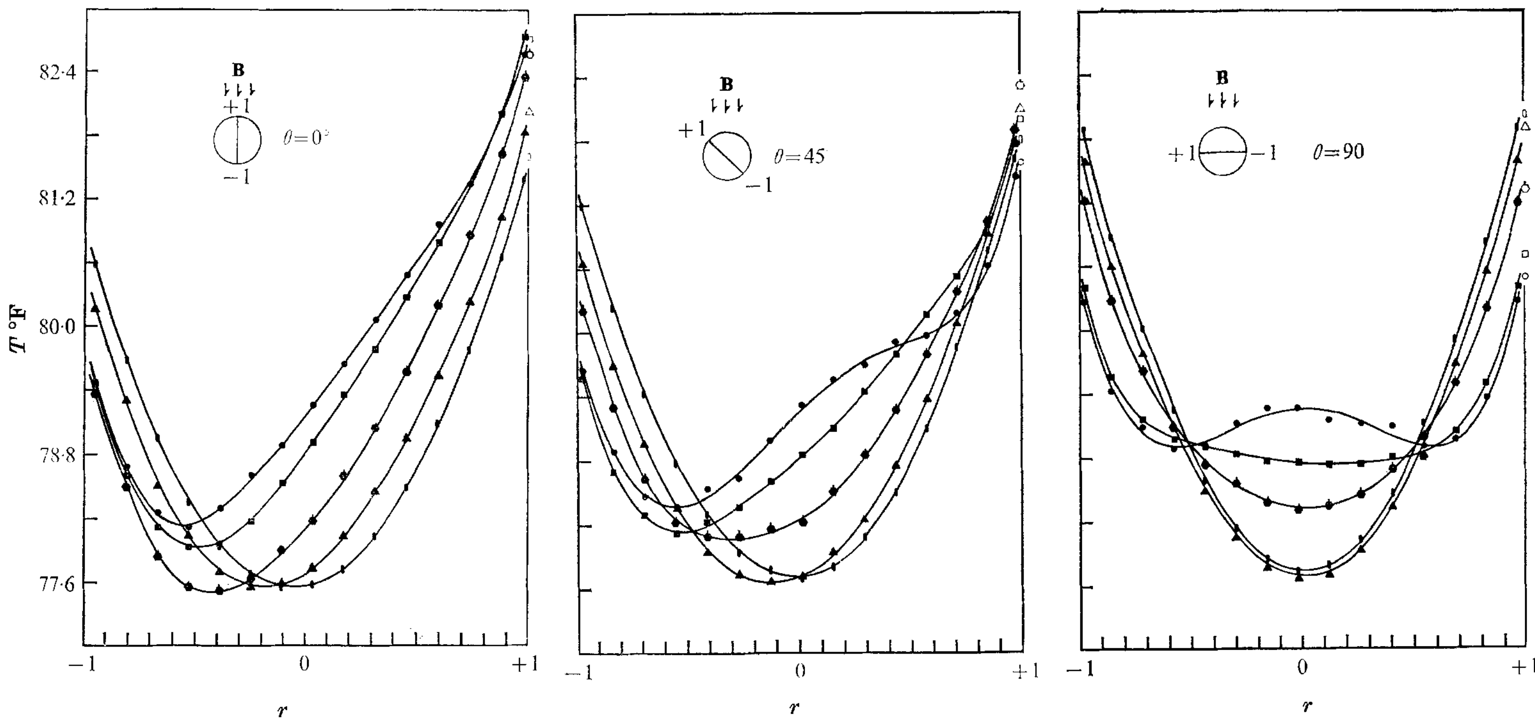

FIGURE 8. MFM temperature profiles for $\theta = 0°$, 45°, and 90° at $Re = 10\,500$. Radial co-ordinate, r, was normalized by the pipe radius. Values of B (gauss); ●, ○, 0; ■, □, 1000; ⬟, ⬠, 2000; ▲, △, 4000; ⬮, 0, 13 000. Open symbols at wall, $r = +1$, were estimated from outside wall thermocouple measurements.

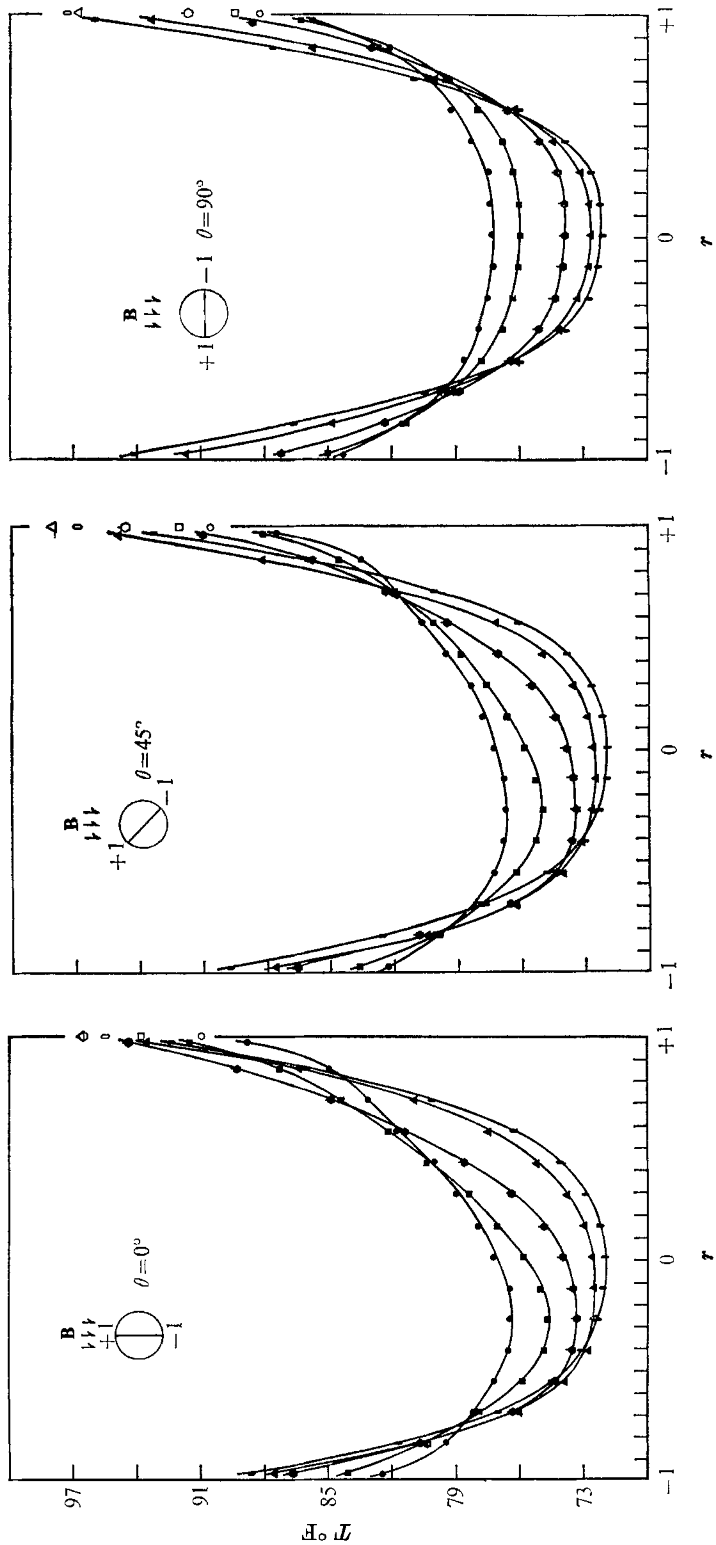

FIGURE 9. MFM temperature profiles for $\theta = 0°$, $45°$, and $90°$ at $Re = 10500$. See figure 8 for symbols.

near the wall indicating that the convective mechanism of heat transfer is being inhibited as the magnetic field is increased. (At each Reynolds number the heat input was kept constant as the field was changed.) The 0° profiles are skewed for $B = 0$ and tend to be symmetric as the field increases indicating the inhibition of the free convection in the flow.

The open points at the $r = +1$ wall in figures 8 and 9 were computed by evaluating a least squares linear fit of the outside wall temperatures at the axial station where the temperature profiles were measured. The wall temperature was extrapolated from this estimate by knowing the heat flux. With few exceptions these data fall on the curves drawn through the temperature profile data. This indicated that the Nusselt number calculated from the outside wall temperature measurements should agree with those that could have been calculated from the temperature profiles.

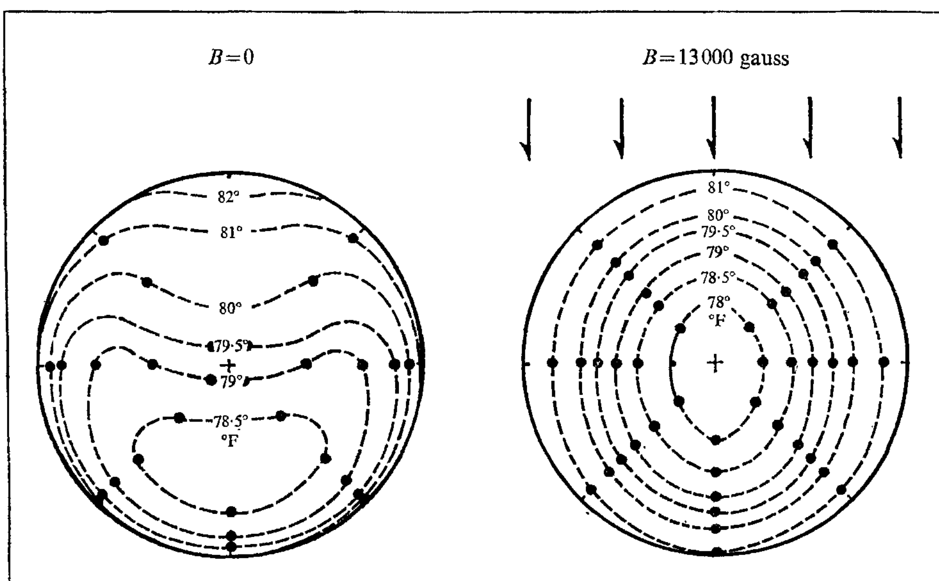

FIGURE 10. Isotherms showing the influence of the transverse magnetic field on the free convection pattern. $Re = 10500$. Heat input was the same in both cases.

At $Re = 10500$, figure 8, the profiles show a strong free convection pattern. For example, see the 90° plot where the two dips in the $B = 0$ profile indicate the presence of the double cell pattern that the free convection sets up. The fluid rises near the wall and returns down the vertical diameter forming a pattern similar to the induced electric current, only rotated by 90°.

Recently Buhr, Carr & Balzhiser (1968) surveyed the then available literature and were able to correlate the temperature profile data in an orderly fashion with the Z parameter discussed in the last section. They concluded that a free convection effect occurs in mercury flows at Reynolds numbers up to at least 50000. In this experiment, in a *horizontal* pipe, it was found that at a Reynolds number of 105000 free convection was present and distorted the temperature profiles.

Even at $Re = 315\,000$ ($Z \approx 12 \times 10^{-4}$) distortion in the near wall region was evident, although not very pronounced.

The distortion of the temperature field due to the free convection pattern is more clearly seen in figure 10 where isotherms are sketched for $Re = 10\,500$. Again one can see that the magnetic field inhibits the free convection and the isotherms tend towards circular symmetry.

5. Summary and conclusions

The present work consisted of an experimental investigation of the influence of a transverse field on forced convection heat transfer. The geometry was an electrically insulated circular pipe in a transverse field, and the wall heat flux was uniform. The fluid used was mercury.

The influence of the transverse magnetic field on the heat transfer was to inhibit the convective mechanism of heat transfer, resulting in reductions up to 70 % in the Nusselt number. The heat transfer was found to have an angular dependence for Reynolds numbers less than 50000 due to the superimposed free convection pattern. The influence of the magnetic field on the temperature profiles was to lower the centreline temperature, increase the temperature near the wall, and also make the skewed profiles more symmetric. (The profiles along the vertical diameter, 0° from the field, were skewed due to the free convection pattern.) Using the influence of the magnetic field on the free convection as a detector, the free convection effect was found to exist at Reynolds numbers up to at least 315000, in contrast to an estimate of 50000 that recently appeared in the literature.†

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REFERENCES

Blum, E. Y. 1967 *High Temp.* **5**, 68.

Buhr, H. O., Carr, A. D. & Balzhiser, R. E. 1968 *Int. J. Heat Mass Trans.* **11**, 641.

Emery, A. & Bailey, D. 1967 *J. Heat Trans.* **89**, 272.

Gardner, R. A., Uherka, K. L. & Lykoudis, P. S. 1966 *AIAA J.*, **4**, 848.

Gardner, R. A. 1968 *Int. J. Heat Mass Trans.* **11**, 1076.

Gardner, R. A. 1969 Ph.D. Thesis, Purdue Univ., Lafayette, Indiana, U.S.A.

Gardner, R. A. & Lykoudis, P. S. 1971 *J. Fluid Mech.* **47**, 737.

Kovner, D., Krasil'nikov, E. Y. & Panevin, I. 1966 *Magnitnaya Gidrodinamika*, **2**, 104.

Krasil'nikov, E. Y. 1965 *Magnitnaya Gidrodinamika*, **1**, 37.

Lubarsky, D. & Kaufman, S. 1955 *NACA TN* 3336.

† Buhr *et al.* (1968).