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Some Observations on the Heat Transfer Characteristics of a Rotating Mixed Convection Thermosyphon

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Some Observations on the Heat Transfer Characteristics of a Rotating Mixed Convection Thermosyphon

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Summary

The results of an experimental programme devised to study the heat transfer performance of a particular form of rotating mixed convection thermosyphon are presented. Actual experimental work was performed with water and 100% glycerol. Generally it was shown that the performance of the device was enhanced with increases in rotational speed. Empirical correlations of the data are presented.

On the basis of the results obtained with the particular rotating geometry tested, these devices offer a compact, reliable method of cooling rotating components operating in high temperature environments. They are particularly useful for applications where the location of the component makes direct cooling awkward if not impossible. Finally suggestions for further investigations are made.

Introduction/

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*Replaces A.R.C.31 064

Introduction

Although numerous thermosyphon systems may be devised they may be broadly defined as fluid systems where circulation of the fluid is effected solely as a consequence of heat transfer and the action of a body force field on the system. In other words the motion of the fluid is achieved without the use of a mechanical agency.

Investigations into the performance of thermosyphon systems have mainly been concerned with the so-called open or closed free convection thermosyphon where the motivation has been to assess their potential as cooling systems for the rotor blades of gas turbines. Notable contributions in this field are exemplified by reference to the work of Schmidt(1), Lighthill(2), Martin(3,4), Martin and Cresswell(5), Martin and Cohen(6), and Cohen and Bayley(7).

However there exists another class of thermosyphon device referred to by Morris(8) and Morris and Davies(9) as the mixed convection thermosyphon where, owing to the nature of the geometry of the containing vessel and the relative location on the boundary where heat transfer occurs, the presence of a net difference in potential energy gives rise to a predominantly unidirectional circulation of the fluid. With a mixed convection thermosyphon the fluid is physically contained in a closed loop of conduit and, depending on the geometry of the loop, numerous configurations may be postulated. Again when these devices are considered for the projected cooling of rotating components the location of the loop in relation to the axis of rotation permits further variations on the basic theme to be made.

It has been suggested by Foster(10) that a particular form of the mixed convection thermosyphon may be used to limit the temperature of the vanes of a radial flow turbine especially when the turbine forms part of a back-to-back centrifugal compressor-radial turbine unit. Also this form of thermosyphon has been proposed as a cooling system for the rotor conductors of large electrical machines, see Morris and Davies(9). Clearly the possibility of incorporating thermosyphonic cooling into certain rotating components has been recognised for a number of years. Suprisingly however, little or no experimental work appears to be currently available which gives quantitative information concerning the behaviour of these devices when actually rotating. It is the purpose of this paper to present the results of a limited experimental programme, the object of which was to determine the influence of rotation on the heat transfer performance of one particular mixed convection thermosyphon geometry.

Details of the configuration tested are shown in Fig.1 where it is seen that the fluid circuit is basically of rectangular form and is arranged to rotate about a vertical axis. Actual leading dimensions are given in Table 1. The outer limb is heated electrically and the inner limb is cooled by means of an internally fitted coil through which mains water was circulated. The actual apparatus has been described elsewhere (see (8) and (9)) but the rudiments of the constructional details may be observed by reference to Figs.2, 3 and 4. Thermocouples installed along the heated limb of the circuit permitted the temperature at a number of points to be measured via a miniature instrumentation slip ring attached to the main rotor assembly. The temperature of the fluid at entry to and exit from the heated limb was also measured using thermocouples.

With/

With the system operating steadily measurements of the heater power consumption, fluid temperatures, heated limb temperature and rotational speed were made for a number of conditions. Two experimental programmes were undertaken one using water as the primary fluid and the other using 100% glycerol. The range of rotational speeds covered was 0 - 300 rev/min which for this geometry is equivalent to a centripetal acceleration on the centre line of the heated limb in the range 0 - 15 g.

Results

It may be easily shown by dimensional arguments that the heat transfer performance of the mixed convection thermosyphon being studied may be expressed as

$$Nu = \Phi\left\{ Gr_r, J, Pr, Ac, \frac{L}{d}, \frac{H}{d} \right\} \qquad \ldots (1)$$

where

$$Nu = \frac{\dot{q}}{\pi L k \Delta T_w} \qquad \text{Nusselt number}$$

$$Gr_r = \frac{H\Omega^2 \beta \rho^2 d^3 \Delta T_w}{\mu^2} \qquad \text{Rotational Grashoff number}$$

$$J = \frac{d^2 \Omega \rho}{2\mu} \qquad \text{Rotational Reynolds number}$$

$$Pr = \frac{\mu c_p}{k} \qquad \text{Prandtl number}$$

$$Ac = \frac{H\Omega^2}{g} \qquad \text{Acceleration ratio}$$

As the test data is restricted to only one geometric configuration the equation (1) simplifies to

$$Nu = \Phi\left\{ Gr_r, J, Pr, Ac \right\} \qquad \ldots (2)$$

The actual circulation rate of the fluid within the thermosyphon loop is not required in equation (2) owing to the fact that this parameter is a dependent variable. The steady flow rate achieved at a given operating condition adjusts itself so that a balance exists between the net difference of potential energy over the entire circuit (referred to the body forces acting on the system) and the combined influence of wall shear stresses, bends and changes in cross section of the loop.

If the heating and cooling of the axially located limbs is uniform then it can be shown (see (8)) that the circulation rate, expressed as Reynolds number, is related to the Nusselt number, rotational Rayleigh number and Prandtl number by an implicit expression which has the form

$$\frac{Nu\ Ra_r}{Pr^2} = F_1\left\{L, H, d\right\}F_2\left\{Re, Ra_r, Pr\right\}Re^3 \qquad \ldots (3)$$

This implies, because of the heat flux assumption, that no circulation is produced when the thermosyphon is stationary. F_1 is a function of the geometric shape of the circuit and F_2 is a function which accounts for the fact that the flow resistance of the circuit when rotating will itself be dependent on the rate of flow, rotation and heat transfer. Although equation (3) implies that no circulation is achieved at zero speed this is virtually impossible to achieve in a real system. One may however consider equation (3) as a suggestion for the correlation of test data. Thus, for the data obtained with water, Fig.5 shows a plot of $\frac{Nu\ Ra_r}{Pr^2}$ against Re.

At each rotational speed separate curves could be detected. If the resistance which the circuit offers to flow is not dependent on speed of rotation then F_2 is a function of Reynolds number and one would expect data at all speeds to correlate on a single unique curve. It has been demonstrated by Morris (11) and Barua (12) that the separate limbs which comprise the complete thermosyphon being studied experience an increase in resistance when these limbs are rotated. That is the function F_2 should increase as the rotational speed is increased. This feature is clearly exhibited by Fig.5 on observation of the relative spacing of the curves. The results with water could be correlated with a root mean square deviation of ±15% by the equation reported in (9) as

$$\frac{Nu\ Ra_r}{Pr^2} = 0.1505 Ac^{0.735}\ Re^{2.45} \qquad \ldots (4)$$

The test data is shown plotted in Fig.6 without reference to the Reynolds number in the form of Nusselt number against rotational Rayleigh number. The data, it is seen, may be correlated by a series of parallel lines for each rotational speed. When plotted in this manner the data obtained at zero rotational speed cannot be included. Nevertheless following the suggestion of equation (2) the following equation correlated the data.

$$Nu = 1.17\ Ra_g^{\ 0.188} + 0.694\ Ra_r^{\ 0.188}\ \ J^{0.043} \qquad \ldots (5)$$

Again following the suggestion of equation (3) the test data obtained with 100% glycerol as the primary fluid are shown in Fig.7 for rotational speeds of 50, 100 and 200 rev/min. Similar tendencies as those obtained with water are evident although in this case wider data scatter was noted. The glycerol data could be correlated by

$$\frac{Nu\ Ra_r}{Pr^2} = 0.082\ Ac^{0.685}\ Re^{3.55} \qquad \ldots (6)$$

When/

When using glycerpol as the convective fluid it was not possible to detect lines of constant speed when Nu was plotted against Ra_r as may be seen by reference to Fig.8. This is probably because the influence of Coriolis forces on the convection inside the loop is less pronounced with the high viscosity fluid. Note that the rotational Reynolds number may be thought of as a relative measure of coriolis to viscous forces.

The discussion of the results so far has been mainly concerned with the internal characteristics of the thermosyphon. However an overall appraisal of its performance may be made by reference to Figs.9 and 10. Here the actual dimensional heat transfer rate is plotted against an overall temperature difference, being the maximum heater wall temperature minus the mean secondary coolant temperature. With both convective fluids used the heat transfer increases with speed for a given overall temperature difference.

It is possible to think of a rotating thermosyphon as an artificial streak of highly conductive material located within the component to be cooled. It is interesting therefore to compare the curves of heat flux against overall temperature difference to that obtained by assuming that solid copper rods operating with the same overall temperature difference replace the radial limbs of the thermosyphon. The dotted line in Fig.9 shows this result for water and clearly rotation of the thermosyphon results in very significant improvement in the performance of the system as a cooling device. The effectiveness of the device may be highlighted by reference to Fig.11 which shows a cross plot of the water data from Fig.9 expressed as a relative conductivity based on the value of copper. Effective conductivities up to 50 times that of copper may occur even at the low rotational speed range tested.

Concluding Remarks and Suggestions for Further Work

On the evidence of the results presented in this paper, it appears that the rotating mixed convection thermosyphon offers an attractive method for cooling the rotating components of certain machines. This is especially true for cases where the location of the component makes direct cooling inconvenient or impossible. The thermosyphon circuit in this instance may be strategically located so that the eventual rejection of heat to the secondary coolant is effected at a more accessible location.

The overall performance of a rotating mixed convection thermosyphon is intimately linked to the problems of flow inside rotating limbs from which its circuit is made up. With detailed knowledge available concerning the influence of rotation on the general problem of flow inside rotating ducts the prediction of thermosyphon performance is but a straightforward step. It is the present author's opinion therefore that there is a strong case for the fundamental problems of flow inside rotating ducts to be investigated in detail not only because of their thermosyphon application but also because of their importance in the general field of cooling rotating components.

Symbols/

Symbols

c_p	specific heat at constant pressure
d	diameter of heated section
g	local gravitational acceleration
H	outer radius of circuit
k	thermal conductivity
L	length of heated section
w	mean velocity in heated section
$\mathring{q}$	heat flux
ΔT_w	maximum measured wall temperature on heated section - mean fluid temperature in heater
β	volume expansion coefficient
μ	absolute viscosity
ρ	density
Ω	angular velocity

Dimensional Parameters

Nu	Nusselt number ($\mathring{q}/\pi Lk\Delta T_w$)
Gr_r	Rotational Grashoff number ($H\Omega^2\beta\rho^2 d^3 \Delta T_w/\mu^2$)
J	Rotational Reynolds number ($d^2\Omega\rho/2\mu$)
Pr	Prandtl number ($\mu c_p/k$)
Ac	Acceleration ratio ($H\Omega^2/g$)
Ra_r	Rotational Rayleigh number ($Pr.Gr_r$)
Ra_g	Gravitational Rayleigh number (Ra_r/Ac)
Re	Reynolds number ($wd\rho/\mu$)

References/

References

No.	Author(s)	Title, etc.
1	Schmidt, E. H. W.	Heat transmission by natural convection at high centrifugal accelerations in water cooled gas turbine blades. General discussion on heat transfer. Procs. Inst. Mech. Eng. p.361. (1951).
2.	Lighthill, M. J.	Free convection in tubes. Quart. Jour. Mech. & App. Phys. Vol 6, p.398. (1953).
3	Martin, B. W.	Free convection in the open thermosyphon. Procs. roy. Soc.,230, p.502. (1955).
4	Martin, B. W.	Free convection in the inclined open thermosyphon. Procs. Inst. Mech. Eng. (1959).
5	Martin, B. W. and Cresswell, D. J.	Influence of Coriolis forces on heat transfer in open thermosyphon. Engineer, Vol.204, p.926. (1957).
6	Martin, B. W. and Cohen, H.	Heat transfer by free convection in an thermosyphon tube. Brit. Jour. App. Phys., Vol.5, p.91. (1954).
7	Cohen, H. and Bayley, F. J.	Heat transfer problems of liquid cooled gas turbines. Procs. Inst. Mech. Engrs. Vol.169, p.1063. (1955).
8	Morris, W. D.	Heat transfer characteristics of a rotating thermosyphon. Ph.D. Thesis, University of Wales. (1964).
9	Davies, T. H. and Morris, W. D.	Heat transfer characteristics of a closed loop rotating thermosyphon. Third. Int. Heat. Trans. Conf. Inst. Mech. Engrs., Chicago. (1966).
10	Foster, B. W.	American patent specification. Case No.1842.
11	Morris, W. D.	Influence of rotation on laminar convection in a heated vertical tube rotating about a parallel axis. Jour, Fluid Mech. March (1965).
12	Barua, S. N.	Secondary flow in a rotating tube. Procs. Roy. Soc., A227, p.133. (1954).

TABLE 1/

TABLE 1

Leading Dimensions of Thermosyphon Circuit

Length of heated and cooled section	12.00"
Radius of centre line of heater	6.00"
Bore diameter of heater and radial limbs	0.25"
Bore diameter of cooling section	2.50"

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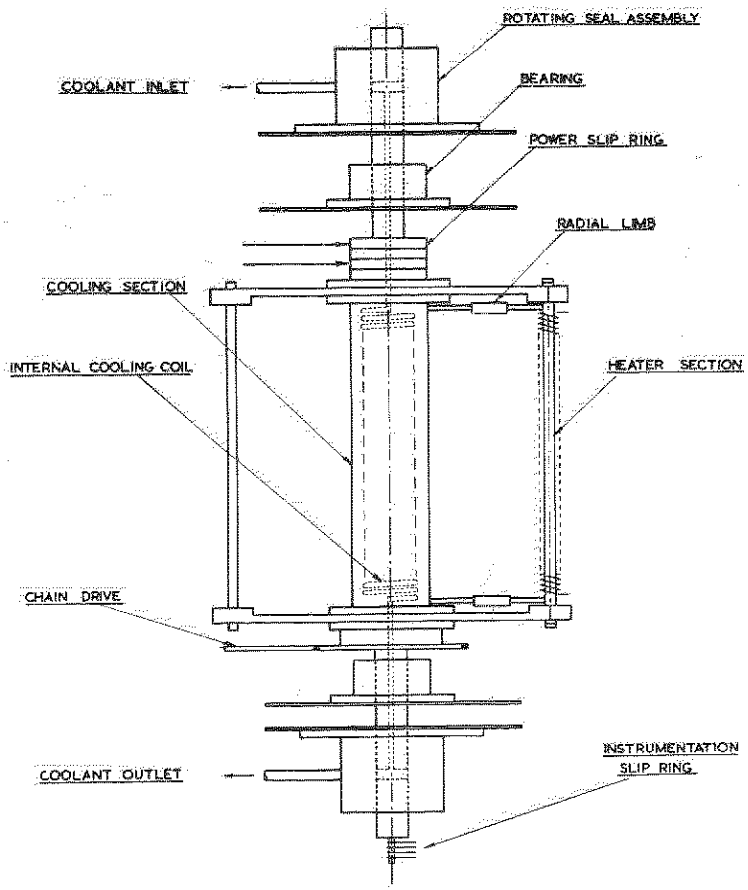
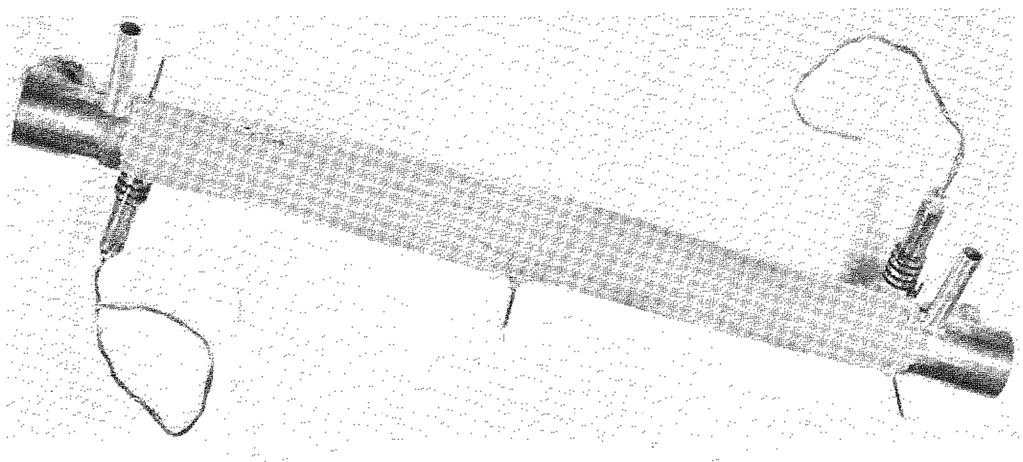


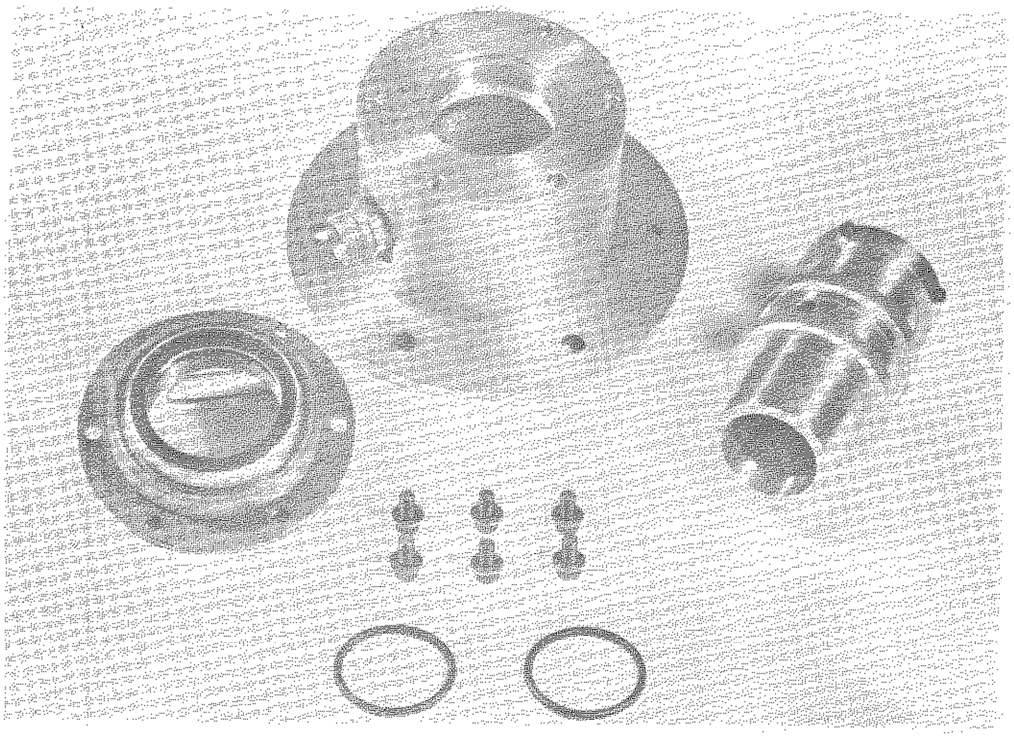
Schematic arrangement of rotating Thermosyphon

FIG. 1



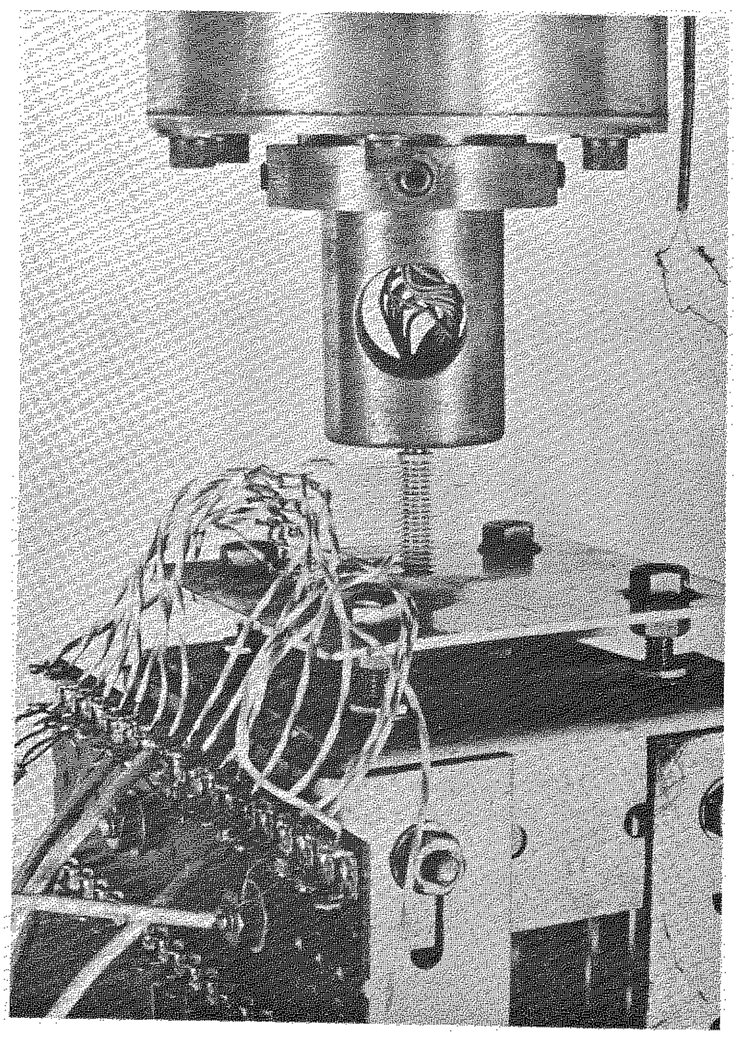
Details of heated section

FIG. 2



Details of rotating seal assemblies

FIG. 3



Instrumentation slip ring assembly

FIG. 4

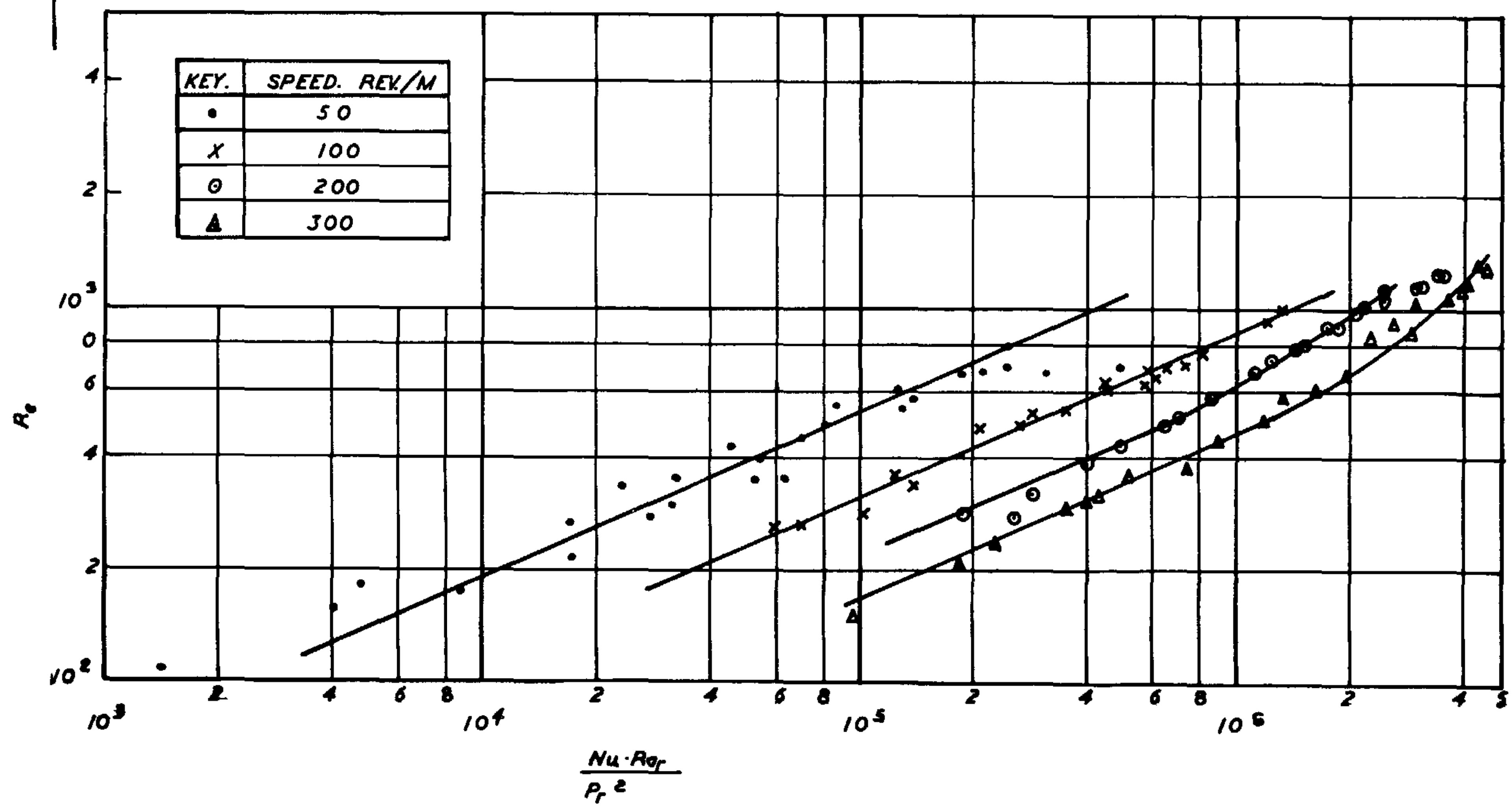


FIG. 5 VARIATION OF Re WITH $\frac{Nu \cdot Ra_r}{P_r^2}$. FLUID: WATER

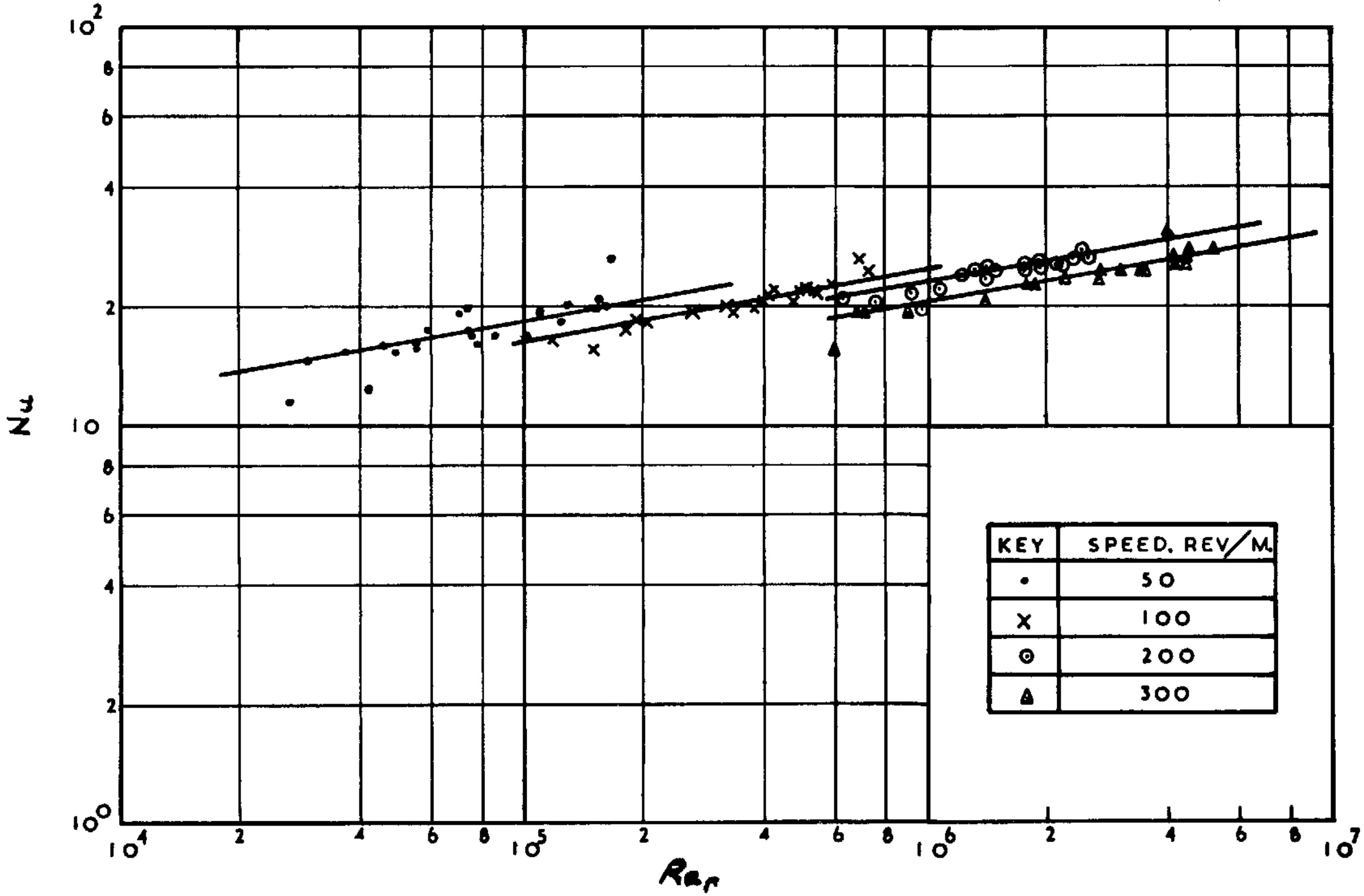


FIG. 6. VARIATION OF NUSSELT NUMBER WITH ROTATIONAL RAYLEIGH NUMBER
FLUID : WATER

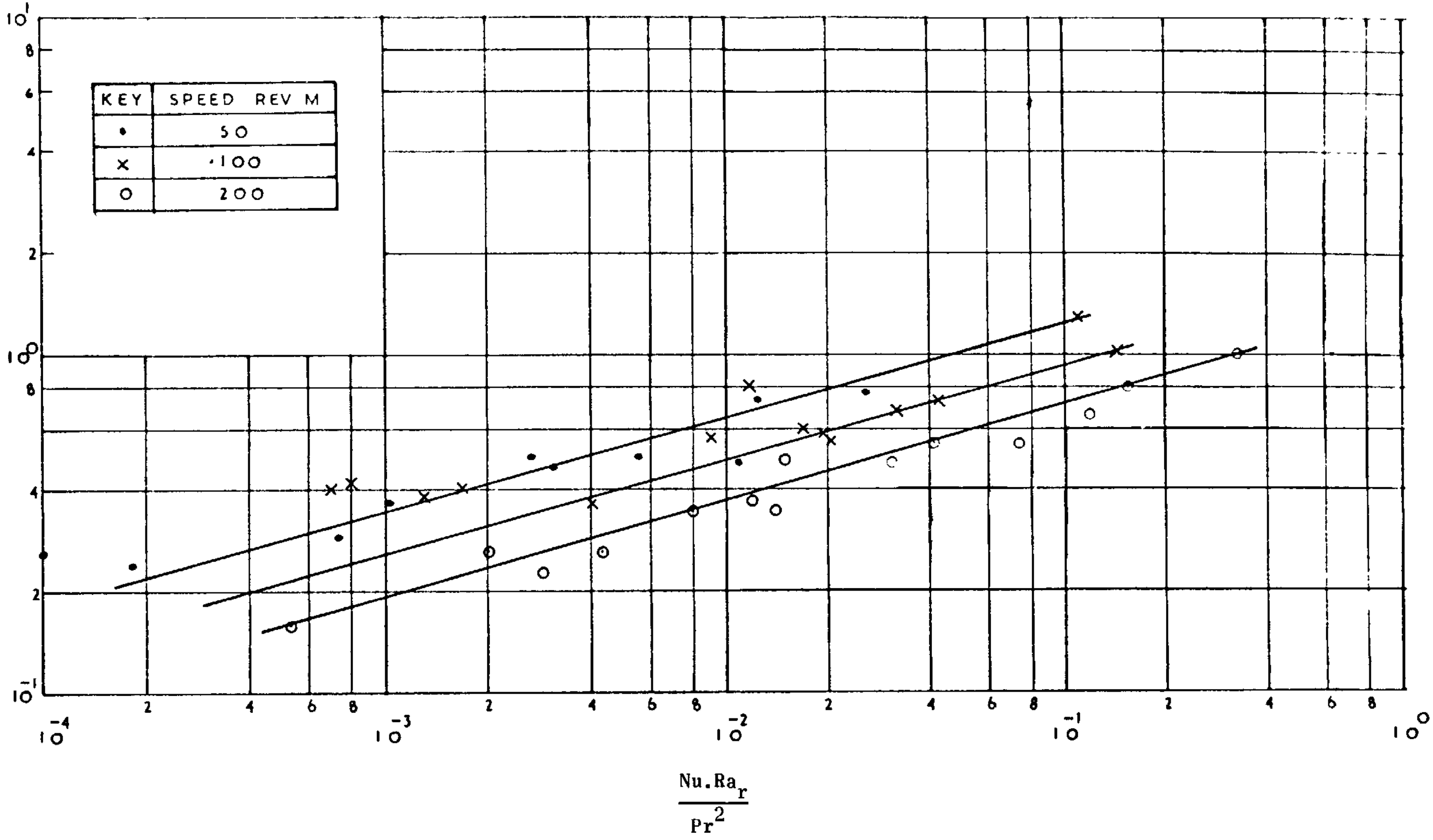
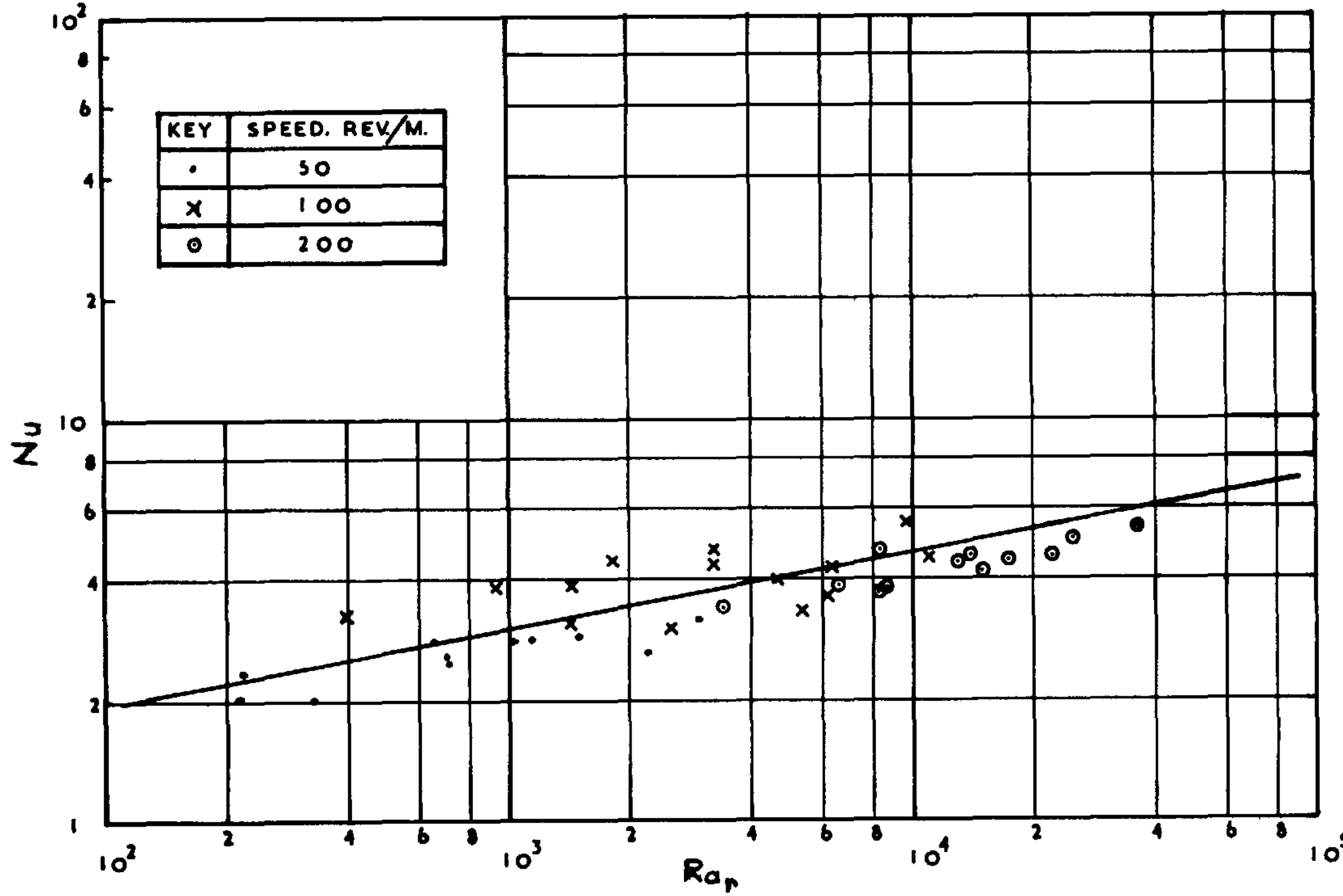


Fig. 7 Variation of Re with $\frac{Nu.Ra_r}{Pr^2}$ Fluid : Glycerol



VARIATION OF N_{NU} WITH N_{RA} FOR SPEED RANGE CONSIDERED.

FLUID · 100% GLYCEROL.

FIG. 8

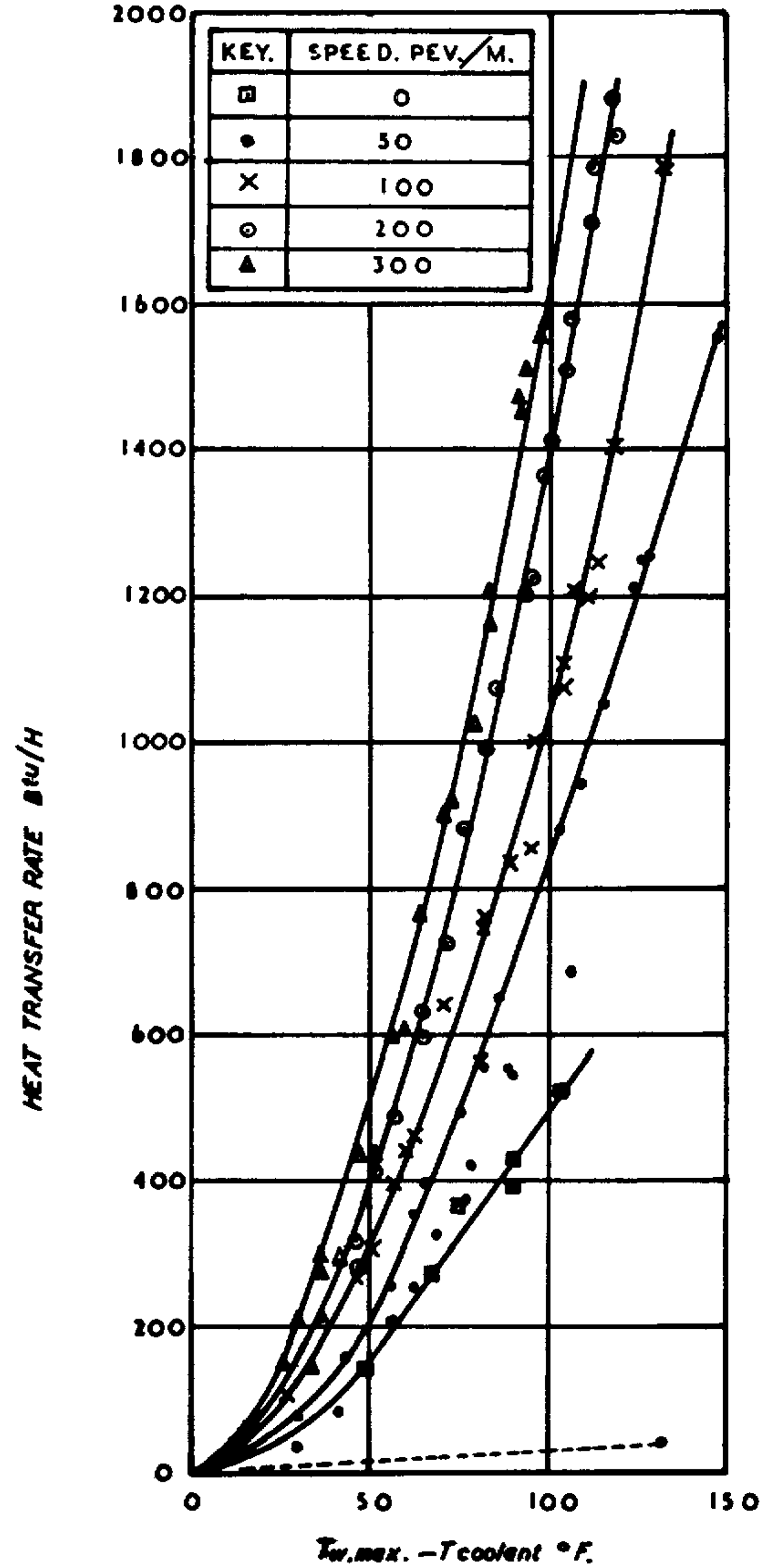
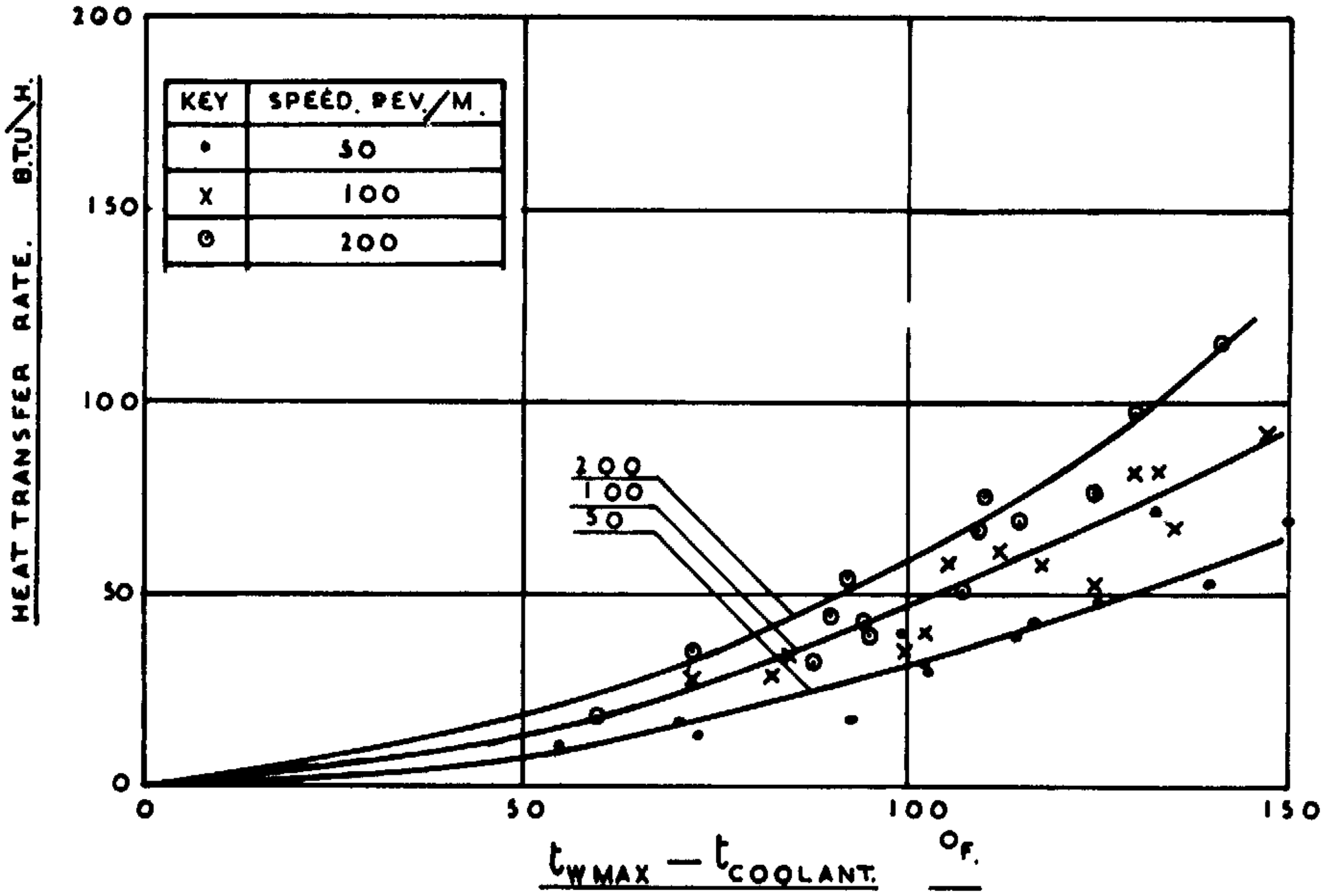


FIG 9 VARIATION OF HEAT TRANSFER RATE WITH OVERALL TEMPERATURE DIFFERENCE. FLUID - WATER



VARIATION OF HEAT TRANSFER RATE WITH OVERALL TEMPERATURE DIFFERENCE FOR SPEED RANGE CONSIDERED. FLUID: 100% GLYCEROL.

FIG. 10

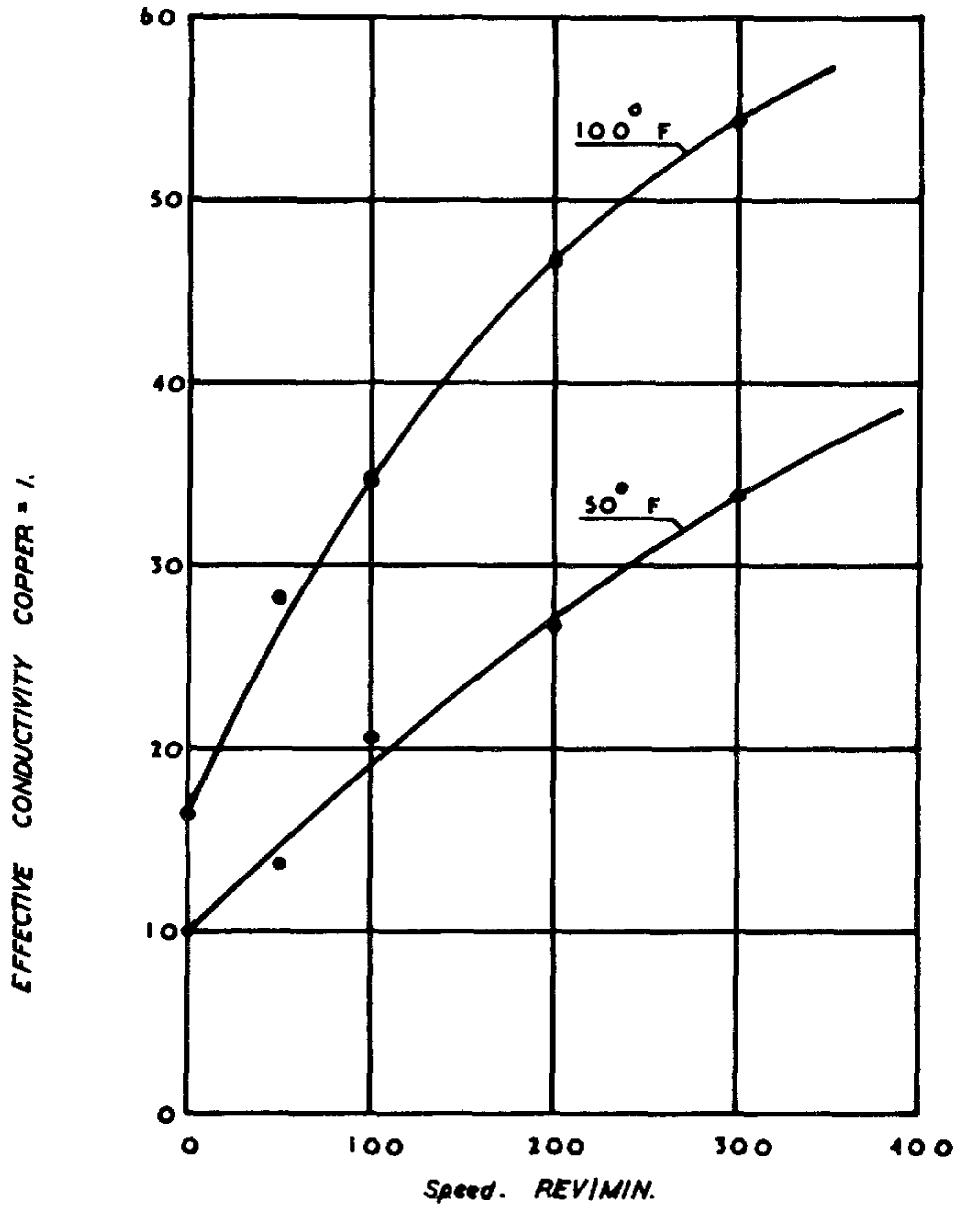


FIG II VARIATION OF EFFECTIVE CONDUCTIVITY WITH SPEED FOR TWO OVERALL TEMPERATURE DIFFERENCES. FLUID: WATER.

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