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TURBULENT CONVECTION BETWEEN TWO HORIZONTAL PLATES

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Abstract—Data from parallel-plate heat flux experiments are reviewed and an alternative method of plotting results is introduced. The graphical form $c_q[=Nu/Ra^{1/3}]$ vs the logarithm of Ra is shown to highlight the role of the interplate spacing d in determining the heat flux. Plotting the data in this form shows that between heat flux transition points, the heat flux (for constant ΔT) increases to a maximum and then decreases with increasing Rayleigh number. This behaviour suggests a heat-transfer efficiency criteria based on the experimental geometry. In this form the data also show an overall decrease in c_q with increasing Ra, towards a probable asymptote of between 0.04 and 0.06.

NOMENCLATURE

c, intercept of the straight line on the $NuRa$ vs Ra plot;
c_p, specific heat per unit mass [cal gm^{-1} °C^{-1}];
c_q, heat transfer coefficient $= Nu/Ra^{1/3}$;
d, interplate spacing [cm];
g, gravitational acceleration [cm s^{-2}];
m, slope of data on $NuRa$ vs Ra graph;
Nu, $\frac{Qd}{\kappa\Delta T}$ Nusselt number;
n, slope of data on log Nu vs log Ra graph;
Pr, ν/κ Prandtl number;
Q, $q/\rho c_p$ buoyancy heat flux [cm °C s^{-1}];
q, heat flux per unit area [cal cm^{-2} s^{-1}];
Ra, $\alpha g \frac{\Delta T}{\nu\kappa} d^3$ Rayleigh number;
Ra_c, critical Rayleigh number ($\simeq$ 1708);
Ra_i, transition Rayleigh number;
T, temperature [°C];
W, representative horizontal distance [cm];
X_i, heat flux transition point.

Greek symbols

α, thermal coefficient of volumetric expansion [°C^{-1}];
ΔT, temperature difference between plates [°C];
κ, molecular diffusivity [cm^2 s^{-1}];
ν, viscosity [cm^2 s^{-1}];
ρ, density [gm cm^{-3}].

1. INTRODUCTION

THE CONVECTIVE flow induced by the temperature difference between two horizontal plates has been studied extensively since the turn of the century (Bénard [1]). The original incentive for this study was the similarity of this flow with flows induced by the heat transfer from the earth's surface. However, the flow has an inherent interest in that with large distances between the horizontal plates (d) or large temperature differences ΔT the source of energy for the turbulent motion comes from the potential energy supplied by the heating and is not complicated by any shearing mechanism. In spite of this apparent simplicity recent reviews of convection theory suggest that very little progress has been made in understanding the flow processes [2, 3].

The parameters affecting the transfer of heat per unit area q_p between two horizontal parallel plates in the normal gravitational field g are the plate spacing of d, a horizontal dimension W, a temperature difference ΔT and the fluid properties. These are the density ρ, kinematic viscosity ν, molecular diffusivity κ, volumetric coefficient of thermal expansion $\alpha[=(-1/\rho)(\partial\rho/\partial T)]$ and the specific heat per unit mass c_p. Dimensional reasoning then yields for the buoyancy flux per unit area $Q[=q_p/\rho c_p]$:

$$\frac{Qd}{\kappa\Delta T} = \varnothing\left(\frac{\alpha g\Delta T d^3}{\nu\kappa}, \frac{\nu}{\kappa}, \frac{L}{d}\right). \tag{1}$$

In this form the term of the left hand side of equation (1) is the Nusselt number Nu and is the ratio of the actual buoyancy flux to the purely diffusive buoyancy flux through a stagnant fluid.

The first term on the right hand side of the equation is the Rayleigh number Ra and is the ratio between the buoyancy force and the two diffusive processes. The remaining terms are the Prandtl number Pr and the aspect ratio.

2. THE PLOTTING OF THE EXPERIMENTAL RESULTS

In the majority of the early measurements it was assumed that the aspect ratio W/d could be neglected and the experimental results could be plotted as graph of the logarithms of the Nusselt number vs the Rayleigh number with the Prandtl number as a parameter. A number of these experimental results [4–9] are plotted in Fig. 1. Below a critical Rayleigh number of about 1700 the fluid

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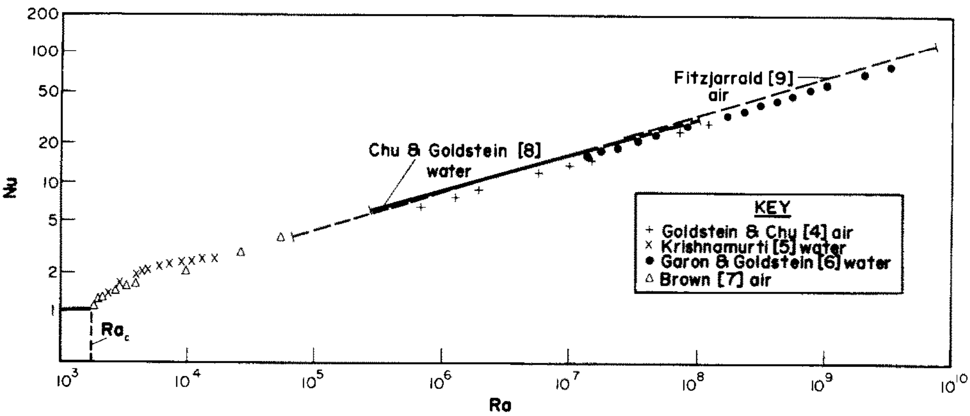

FIG. 1. Nusselt number data from parallel-plate experiments plotted as a function of Rayleigh number. Both axes have logarithmic scales.

layer is stagnant and heat is transferred by conduction alone ($Nu = 1$). Within the range $1700 < Ra < 10^5$ the fluid motion between the plates is regular in both a spatial and temporal sense. This range is therefore often referred to as the laminar range [10]. At higher Rayleigh numbers ($Ra > 10^5$) the fluid motions lose their regularity and the flow is described as turbulent. For large plate spacing and hence large Ra it might be expected that the heat transfer will be independent of the plate spacing. In this case for a constant Prandtl number and aspect ratio equation (1) would have the form:

$$Nu = kRa^n, \qquad (2)$$

with $n = \frac{1}{3}$. However the formulâe in Table 1 and the data plotted in Fig. 1 show that the values of n are slightly less than $\frac{1}{3}$. Because of the greater control obtained from steady state experiments and the practical requirements of experimental apparatus design the majority of experiments are performed using parallel plates set at fixed distances (d) apart with the temperature difference ΔT being varied and the buoyancy flux Q measured.

For each run it is therefore best to use dimensionless numbers which separate Q and ΔT. Malkus [11] introduced this idea by using equation (1) in the form

$$NuRa = \varnothing(Ra, Pr, W/d). \qquad (3)$$

The use of the product ($NuRa$) removes ΔT from the left hand side of the equation and is a more logical way of plotting the results of an experiment where depth is not varied. Plotted in this form the data for runs with one fluid (constant Prandtl number) appears as a series of straight lines with sharp transitions in slope (Fig. 2).

Krishnamurti [5, 13] studied the occurrence of these heat flux transitions in great detail over a wide range of Rayleigh and Prandtl numbers (Fig. 3). The first transition at the critical Rayleigh number Ra_c is the onset of convection. Immediately above this first transition two dimensional rolls occur. The second transition in the heat flux data occurs in conjunction with a change to a steady flow pattern of three

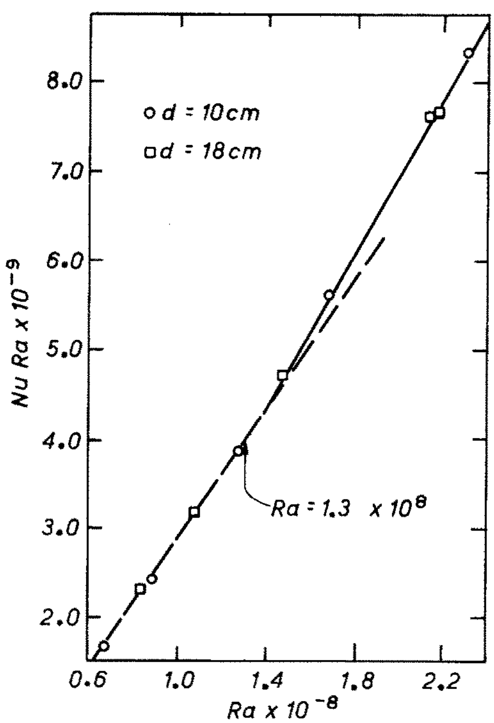

FIG. 2. Non-dimensional heat flux $NuRa$ as a function of Rayleigh number at high Ra showing a heat flux transition. (From Garon and Goldstein [6].)

dimensional hexagonal cells. Between the third and the fifth transitions the flow becomes time dependent. Willis and Deardoff [15] also found the flow to be intermittent in this range of Rayleigh numbers. At higher Rayleigh numbers the flow appears turbulent.

Krishnamurti's data shows a high Prandtl number dependence for $Pr < 100$ (Fig. 3). At higher Prandtl numbers the buoyant fluid retains its heat but the fluid motion is damped. This forces the flow to remain steady at higher Rayleigh numbers than would be the case for low Prandtl number flows. In the case of mercury with a low Prandtl number [0.025] the onset of turbulence occurs at Ra_c [2].

Table 1. Details of previously reported thermal convection experiments
Double plate experiments

Experimenter	Prandtl No. Range	Rayleigh No. Range	Heat flux in turbulent regions	Aspect ratio
Malkus [11]	3.7–7	$\rightarrow 10^{10}$	$Nu = 0.08456Ra^{0.325}$	0.5–77
Thomas and Townsend [12]	0.71	8.52×10^4, 3.76×10^5, 6.75×10^5	—	5.1–10.3
Schmidt and Silveston [13]	3–4000	$\rightarrow 10^5$	$Nu = 0.10Ra^{0.31}Pr^{0.05}$	15.3–137
O'Toole and Silveston [10]	$0.03–10^4$	$10^3–10^9$	$Nu = 0.104Re^{0.305}Pr^{0.084}$	1.9–137
Deardoff and Willis [14]	0.71	6.3×10^5, 2.5×10^6, 1×10^7	$Nu = 6$ (4.5–6.5), $Nu = 8.2$ (5.5–11), $Nu = 11$ (9–17)	5.2–9.4
Willis and Deardoff [15]	0.71–57	$5 \times 10^3–2 \times 10^6$	—	33–76
Willis and Deardoff [16]	0.71–57	$\rightarrow 2.8 \times 10^6$	—	6.7–76
Gille [17]	0.71	2.6×10^3, 6.8×10^3, 2.85×104	—	8.2–12.8
Goldstein and Chu [4]	0.71	$6.88 \times 10^6–1.23 \times 10^8$	$Nu = 0.123Ra^{0.294}$	1.0–4.7
Krishnamurti [5, 18]	0.71–8500	$10^3–10^6$	—	9.8–98
Chu and Goldstein [8]	6	$2.76 \times 10^5–1.05 \times 10^8$	$Nu = 0.183Ra^{0.278}$	1.5–6.0
Garon and Goldstein [6]	5.5	$1.36 \times 10^7–3.29 \times 10^9$	$Nu = 0.130Ra^{0.293}$	2.5–4.5
Wendell Brown [7]	0.71	$10^3–5.4 \times 10^4$	—	12–53
Threlfall [19]	0.66–0.91	$60–2 \times 10^9$	$Nu = 0.173Ra^{0.28}$	2.5
Fitzjarrald [9]	0.71	$4 \times 10^4–7 \times 10^9$	$Nu = 0.13Ra^{0.30}$	1.9–58

Single plate experiments

Experimenter	Prandtl No. Range	Rayleigh No. Range	Heat flux in turbulent regions	Aspect ratio
Thomas and Townsend [12]	6.7	3.43×10^9, 9.10×10^9, 1.36×10^{10}	$Nu = 120.1$, $Nu = 145.6$, $Nu = 169.8$	2.0
Townsend [20]	0.71	$1.39 \times 10^9–1.74 \times 10^{10}$	$Nu = 79.6–179.7$	0.5–11
Katsaros *et al.* [21]	6.7	$3.1 \times 10^9–3.2 \times 10^{10}$	$Nu = 0.062Ra^{0.33}$	1.0

For these cases the Rayleigh number has been computed assuming that ΔT is twice temperature difference between the plate and its surroundings and d is twice depth from the plate to the unheated surface.

Even in the turbulent convection region there appears to be some organisation in the flow. Figure 2 shows heat flux transitions in the *NuRa* vs *Ra* data of Garon and Goldstein [6] at $Ra = 1.3 \times 10^8$.

The occurrence of heat flux transitions at all Rayleigh numbers appears to be well established. Figure 4 shows the transition Rayleigh numbers reported by investigators for water [5, 6, 8, 11, 15, 18]. They are plotted on the empirical heat flux curves of O'Toole and Silveston [10] which are given by:

$$\left.\begin{array}{ll} Nu = 2.38 \times 10^{-3} Ra^{0.816} & 1700 < Ra < 3500 \\ Nu = 0.229 Ra^{0.252} & 3500 < Ra < 10^5 \\ Nu = 0.104 Ra^{0.305} P_r^{0.084} & 10^5 < Ra < 10^9 \end{array}\right\} \quad (4)$$

The regularity of the transition Rayleigh numbers from each set of results is remarkable. At high Rayleigh numbers the spacings represent approximate multiples of two.

Some confusion exists when the results of Willis and Deardoff [16] are compared with those of Malkus [11]. For air and silicon oil $Pr = 0.71$ and 57. Willis and Deardoff found approximately the same transition Rayleigh number as Malkus [11] who used acetone and water ($Pr = 3.7$ and 7). Willis and Deardoff [16] therefore suggested that the heat flux transitions are independent of the Prandtl numbers. This is in direct conflict with Krishnamurti's data [15, 18] which clearly show Prandtl number dependence (Fig. 3).

Except for Threlfall [19] who removed the trend in his data by plotting them in the form of $Nu/Ra^{1/4}$ vs $\log Ra$ the majority of the recent investigators have plotted their data in form of *NuRa* vs *Ra*. In this form the product *NuRa* has been described as a non-dimensional heat flux because for a fixed interplate spacing d and fixed fluid properties a plot of *NuRa* vs *Ra* represents the variation of the buoyancy heat flux with changes in ΔT.

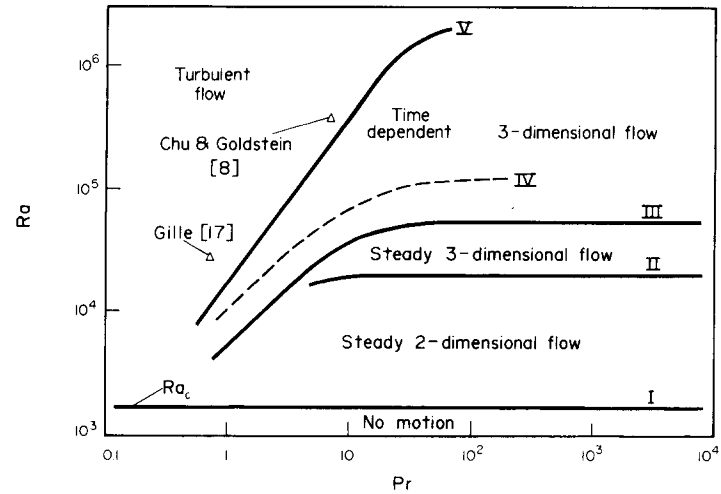

FIG. 3. Diagram showing the heat flux transition and the types of convective flow observed between them as functions of Rayleigh number and Prandtl number. (From Krishnamurti [5, 18].) Triangular data points show Rayleigh numbers at which temperature gradient reversals have been observed in air and water.

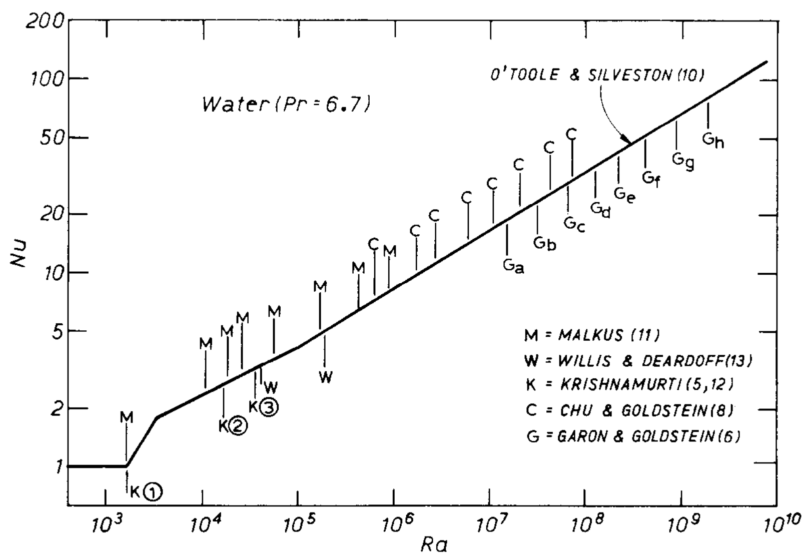

FIG. 4. Heat flux transition Rayleigh numbers for water ($Pr = 6.7$) plotted on the empirical curves of O'Toole and Silveston [10].

It is also worth exploring the manner in which Q varies as a function of d. In order to do this the data should be plotted such that apart from the properties of the fluid the ordinate contains only Q and ΔT and the abscissa ΔT and d. This plotting form ($c_q = Nu/Ra^{1/3}$ vs Ra) would be the most logical way in which to plot the data from an experiment in which the temperature difference ΔT is held constant but the plate spacing is varied. This form of plotting is explored in the next section.

3. THE PLOT OF c_q VERSUS Ra

An indication of how c_q varies with Ra is obtained by using the experimentally determined straight lines from the $NuRa$ vs Ra plot and then mapping these onto the c_q, Ra plane. If in between the two heat flux transitions on the $NuRa$ vs Ra plot defined by Ra_i and Ra_{i+1} the straight line is represented by

$$NuRa = m_{i,i+1}Ra - c_{i,i+1},$$

where m and c are the slope and negative intercept of this straight line then the maximum value of $Nu/Ra^{1/3}$ is $0.48\ (m_{i,i+1})^{4/3}(c_{i,i+1})^{-1/3}$ and this occurs at:

$$Ra = 4c_{i,i+1}/m_{i,i+1}. \tag{5}$$

The logarithmic scale is used for the Rayleigh number abscissa because it allows for a greater range of points to be plotted. Heat flux transition Rayleigh numbers also appear to be more regular on a logarithmic scale (Fig. 4).

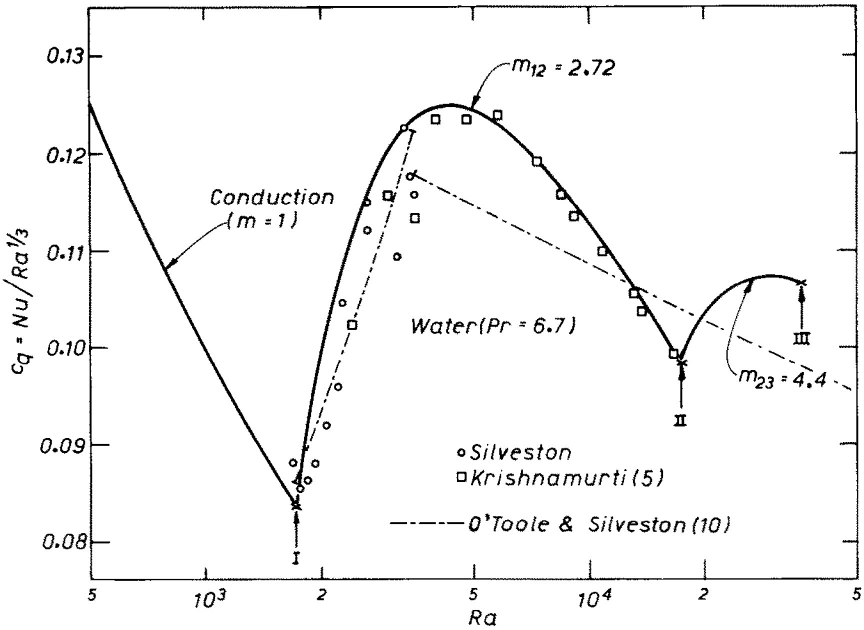

FIG. 5. Heat transfer coefficient c_q for water ($Pr = 6.7$) at low Rayleigh number plotted against the logarithm of the Rayleigh number.

Figure 5 shows the c_q vs $\log Ra$ from the experimental data of Krishnamurti [5] and Silveston (as reported by Brown [7] for water between transitions $K1$, $K2$ and $K3$, Fig. 4). The fitted curves are transformed straight line data from an $NuRa$ vs Ra plot. The slope of the straight lines reported by Krishnamurti [5] were 2.72 and 4.4. For transitions $K1$, $K2$ and $K3$ the transitional Rayleigh numbers were Ra_c, $10Ra_c$ and $21Ra_c$ respectively. Also plotted are O'Toole and Silveston's [10] empirical curves for $1700 < Ra < 3500$ and $3500 < Ra < 10^5$ (equation 4). It is apparent that between transitions $K1$ and $K2$ the transformed straight line fits the c_q vs $\log Ra$ data best for the higher Rayleigh numbers (above the value of 4320 corresponding to the maximum value of c_q). On the plot of $NuRa$ vs Ra the departure of the experimental points from the straight line below the maximum value of c_q would not be apparent.

A similar c_q vs $\log Ra$ plot for high Rayleigh number can be obtained from Garon and Goldstein's [6] data (Fig. 4). Garon and Goldstein reported four heat flux transitions (corresponding to transitions c, d, e and f in Fig. 6). However, their data suggest four more transitions although these are not accurately defined. For instance, only one data point occurred above transition a, and between transitions g and h (Fig. 6). In these cases, the slope of the straight line on an $NuRa$ vs Ra plot was chosen by assuming that the spacing of the transition Rayleigh numbers on a logarithmic scale is regular (e.g. Fig. 4).

High Rayleigh number data produces less distinct c_q vs $\log Ra$ curves (Fig. 6). Consider, for instance, the data point (for $d = 10$ cm) which does not lie on the arc between transitions c and d. If it is in fact inaccurate then the experimental scatter is as great as the amplitude of the c_q vs $\log Ra$ arcs. It should be noted that if this data point is accurate then Garon and Goldstein's [6] results for $d = 10$ and 18 cm could be fitted with two separate curves. This would suggest c_q has an additional dependence of the plate spacing d and would not support the form of c_q curves in Fig. 6. However, if the apparent linearity of $NuRa$ vs Ra data is accepted then the occurrence of the concave downward arcs between the heat flux transitions on a c_q vs $\log Ra$ plot must also be accepted.

It is worth noting at this stage that the straight line data on an $NuRa$ vs Ra plot should appear as a series of shallow concave downwards arcs on the $\log Nu$ vs $\log Ra$ plot of Fig. 1. However for this form of presenting the data only the arc between the first and second transition is apparent.

4. VARIATION OF c_q BETWEEN THE TRANSITION RAYLEIGH NUMBERS

For experiments where the fluid properties and ΔT remain constant and d is varied, the heat transfer coefficient c_q represents a non-dimensional heat flux and the plot of c_q vs Ra gives the variation of the heat flux with d. The shape of this data suggests that between each pair of heat flux transition Rayleigh numbers the heat flux at first increases with increasing plate spacing, goes through a maximum and then decreases. If the heat flux transitions also correspond to a change in flow pattern then each concave downwards curve represents a heat transfer efficiency curve for a given flow pattern.

With increasing d the heat flux decreases until another flow pattern becomes marginally more efficient. A transition to this pattern will then occur (this may be complicated by the hysteresis effect

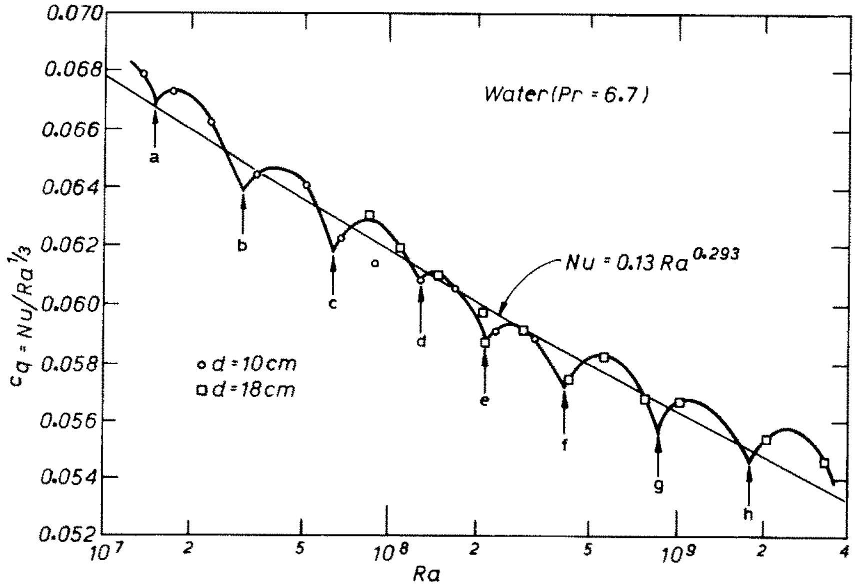

FIG. 6. Heat transfer coefficient c_q for water ($Pr = 6.7$) at high Rayleigh number plotted against the logarithm of the Rayleigh number. Data from Garon and Goldstein [6].

noted by Krishnamurti [5]). The curves for c_q suggest that the heat flux transitions may be caused by some form of maximization of the heat transfer.

It is also apparent from the shape of the c_q curves that for the same temperature difference ΔT, there may be two or sometimes as many as four or five different plate spacings which will produce the same heat flux. For example from Fig. 5 the same value of c_q of 0.105 is obtained for plate spacings represented by Rayleigh numbers of approximately 9×10^2 (conduction) 2.5×10^3, 1.3×10^4, and 2.2×10^4. This is not obvious from the previous methods of presenting thermal convection data.

5. THE MEAN VARIATION OF c_q WITH RAYLEIGH NUMBER

The value of c_q has been discussed previously in the literature in the context of the high Rayleigh number equation:

$$Nu = c_q Ra^{1/3}.$$

Turner [2] suggested that for water and air the values of c_q for this equation are 0.09 and 0.08 respectively. A plot of c_q from the available data over the full experimental range of Ra is shown in Fig. 7. (Where only a power relationship of the form $Nu = kRa^n$ was available this was plotted.) Figure 7 highlights both the approximate consistency of each

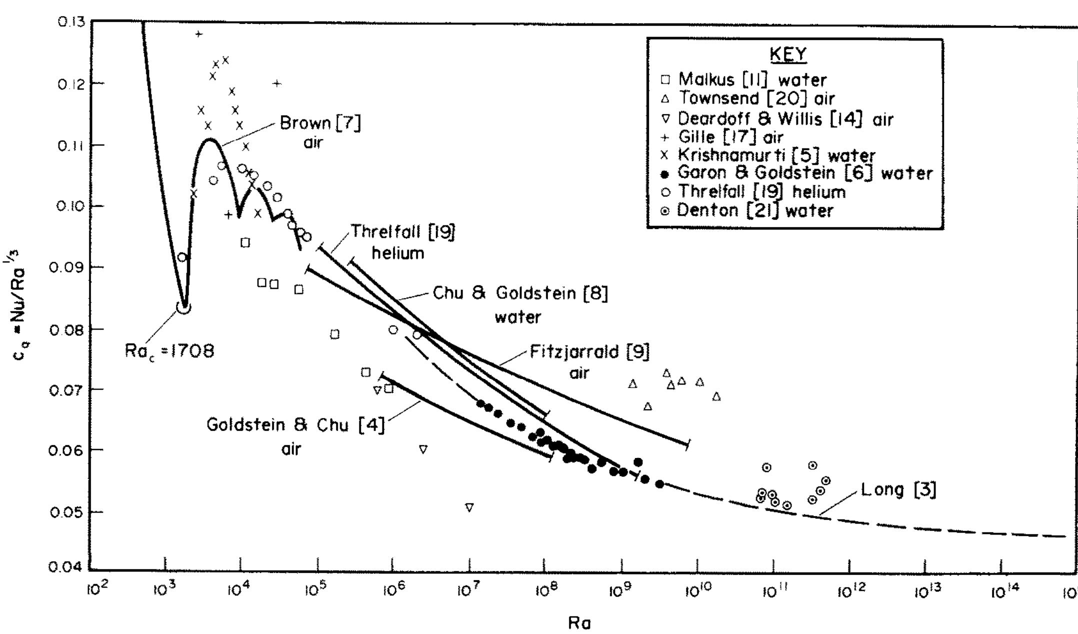

FIG. 7. Heat transfer coefficient c_q from parallel- and single-plate convection experiments plotted as a function of Rayleigh number over the full experimental range of Ra.

experiment and the marked difference between different experiments. It shows more clearly than Fig. 1 that at high Rayleigh numbers the differences are unlikely to be explained by simple Prandtl number dependence. A possible reason for these differences is aspect ratio dependence.

To calculate the Rayleigh number for the single plate data on Fig. 7 (Townsend [20] and Denton's [22] unsteady heat flux experiments), the temperature difference between the plate and the mean fluid temperature was assumed to be equivalent to $\frac{1}{2}\Delta T$. Twice the height of the enclosed fluid column was used for d. This likens these single-plate experiments to the lower half of a parallel-plate experiment. It is, however, debatable whether twice the fluid depth or the actual depth should be used. The latter case would give a Rayleigh number one-eighth the value of that calculated.

A plot of Long's [3] theoretical relationship, with constants obtained by fitting the two extreme points of Garon and Goldstein's data, is also shown. Long's factor $s = \frac{1}{3}$ has been assumed.

The overall variation of c_q with Rayleigh number suggests that over the experimental range of higher Rayleigh numbers, c_q decreases with increasing Ra (Fig. 7). At much higher Rayleigh numbers ($Ra > 10^{15}$), c_q tends to a probable asymptote between 0.04 and 0.06.

To avoid confusion, O'Toole and Silveston's [10] empirical curves (4) have not been plotted on Fig. 7. However, they are in good agreement with the plotted data. An empirical formula suggested by Hollands, Raithby and Konicek [23] which includes the large Rayleigh number asymptote of $c_q = 0.0555$, also agrees well with the data in Fig. 7. Empirical formulae based on $Ra^{1/3}$ do not allow for the decreasing value of c_q at high Ra.

6. SUMMARY AND CONCLUSIONS

The plotting of heat flux data in the form of $c_q(Nu/Ra^{1/3})$ vs $\log Ra$ highlights the role of interplate spacing in thermal convection. Data plotted in this manner show that for a given interplate temperature difference these may be several fluid layer thicknesses that will produce the same interplate heat flux. It also shows that at large Rayleigh numbers c_q decreases to a probably asymptote of between 0.04 and 0.06.

The shape of the c_q vs $\log Ra$ curves suggest that for a given Prandtl number the heat transfer rate might be subject to some maximization criterion which depends on the geometry of the horizontal plates (i.e. spacing and horizontal dimensions). Further work is required in this area.

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CONVECTION TURBULENTE ENTRE DEUX PLANS HORIZONTAUX

Résumé—On présente des résultats expérimentaux thermiques sur des plans parallèles et on introduit une méthode de représentation. La forme graphique $c_q[=Nu/Ra^{1/3}]$ en fonction du logarithme de Ra éclaire l'influence du rôle de l'espacement d des plaques en déterminant le flux thermique. Avec cette forme, on montre qu'entre les points de transition, le flux de chaleur (a ΔT constant) augmente jusqu'a un maximum, puis décroit lorsque le nombre de Rayleigh augmente. Ce comportement suggere un critere basé sur la géométrie. Les résultats montrent aussi une décroissance de c_q, quand Ra croit, vers une asymptote probable entre 0,04 et 0,06.

TURBULENTE KONVEKTION ZWISCHEN ZWEI HORIZONTALEN PLATTEN

Zusammenfassung—Experimentelle Daten über den Wärmestrom zwischen parallelen Platten werden gesichtet; zur Darstellung der Ergebnisse wird eine alternative Methode eingeführt. Es wird gezeigt, daß die grafische Darstellung von c_q $[=Nu/Ra^{1/3}]$ über dem Logarithmus von Ra den Einfluß des Plattenabstands d auf den Wärmestrom besonders hervorhebt. Die Auftragung der Daten in dieser Form zeigt, daß zwischen Wärmestrom-Übergangspunkten der Wärmestrom (bei konstantem ΔT) bis zu einem Maximum ansteigt und dann mit zunehmender Rayleigh–Zahl abnimmt. Dieses Verhalten deutet auf ein auf der experimentellen Geometrie beruhendes Gütekriterium für den Wärmeübergang hin. In dieser Darstellung zeigen die Daten insgesamt gesehen auch eine Abnahme von c_q mit zunehmendem Ra mit einer Tendenz zu einer Asymptote zwischen 0,04 und 0,06.

ТУРБУЛЕНТНАЯ КОНВЕКЦИЯ МЕЖДУ ДВУМЯ ГОРИЗОНТАЛЬНЫМИ ПЛАСТИНАМИ

Аннотация—В работе дан обзор экспериментальных данных по плотности теплового потока между параллельными пластинами и предложен новый метод графического представления результатов. Показано, что график зависимости c_q $[=Nu/Ra^{1/3}]$ от $\log R$ отражает влияние расстояния между пластинами, d, на плотность теплового потока. При таком графическом представлении видно, что между переходными точками плотность теплового потока (при постоянном ΔT) возрастает до максимума, а затем уменьшается с ростом числа Релея. Данная картина свидетельствует о наличии критериев эффективности теплопереноса, основанных на геометрии эксперимента. При таком представлении данные также свидетельствуют о суммарном снижении значения c_q с ростом Ra до возможной асимптоты в пределах 0,04–0,06.