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A CONTRIBUTION TO THE STUDY OF FREE CONVECTION IN A FLUID LAYER HEATED FROM BELOW

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Abstract—Heat transfer by free convection in an evaporating water layer is examined. In the experimental range of *Ra* numbers ($1{\cdot}8 \,.\, 10^3 \div 1{\cdot}15 \,.\, 10^7$) two free convection regimes are found with a transition point located at $Ra = (2{\cdot}2 \pm 0{\cdot}4) \,.\, 10^4$.

The different trends of the measured mean temperature profiles confirm the existence of the two regimes of free convection.

The results are compared with the available theories on free convection.

NOMENCLATURE

- c_p, specific heat at constant pressure;
- d, thickness of water layer;
- G, mass rate of water evaporation;
- Q, upward heat flux;
- r, latent heat of vaporization;
- T, temperature;
- T_a, temperature of the air;
- T_b, temperature of the rigid surface;
- T_m, temperature of the middle of the layer;
- T_s, temperature of the evaporating surface;
- v, velocity;
- z, vertical coordinate;
- α, coefficient of heat transfer in the water layer;
- α_a, coefficient of heat transfer in the air;
- β, coefficient of volumetric expansion;
- λ, thermal conductivity;
- μ, viscosity;
- ξ, $= (\pi z/d)(Ra/Ra_{te})^{\frac{1}{4}}$, dimensionless vertical coordinate;
- ρ, fluid density.

Superscripts

- —, mean values;
- ′, fluctuations.

Subscripts

- c, critical;
- e, evaporating layer;
- f, free–free boundaries;
- LT, laminar turbulent transition;
- r, rigid–rigid boundaries.

INTRODUCTION

THE DIFFICULTIES arising in the studies of fluid turbulence make the experimental investigations conducted in systems of simple geometry, characterized by a minimum of parameters, very interesting. In view of this, Malkus [1–4] examined theoretically and experimentally the field of turbulence that occurs in a horizontal fluid layer heated from below when the Rayleigh numbers are high enough; indeed, in this situation the layer height is the only geometric parameter, and the mean energy transport is independent of position. In the experimental research Malkus examined liquid layers bounded by two horizontal rigid surfaces, measuring the heat transport and the mean velocities up to Rayleigh numbers of 10^{10}.

Townsend [5–8] extended the research, measuring the mean temperature profiles, the mean squares of the temperature fluctuations, the autocorrelation functions and the heat transfer in the air above a heated horizontal surface, with and without a cold upper boundary. His results, agreeing with those of Malkus, suggest that for high Rayleigh numbers, a convection layer with a structure determined by the heat flux through it and independent of the conditions on the other boundary surface, develops close to each boundary; thus the resistence to heat transfer seems almost completely localized in the convection layers, and, away from these, the mean local temperatures should be approximately constant. The comparison of his results with Priestley's similarity theory [9] and with Malkus' theory of *maximum heat transfer* shows only a qualitative agreement.

Afterwards, many theoretical researches [8, 10–22] were developed both extending Malkus' ideas and Priestley's mixing length theory, and considering directly the non-linear hydrodynamic problem, also because the free convection problem has became one of the important points of departure for the formulation of ideas on the general dynamical behaviour of fluids.

The experiments reported in this paper were undertaken to examine a situation with particular boundary conditions, such as an evaporating horizontal water layer* heated from below, where turbulent paths [23] and large temperature fluctuations may develop on the evaporating boundary surface, by studying the heat transfer and the temperature profiles in the layer at different free convection regimes and comparing the results with available theories of thermal convection

The obtained data show that heat transfer in evaporating layers is higher than that found by other authors for fluid layers bounded by two rigid isothermal surfaces, and this may be explained as due to the turbulent transport in the convection layer near the evaporating surface.

In the experimental range of Rayleigh numbers ($1{\cdot}8 \,.\, 10^3$–$1{\cdot}15 \,.\, 10^7$) two regimes of free convection are found with a transition point located at $(2{\cdot}2 \pm 0{\cdot}4) \,.\, 10^4$ Ra. In the first regime, $Ra < (2{\cdot}2 \pm 0{\cdot}4) \,.\, 10^4$, Nu is proportional to $Ra^{\frac{1}{4}}$ while in the second Nu is proportional to $Ra^{\frac{1}{3}}$.

The two different convection regimes are revealed also by the mean temperature profiles, which show gradients also in the core of the layer in the lowest range of Ra, while in the highest one the gradients are all localized near the boundaries.

EXPERIMENTAL APPARATUS

The experimental apparatus, described in detail [24], consists of an externally insulated tank with square cross section (side 150 mm) where a heating copper plate, 10-mm thick, is placed with a minimum of clearance between the edges of the plate and the sides of the tank.

The heating is obtained by circulation, underneath the copper plate, of water from a thermostatic bath with temperature fixed within $\pm 0{\cdot}05$ degC to assure a constant temperature on the upper plate surface, i.e. on the lower boundary of water layer (with the higher heat flux we measured a temperature constant within $\pm 0{\cdot}1$ degC).

The copper plate is supported by three levelling screws to make it possible to place it horizontally and to change the distance between the heating surface and the free surface of the water layer exposed to the atmosphere.

During each measurement, to maintain a constant layer height, a flow of degassed and distilled water was introduced through the tank bottom in the mass of water lying below the copper plate, at a rate equal to the rate of evaporation. Thus the feed to the evaporating layer consisted of water passed uniformly through the plate-tank clearance and having the temperature of the plate surface. The

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* The start and preservation of convective circulation in liquid layers with an evaporating surface has been studied by Spangenberg and Rowland [25] and Foster [26].

velocity in the clearance was 0·01 cm/s at most, while convection velocities measured by Malkus [1] were 0·25–0·50 cm/s.

The temperatures were measured with copper constantan thermocouples (diameter 0·03 mm). The thermocouple probes consist of a horizontal length of wire (80 mm: copper wire electrically insulated 40 mm, constantan wire 40 mm), with the measuring junction at the mid-point. It was stretched between the extremities of a U-shaped support of plexiglas. This configuration makes negligible the errors for heat conduction along the wires in the mean temperature measurements, and the probe does not disturb the fluid layer near the point of measurement.

The vertical displacements of the thermocouple were obtained with a micrometric screw, and they were measured with a cathetometer.

The measurements of the thermocouple e.m.f. were made with a light-beam millivoltmeter, and a suitable recorder was operated by the light spot displacements. The whole apparatus was calibrated with an accuracy of 0·1 degC. The time of response of the recorder was 0·5 s for a 20 degC displacement.

At each position the duration of the temperature recording was up to 20 min: thus using a planimeter, we have obtained mean temperature values reproducible within ±0·1 degC.

Particular care was taken in the temperature measurements at the evaporating surface. Many tests were made in a glass tank: in the course of these the distance of the measuring junction from the evaporating surface was determined by measuring with the cathetometer, the distance of the junction from its image reflected from the surface.

The tests showed that the surface tension makes it very difficult to place the thermocouple junction near the surface without deformations. The best procedure seemed to be to give a very slight inclination on the horizontal plane to the thermocouple length having the junction in the mid-point. After a complete immersion of this length, the thermocouple probe was raised until the higher part of the wire emerged from the layer deforming the surface, while the junction was very near the layer's surface in an underformed area. With suitable lighting of the surface, the deformation was revealed directly and from the shadow on the copper plate.

HEAT-TRANSFER MEASUREMENTS

The measurements were carried out with water layers of height variables from 3 to 31 mm and Ra and Pr in the ranges $1{\cdot}38 . 10^3$–$1{\cdot}15 . 10^7$ and $2{\cdot}8 \div 4{\cdot}4$ respectively.

Let us define [24] the heat-transfer coefficient across the layer, with respect to conductive and turbulent transport only, as

$$Q \equiv \alpha(\overline{T}_b - \overline{T}_s) = \left(-\lambda \frac{\partial \overline{T}}{\partial z} + \rho \overline{h'v'_z}\right) \qquad (1)$$

where the right term can be calculated, from the experimental data, as

$$\left(-\lambda \frac{\partial \overline{T}}{\partial z} + \rho \overline{h'v'_z}\right)_s = rG + \alpha_a(\overline{T}_s - \overline{T}_a). \qquad (2)$$

The heat-transfer results are plotted in Fig. 1 as $Nu = f(Ra)$.

Nusselt numbers:

$$Nu \equiv \frac{\alpha d}{\lambda} = \frac{rG + \alpha_a(\overline{T}_s - \overline{T}_a)}{\lambda(\overline{T}_b - \overline{T}_s)} \qquad (3)$$

and Rayleigh numbers:

$$Ra = \frac{\rho^2 c_p g \beta(\overline{T}_b - \overline{T}_s)\, d^3}{\mu\lambda} \qquad (4)$$

were calculated from the experimental data considering the physical properties at the temperature in the middle of the layer, except for r regarding which $\overline{T}_s$ was considered. As $\alpha_a(\overline{T}_s - \overline{T}_a)$ was, in all the tests, about 0·1 rG, it became unnecessary to know α_a with a high degree of accuracy. Therefore we have assumed the values for the air free convection on the flat horizontal surface. Furthermore, as the influence of mass transfer was negligible in the situation considered, we have not taken it into account.

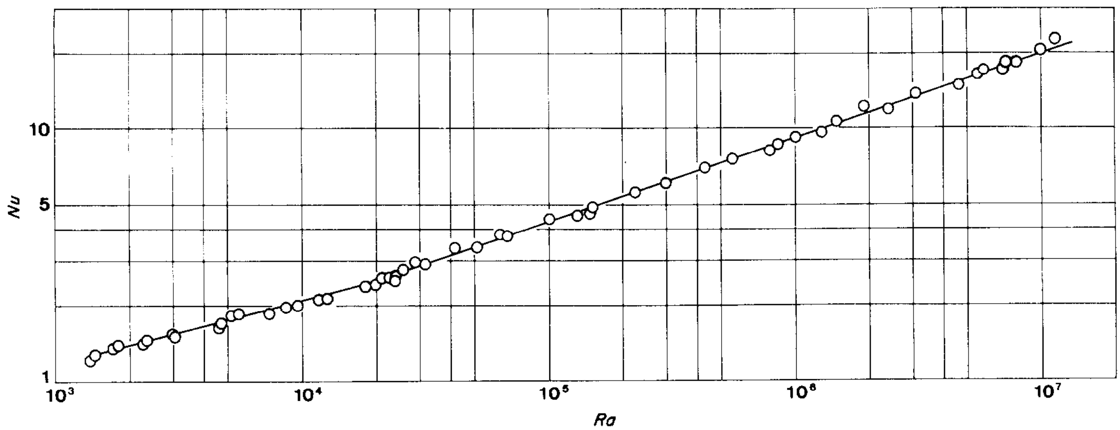

FIG. 1. Free convection heat transfer in the evaporating water layer.

Because of the limited range of Pr numbers the dependence of Nu upon Pr could not be tested in the present experiments.*

From Fig. 1 one observes that Nu dependence upon Ra changes from

$$Nu = 0{\cdot}208\,Ra^{\frac{1}{4}} \tag{5}$$

for

$$Ra < (2{\cdot}2 \pm 0{\cdot}4)\,.\,10^4,$$

to

$$Nu = 0{\cdot}092\,Ra^{\frac{1}{3}} \tag{6}$$

for

$$Ra > (2{\cdot}2 \pm 0{\cdot}4)\,.\,10^4.\dagger$$

It seems that the change may be due, as for the layer bounded by two rigid surfaces, to the transition from a laminar regime where—in accordance with the results for free convection cases studied as problems of laminar boundary layer—Nu is proportional to $Ra^{\frac{1}{4}}$, to a turbulent one, where the layer height is no more a significant parameter for heat transfer.

It is worthwhile to note the lower value of Ra at which the transition from one mode of convection to another occurs in the present case in comparison with that experimentally found [1, 27] for both rigid surfaces (about $5\,.\,10^4$). Indeed, the "weaker" constraints imposed on the temperature in the upper surface of the evaporating layer, where velocity (also in the vertical direction) and temperature fluctuations may occur up to the free surface, suggest that the critical Ra needed to sustain any perturbation imposed on the system will be smaller than those in case with two isothermal rigid boundary surfaces.

It is interesting to examine equations (5) and (6) in relation to the available experimental data and to the numerical results of theoretical analyses.

Important correlations of experimental heat transfer measurements for both rigid isothermal boundaries are those obtained, by means of a regression technique, by O'Toole and Silveston [28] from a large body of experimental data

* The heat flux through the layer in the apparatus is maintained by the evaporating surface at the upper boundary and therefore the variation of Pr that can be achieved is limited because we must work with liquids that have a sufficiently high volatility, and substances with this property have Pr numbers of about the same order of magnitude.

† In a previous paper [2] experimental data in the range $1{\cdot}33\,.\,10^5$–$1{\cdot}15\,.\,10^7$ of Ra numbers, were correlated, following the Pr dependence suggested by Globe and Dropkin [30], as

$$Nu = 0{\cdot}080\,Ra^{\frac{1}{3}}\,Pr^{0{\cdot}074}$$

with a very small scattering of the experimental results and good agreement with the correlation given here.

of several authors, and by Silveston [29]; following this *Pr* is a significant parameter only at high *Ra* (turbulent regime).

The plots of the O'Toole and Silveston correlations (Fig. 2) give higher *Nu* than equation (5) in the laminar regime and when a *Pr* of 3·6 (mean value in the present experiments) is considered, lower *Nu* than equation (6) in the turbulent one. Nevertheless, plotting Poots' correlation for air, which accords with Jakob [31] we obtain *Nu* lower than those given by equation (5); considering low *Ra* values, the same result is obtained by plotting De Graaf's [30] experimental data for air.

Thus it seems of particular interest to compare the results of present experiments with those achieved, working with water, by Malkus in the laminar and turbulent regimes and Globe and Dropkin in the turbulent one.

In the turbulent regime the results of Malkus, Globe and Dropkin are only a little lower than those given by the correlation of O'Toole and Silveston: *Nu* are proportional to about $Ra^{\frac{1}{3}}$, as in equation (6), and are about 15–20 per cent lower than those given by this.

In the laminar regime *Nu* values obtained by Malkus are about 5 per cent lower than those given by equation (5).

The different increasing values of *Nu* in the laminar and turbulent regimes given by (5) and (6) compared to Malkus' experimental results, may be explained as due to the different weight of the heat-transfer resistances of the convection layers in the two regimes.

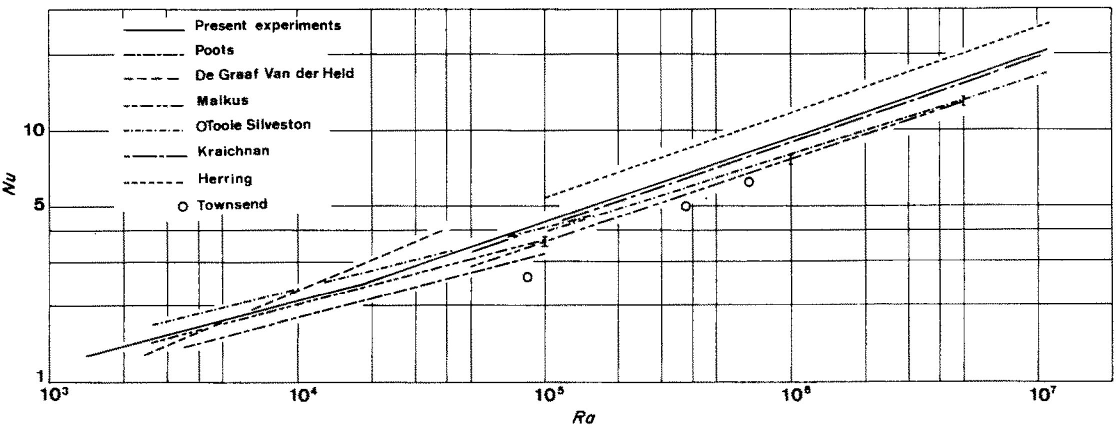

FIG. 2. Comparison between heat transfer in the evaporating water layer and in fluid layers confined by two rigid boundaries.

A comparison with numerical results of theoretical research may be developed considering the correlations of Kraichman [16] and Herring [12] for turbulent convection.

In considering the correlation of Kraichman, in which the numerical coefficient for rigid surface bounded layers must be regarded as approximate estimates based on idealized situations, it will be observed that *Nu* is proportional to $Ra^{\frac{1}{3}}$, except at extremely large *Ra*, and are a little lower than those reported here.

Herring finds for rigid boundaries, at large Rayleigh numbers, Nusselt numbers 50 per cent greater than those found experimentally for the same configuration and thus greater than the present results. Fromm [10] ascribes this difference to the presence in the experimental tests of rigid vertical walls, while in the theoretical analysis a layer of infinite horizontal extent is considered.

Furthermore, it is worth while to examine the obtained experimental results in comparison with the Malkus theory of "maximum heat transport" [2, 4].*

Malkus' theory states, for the turbulent regime† that

$$Nu = \left(\frac{Ra}{Ra_t}\right)^{\frac{1}{3}} \quad (7)$$

where Ra_t is the critical Ra of the "smallest scale of motion" in the turbulent field.

Nu dependence on Ra given by (7) accords with (6). Assuming that (7) may be applied in the examined case, we have from (6) and (7):

$$Ra_{te} \simeq 1284 \quad (8)$$

where Ra_{te} is the transition Ra for the considered evaporating layer. Malkus, for free–free isothermal boundary conditions, obtains

$$Ra_{tf} \simeq 1513. \quad (9)$$

If we extend his approximate procedure to get Ra_{tr}, for rigid–rigid surface bounded layers, from Ra_{tf}, it is possible to calculate approximately the critical Ra for the onset of free convection in the evaporating layer

$$Ra_{ce} = \frac{Ra_{cf}}{Ra_{tf}} Ra_{te} \simeq 550. \quad (10)$$

Thus it results that the possibility of perturbation of temperature on the free surface and of convection currents moving downward into the bordering region, would determine the onset of free convection at Ra lower than for two free isothermal boundary surfaces ($Ra_{cf} \simeq 656$). This accords qualitatively with the experimental results of Spangenberg and Rowland [25] who found that $Ra \simeq 102$ was sufficient to maintain an established uniform circulation in an evaporating water layer, and with the theoretical results of Gribov and Gurevich [33] about the onset of free convection in fluid layers, when the convection currents are free to move into the bordering stable regions.

If we apply the same procedure to calculate the Ra of transition from laminar to turbulent regimes from that for rigid–rigid boundary surfaces, we have:

$$Ra_{LTe} = \frac{Ra_{ce}}{Ra_{cr}} Ra_{LTr} \simeq 1{\cdot}61 \,.\, 10^4 \quad (11)$$

which is in good agreement with the value experimentally found.

MEAN TEMPERATURE PROFILE MEASUREMENTS

Mean temperature profiles were measured in both convective regimes singled out in the heat transfer measurements, changing the lower boundary surface temperature, the layer height and, consequently, the evaporating rate and the temperature on the evaporating surface. Some of the recorded mean temperature profiles are plotted in Figs. 3 and 4; the temperature profiles were made dimensionless, introducing the temperature $(\bar{T} - \bar{T}_s)/(\bar{T}_b - \bar{T}_s)$ and the vertical coordinate z/d.

We will point out that experimental results show very good agreement between the heat flux computed from the heat and mass transfer from the upper free surface and the molecular heat flux computed from the temperature gradient recorded near the lower rigid boundary (in comparing the two results, the radiative heat transport contribution was not taken into account because negligible in the experiments).

All the mean temperature profiles at about $Ra > 2{\cdot}4 \,.\, 10^4$ show large temperature changes localized in comparatively thin layers near the upper and lower boundary, while in a large part of the layer the mean temperature is constant, in accordance with the theories of turbulent free convection.

Mean temperature profiles at about $Ra < 2{\cdot}4 \,.\, 10^4$, instead show a non-null mean temperature gradient even in the core of the layer where,

* The hypothesis of "maximum heat transport" and the stability of the "smallest scale of motion" which contributes to the heat transport are analysed extensively in references [8, 14, 21].

† Correlations of the same kind are used by many authors [3, 13–15, 17, 18, 20] to give the heat transport across a fluid layer heated from below for different boundary conditions, in the neighbourhood of the onset of the convective motion.

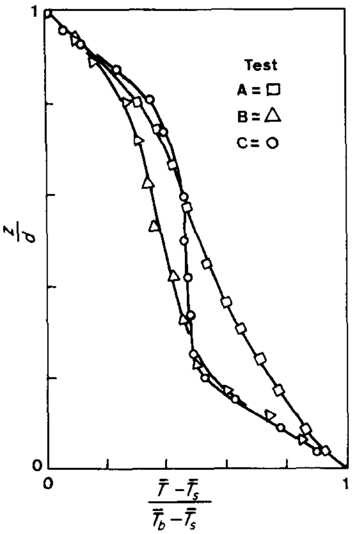

FIG. 3. Dimensionless mean temperature profiles in the evaporating water layer:

Test A
($Ra = 8{\cdot}85 . 10^3$, $Nu = 1{\cdot}90$, $d = 4$ mm, $Q = 804$ kcal/h m^2, $\bar{T}_b = 47$°C, $\bar{T}_s = 43{\cdot}9$°C).

Test B
($Ra = 2{\cdot}34 . 10^4$, $Nu = 2{\cdot}45$, $d = 5$ mm, $Q = 1006$ kcal/h m^2, $\bar{T}_b = 50{\cdot}4$°C, $\bar{T}_s = 46{\cdot}6$°C).

Test C
($Ra = 3{\cdot}19 . 10^4$, $Nu = 2{\cdot}85$, $d = 4{\cdot}9$ mm, $Q = 1489$ kcal/h m^2, $\bar{T}_b = 58{\cdot}1$°C, $\bar{T}_s = 53{\cdot}5$°C).

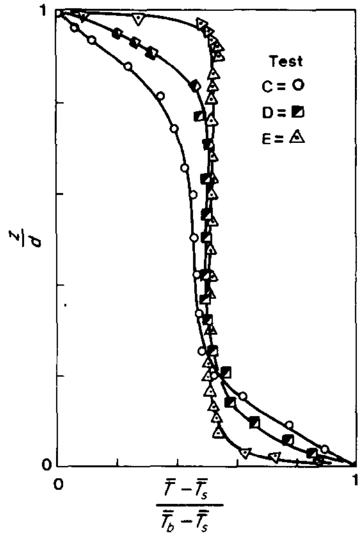

FIG. 4. Dimensionless mean temperature profiles in the evaporating water layer:

Test C
($Ra = 3{\cdot}19 . 10^4$, $Nu = 2{\cdot}85$, $d = 4{\cdot}9$ mm, $Q = 1489$ kcal/h m^2, $\bar{T}_b = 58{\cdot}1$°C, $\bar{T}_s = 53{\cdot}5$°C).

Test D
($Ra = 1{\cdot}48 . 10^5$, $Nu = 4{\cdot}60$, $d = 9{\cdot}8$ mm, $Q = 853$ kcal/h m^2, $\bar{T}_b = 48$°C, $\bar{T}_s = 44{\cdot}7$°C).

Test E
($Ra = 5{\cdot}79 . 10^6$, $Nu = 16{\cdot}9$, $d = 29{\cdot}2$ mm, $Q = 1316$ kcal/h m^2, $\bar{T}_b = 55{\cdot}8$°C, $\bar{T}_s = 51{\cdot}9$°C).

therefore, the heat transferred by molecular conduction is not negligible in comparison with convective transport.

This difference between temperature profiles at $Ra \gtrless 2{\cdot}4 . 10^4$ confirms the existence of the two kinds of convective regimes pointed out in the analysis of heat-transfer results: indeed, the non-null mean temperature gradients also in the middle of the layer make the layer height a significant parameter for heat transfer, and particularly make the heat-transfer coefficients decrease with the layer height at the fixed temperature difference ($\bar{T}_b - \bar{T}_s$).

It is interesting to remark that all temperature profiles are asymmetric with respect to the temperature in the middle of the layer: indeed, as a consequence of the constraints imposed on the convection flow by the boundary conditions considered in the experiments, the mean temperature gradients near the upper boundary are lower than those near the rigid one and the height of the convection layer is greater at the evaporating surface.*

From the temperature measurements it was possible to note some qualitative aspects of temperature fluctuations in laminar and convective regimes.

In the turbulent one the temperature fluctuations were practically zero close to the lower rigid surface, then they augmented becoming

* It is important to observe that the experimental temperature profiles for turbulent free convection in air layers with symmetric rigid–rigid boundaries reported by Thomas and Townsend [5] are asymmetric and show temperature differences larger in the upper convection layer than in the lower one.

larger at the transition between the convection layer and the isothermal core, in the middle of which they were small. In the upper convection layer the temperature fluctuations were very large, augmenting near the surface. In the lower part of the constant temperature zone an alternation of periods with constant temperature and periods with positive fluctuations occurred; the opposite took place in the upper part. This is in agreement with Townsend's observations of quiescent and active temperature fluctuations far from the surface. This should be a consequence of the temperature profiles: when the turbulent motion determined flow from the constant temperature zone the constant temperature periods occur, while when it determined flow from the convection layers, where large temperature gradients are present, temperature fluctuations, positive in the lower part, negative in the upper one, occur.

The qualitative aspect of temperature fluctuations in the laminar case was about the same as in the turbulent one, but with smaller amplitude and larger periods and with fluctuations also in the middle of the layer.

In the turbulent regime, in view of the independence of the two convection layers near the boundary surfaces,* we may compare the measured mean temperature profile near the rigid surface with the theoretical ones obtained by Malkus [4] for free–free isothermal boundaries, following the procedure used by him to examine Townsend's experimental results. Thus, to take account of the different boundary conditions we calculate the value of Malkus' dimensionless geometrical coordinate ξ, at which:

$$\frac{\bar{T}(\xi_b) - \bar{T}_m}{T(0) - \bar{T}_m} = \left(\frac{Ra_{te}}{Ra_{tf}}\right)^{\frac{1}{4}} \simeq 0{\cdot}96. \qquad (12)$$

The experimental mean temperature profiles in the lower convection layer, for three different Q, are plotted in Fig. 5 as $(T(\xi) - \bar{T}_m)/(T(0) - T_m)$ vs. ξ, superimposed on the theoretical curve, obtaining a good agreement; this is particularly interesting because no disposable constant appears in Malkus theoretical mean temperature profile.

* In a previous paper [34], where the evaporation rate from deep non-isothermal liquid layers is studied, the mean temperature profiles in the convection layer near the evaporating surface were made dimensionless introducing similarity scales like those used by Townsend.

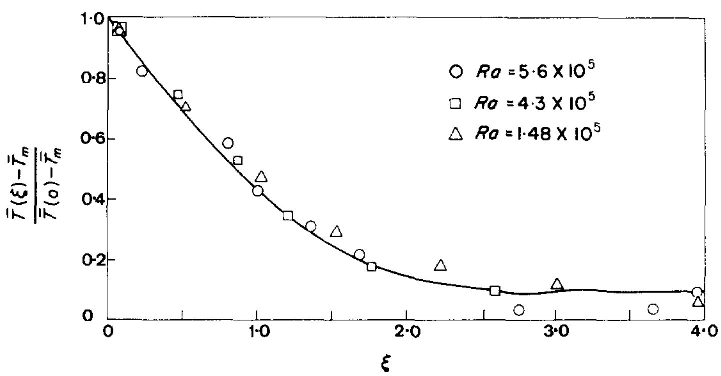

FIG. 5. Comparison of the measured mean temperature profiles near the rigid surfaces in the evaporating layer with the Malkus' theoretical curve.

(Ra = 1·48 . 10^5, Nu = 4·60, d = 9·8 mm, Q = 853 kcal/h m^2, $\bar{T}_b$ = 48·1°C, $\bar{T}_s$ = 44·7°C; Ra = 4·3 . 10^5, Nu = 6·94, d = 16·3 mm, Q = 578 kcal/h m^2, $\bar{T}_b$ = 42·9°C, $\bar{T}_s$ = 40·4°C; Ra = 5·6 . 10^5, Nu = 7·46, d = 13·6, Q = 1274 kcal/h m^2, $\bar{T}_b$ = 53·6°C, $\bar{T}_s$ = 49·4 C).

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Résumé—Le transport de chaleur par convection libre dans une couche d'eau qui s'évapore est étudié. On a trouvé dans la gamme expérimentale des nombres Ra ($1{,}8 \cdot 10^3$–$1{,}15 \cdot 10^7$) deux régimes de convection libre avec un point de transition placé à $Ra = (2{,}2 \pm 0{,}4) \cdot 10^4$.

Les différentes tendances des profils de températures moyennes mesurées confirment l'existence de deux régimes de convection libre.

Les résultats son comparés avec les théories actuelles de la convection libre.

Zusammenfassung—Der Wärmetransport durch freie Konvektion in einer verdampfenden Wasserschicht wird untersucht. Im Versuchsbereich der Ra zahlen ($1{,}8 \cdot 10^3$–$1{,}15 \cdot 10^7$) wurden zwei Regime der freien Konvektion gefunden mit einem Umschlagpunkt bei $Ra = (2{,}2 \pm 0{,}4) \cdot 10{,}4$.

Unterschiedliche Tendenzen der gemessenen mittleren Temperaturprofile bestätigen die Existenz der beiden freien Konvektionsregime.

Die Ergebnisse sind mit verfügbaren Theorien der freien Konvektion verglichen.

Аннотация—В работе проведено исследование теплообмена в условиях свободной конвекции при испарении слоя воды. В исследованном диапазоне чисел Ra ($1{,}8 \cdot 10^3 - 1{,}15 \cdot 10^7$) установлено наличие двух режимов свободной конвекции с точкой перехода, соответствующей числу $Ra = (2{,}2 \pm 0{,}4)10^4$. Существование двух режимов свободной конвекции подтверждается наличием различных видов измеренных профилей температуры. Результаты работы сравниваются с известными теоретическими расчетами по свободной конвекции.