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EXPERIMENTAL STUDY OF FLOW PATTERNS AND TEMPERATURE FIELDS IN HORIZONTAL FREE CONVECTION LIQUID LAYERS

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Аннотация—Призодятся резудьтаты экспериментадьного исследования гидродинамической картины течения хидкости в горизонтадьных слоях и в полубесконечном горизонтальном слое волизи поверхности теплообмена при свободной конвекции, а такхе измеряются профили температур в отдельной вихревой ячейке

NOMENCLATURE

Ra,	Rayleigh number, $= Gr\,Pr$;
$\bar{x}$,	dimensionless horizontal coordinate, $= x/l$;
l',	cell side;
$\bar{y}$,	dimensionless vertical coordinate, $= y/l$;
l,	height of bed;
Δt,	temperature difference between heat-transfer surfaces, $= t_1 - t_2$;
$\Delta t_{\max}$,	temperature difference in up- ($x = 0$) and down- ($x = 1$) flows;
v_0,	maximum value of the velocity normal to heat-transfer surfaces in the middle cross-section of cellular layer;
a,	apothem of regular "n"-angular;
λ,	thermal conductivity coefficient;
ν,	kinematic viscosity;
Q,	heat flux;
t_0,	$= t_1 + t_2/2$.

A NUMBER of papers [1-6] have been published on the study of hydrodynamic liquid flow patterns in horizontal layers at natural convection.

According to [3] a steady-state cellular flow is observed up to the values of $Ra \approx 30000$ and at $Ra > 30000$ the flow in a layer is turbulent. Croft [5] comes to the conclusion that at $Ra > 45000$ and also in the bulk near a horizontal heat-transfer surface, a cellular layer exists. In paper [5] a great variety of flow patterns are described in a horizontal layer of molten sulphur. It is not known, however, under which conditions and at what Rayleigh numbers the transitions from one kind of flow to another are possible. Thus so far no systematic study is available on hydrodynamic liquid flow patterns in a horizontal flow at natural convection.

The aim of the present paper is an experimental study of hydrodynamic liquid flow patterns in a horizontal layer and semi-infinite layer near a horizontal surface of natural convection and the measurement of the temperature profile in an individual cell.

The experimental unit, the scheme of which is shown in Fig. 1, consists of two plane horizontal heat exchangers. The upper one is made of two ground glass plates (1) (7 × 210 × 280 mm) glued along the perimeter with epoxy resin, so that a slit 7-mm high is formed through which flows (5-6) thermostatic water at a temperature near to that of the surrounding air. The lower heat exchanger is made of a copper plate (2) (10 × 260 × 350 mm) the surfaces of which are carefully machined.

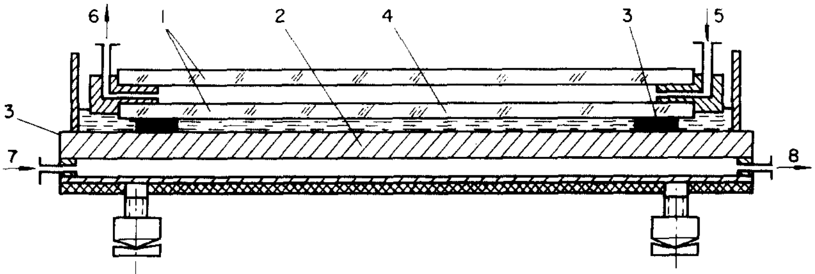

FIG. 1. Scheme of the experimental installation:

1, glass plates of upper heat exchanger;
2, copper plate of lower heat exchanger;
3, plates determining the height of the stream of the tested liquid, 4;
5–7, inflow of thermostatic water into heat exchanger;
6–8, water outflow from heat exchanger.

The heat-transfer surfaces (2) and (4) are made parallel by means of two plates (3) of calibrated thicknesses and upon which the upper heat exchanger is resting. The temperature of the heat-transfer surface of the upper heat exchanger was measured by two nichrome–constantan thermocouples 0·06 mm in diameter. The thermocouples were glued upon the glass with epoxy resin and then the plate was baked at $t = 120°C$. The thermocouple junctions were set flush with the heat-transfer surface before baking. The temperature of the lower heat-transfer surface was measured with nichrome–constantan thermocouples 0·2 mm in diameter. The thermocouple junctions were built into the plate by being placed in 1·5 mm dia. holes drilled at a distance of 0·5 mm from the heat-transfer surface and were terminated in the plate face along a groove 9 mm deep. After the thermocouples were put, the grooves were filled with epoxy resin and the plate was treated thermally at $t = 120°$. The e.m.f. of the thermocouples was measured on low-resistant d.c. potentiometer P-306, class 0·015, with 1·0 class galvanometer M195/I whose resolution for current measurement was 1·1 10^{-8}A/division.

Constant temperatures of heat-transfer surfaces were obtained by circulating thermostatic water. In the thermostats the water temperature was kept constant within 0·1 degC. As the test liquid, 96% ethyl alcohol was used. To visualize the flow, well-wettable aluminum particles 5–20 μ in size were placed in the alcohol. The photograph of the flow patterns was taken with the camera "canvas" and the photocamera "start" with nozzle rings.

The experiments were carried out as follows.

The temperature of the circulating water was measured in each heat exchanger. After filling the working volume (4) with ethyl alcohol, the upper heat exchanger (1) was mounted on plates (3). For some time a transient heat-transfer process was observed. The time of transition to steady regime was the shorter, the higher was the initial temperature difference. Under steady conditions the liquid flow patterns also varied depending on the initial temperature difference between the heat-transfer surfaces. In Figs. 2(a, b) the characteristic liquid flow pictures are shown in the layer under the transient regime which preceded the polygonal flow structure at steady-state conditions with $Ra = 17600$. At the beginning the flow is of roller form (Fig. 2a), then the rollers disintegrate and are replaced by chains of cells with liquid upstream taking place in the centre of the cell (Fig. 2b). Gradually the flow pattern changes to a stable polygonal structure (Fig. 2c). Under steady-state conditions of the heat exchanger the downflow always takes place in the centre and the upflow at the bounding walls of the polygonal cell.

In Fig. 2 photographic pictures of the liquid

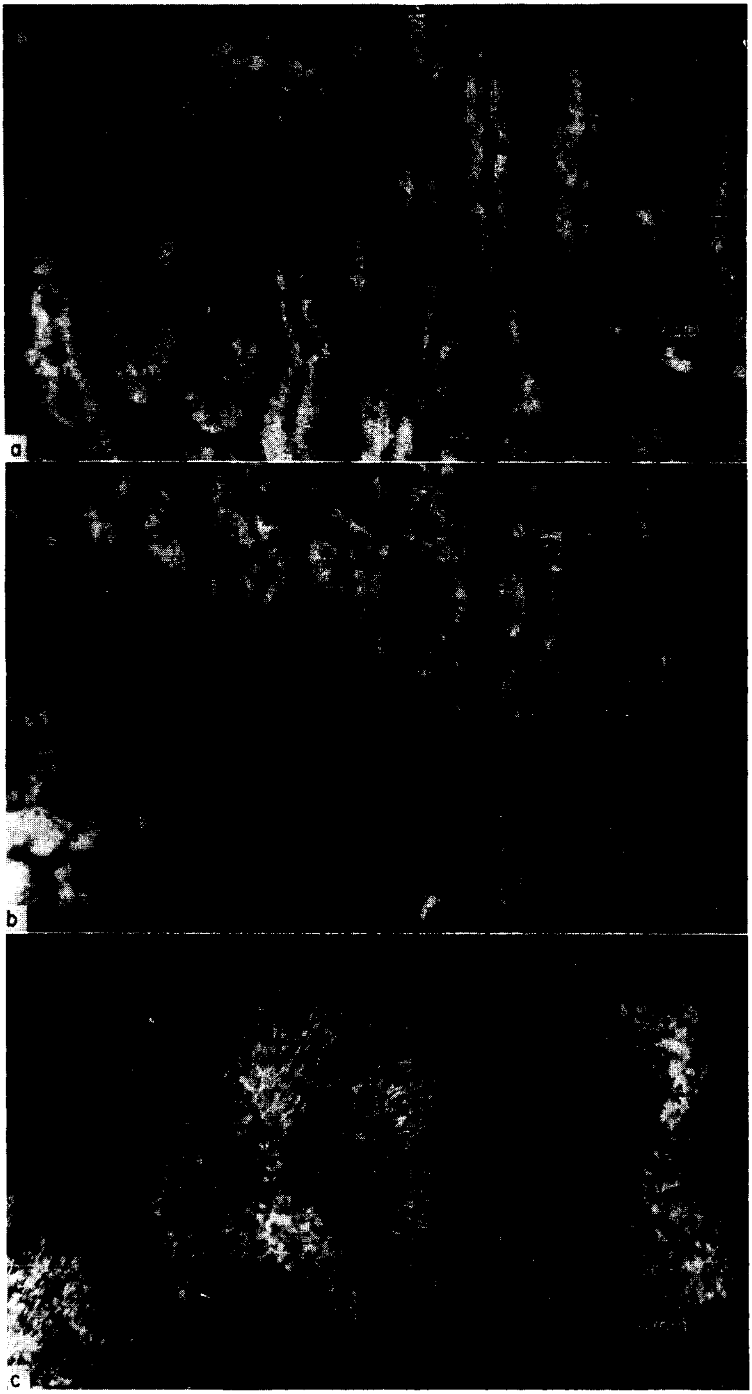

FIG. 2. Liquid flow patterns: (a, b) Unsteady eddy flow in the bed, $l = 4$ mm; (c) steady cellular flow in the bed, $l = 4$ mm, $Ra = 17\,600$ preceded by the flows shown in Fig. 2 (a, b); (d) $l = 4$ mm, $Ra = 22\,600$; (e) $l = 4$ mm, $Ra = 38\,000$; (f) $l = 5{\cdot}5$, $Ra = 93\,000$.

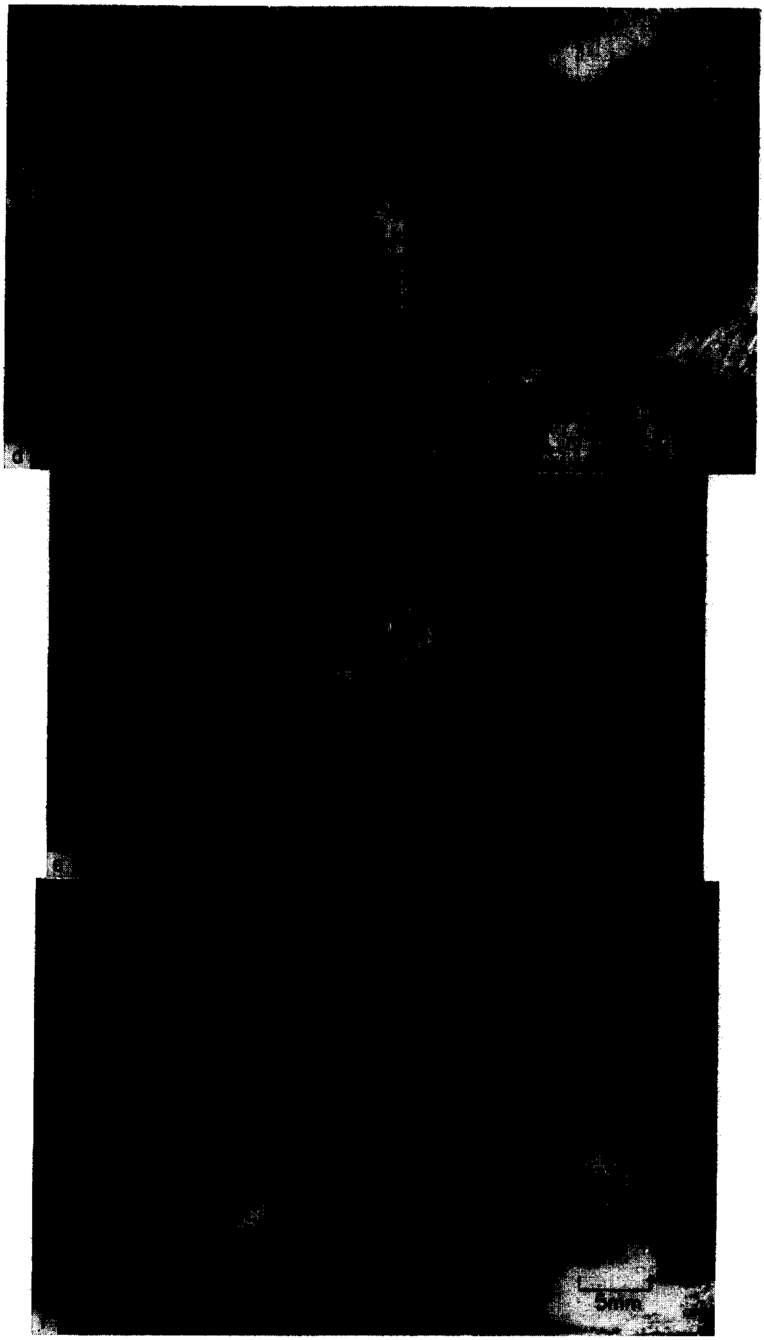

FIG. 2—*continued.*

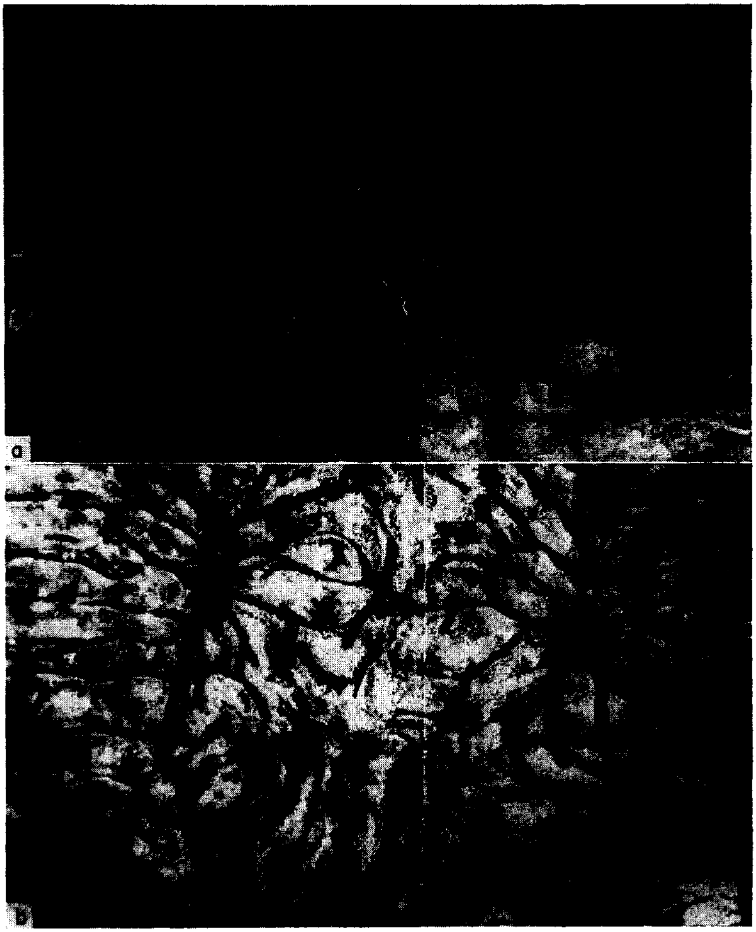

FIG. 3. Liquid flow patterns: (a) $l = 5{\cdot}5$ mm, $Ra = 10^5$; (b) $l = 10$ mm, $Ra = 730\,000$; (c) $l = 10$ mm, $Ra = 730\,000$; (d) $l = 10$ mm, $Ra = 1\,500\,000$.

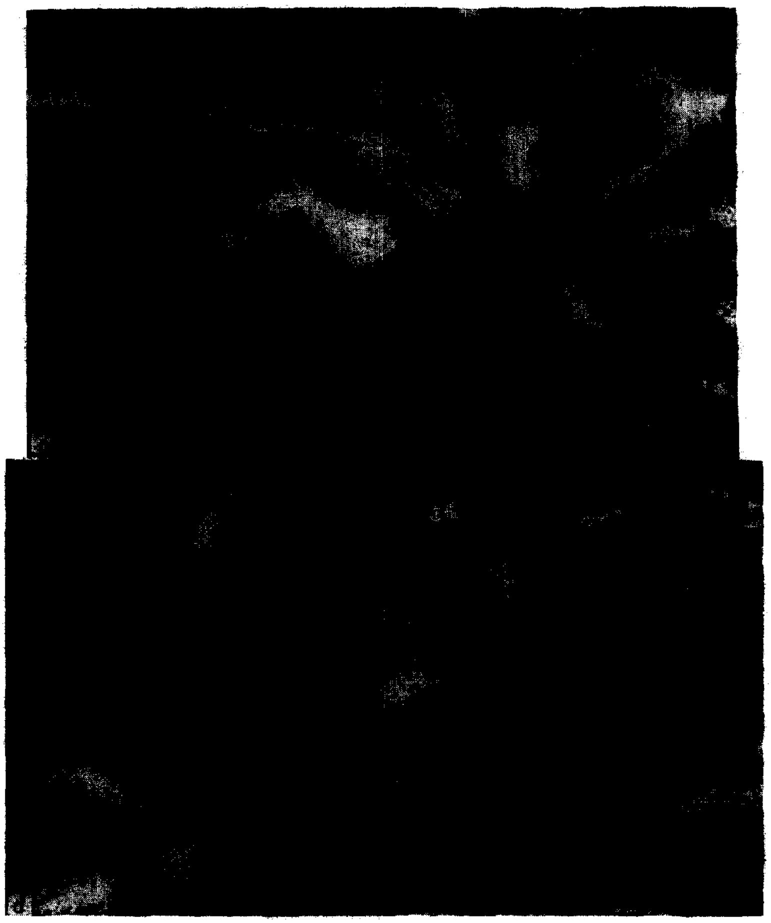

FIG. 3—*continued.*

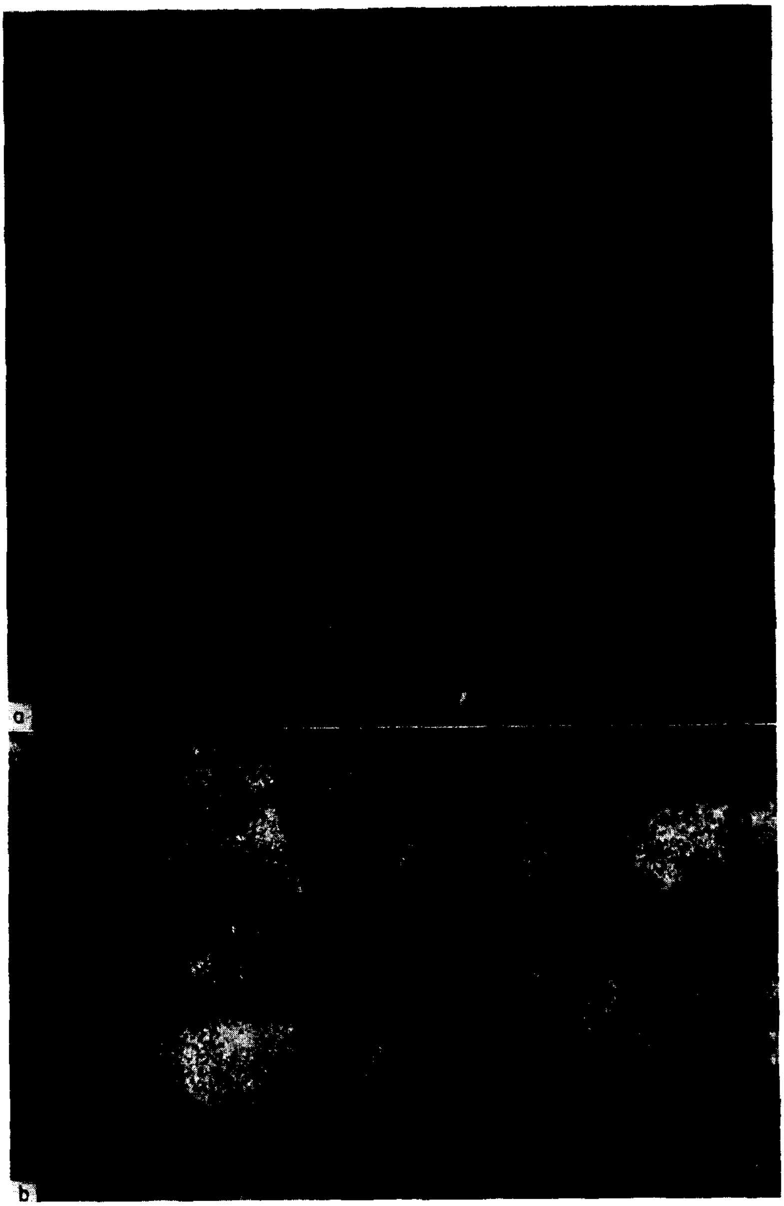

FIG. 8. Liquid flow patterns near the heat-transfer surface in large volume: (a) height of bed, 75 mm; cell size, 6 mm; cooling surface—evaporating surface, $Ra_{\text{h.l.}} = 7000$; (b) height of bed 40 mm, $Ra_{\text{h.l.}} = 3100$, liquid cooling surface–solid surface.

flow patterns are presented in a horizontal layer at various Rayleigh numbers. In the pictures taken with a time lag of 0·735 s and considerable magnification, the traces of particles are seen. The character of the flow of the liquid in the convective cell can be judged by these pictures. As seen from Fig. 2, the flow is of polygonal structure when $Ra < 95000$. The flow in a polygonal cell is laminar. Beginning from $Ra \sim 25000$ transformation of a radial flow form the bounding sides of the polygon to the centre takes place and at $Ra \approx 10^5$, polygonal structure of the liquid flow destroys completely and transforms into a roller structure (Fig. 3a). The flow in the roller is of complicated character. Dark strips across the roller indicate the existence of a downflow at the given place.

Further increase of Rayleigh number leads to greater complication of the liquid flow pattern.

As seen from Figs. 3(b, c, d) at $Ra > 3 \, . \, 10^5$ the flow is of very complicated shape (dark lines on pictures are downflows). Roller flows of smaller scale are observed against the background of slow large-scale movement. The rollers change their places continuously, however, in the roller the flow is laminar up to $Ra \sim 1{\cdot}5 \, . \, 10^6$.

Further increase of the Rayleigh numbers in the present installation was impossible because of substantial effect of lateral flows.

In the region of steady cellular convection the effect of the layer height and Ra upon the cell size was studied. The flow pattern in the layer was photographed and the mean area of the cell and the lateral size of the hexagonal cell were determined from the known scale of the photographic picture. It is seen from Fig. 4 that the relative value of the cell side (hexagonal side l' to layer height l ratio) slightly depends upon Ra.

As pointed out above, in a horizontal bed the cellular structure of the liquid flow is fairly steady. An attempt was, therefore, made of measuring the temperature over the volume of a separate cell. The difficulty of measuring temperature in a cell is that the measurements have to be made in small volumes. The temperatures were measured with combs of nichrome–constantan thermocouples 0·06 mm in diameter. The thermocouples were mounted on a $2 \times 120 \times 140$ mm plate of stainless steel with a 60×100 mm inner hole and a ground lower surface. The plate allowed movement in the horizontal plane. The vertical comb had five thermocouples, the horizontal one, nine. The e.m.f. of the thermocouples in the thermostatic volume differed from the mean value by not more than $\pm 0{\cdot}001$ mV. In the vertical comb the distance between the thermocouples was determined by photographing it before and after the experiment with the known scale of photography. In the cell the coordinates of the thermocouple junctions were determined by photographing the liquid flow patterns in the cell with the thermocouples at the moment of the temperature measurement. The films were analysed under the microscope.

The horizontal comb was made only for measuring temperatures within the middle section of the layer. The presence of the thermocouples did not cause any noticeable disturbances in the cell.

In Fig. 5 some temperature measurements

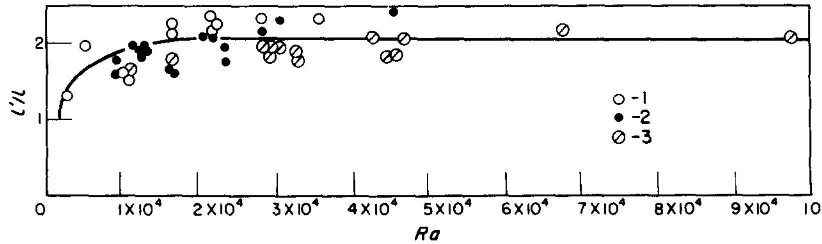

FIG. 4. Cell size at various Rayleigh numbers: 1, $l = 4$ mm; 2, $l = 3{\cdot}2$ mm; 3, $l = 5{\cdot}5$ mm.

along the layer height are presented for various sections and various Rayleigh numbers with $\bar{x} = x/l$. The reference point of the x coordinate is at the generating sides of the polygonal cells.

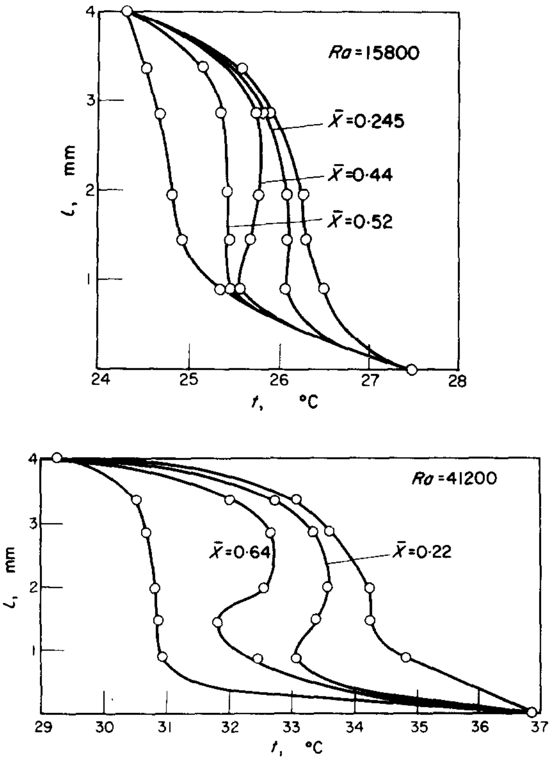

FIG. 5. Temperature profiles in an individual cell: (a) Ra = 15800; (b) Ra = 41200.

As seen from Fig. 6 which shows the picture of isotherms in the cell at $Ra = 41000$, the highest temperature gradient is observed in the near-wall region.

It follows from [7] that the temperature difference in the up- and downflows in the middle horizontal cross-section, is described by the relation

$$\Delta t_{\max} = \frac{Q}{c_p \gamma \Delta x v_0} \tag{1}$$

where Δx is the value commensurable with the thickness of the boundary layer

$$\Delta x \sim \frac{1}{Pr^{0\cdot4}} \frac{\nu l}{v_0}^{\frac{1}{2}}. \tag{2}$$

Since

$$Q = 0\cdot265 \lambda l \Delta t Pr^{0\cdot4} \frac{v_0}{\nu l}^{\frac{1}{2}} \tag{3}$$

then

$$\frac{\Delta t_{\max}}{\Delta t} \sim \frac{\text{const}}{Pr_0^{0\cdot2}}. \tag{4}$$

It means that the relative temperature difference in the down- and upflows in the middle of the horizontal section (at $\bar{y} = 0\cdot5$) depends only on the physical properties of the liquid.

As seen from Fig. 7, the ratio $\Delta t_{\max}/\Delta t$ is constant for various Ra.

From Fig. 7 it follows that relation (4) is valid over most of the height of the layer.

It has been established experimentally that in the larger volume near the horizontal heat-transfer surface the cellular eddy flows are observed (Figs. 8a, b). Estimation of $Ra_{\text{h.t.}}$ was carried out for two boundary conditions: (1) heat-transfer surface is the free liquid surface; and (2) the heat-transfer surface is the hori-

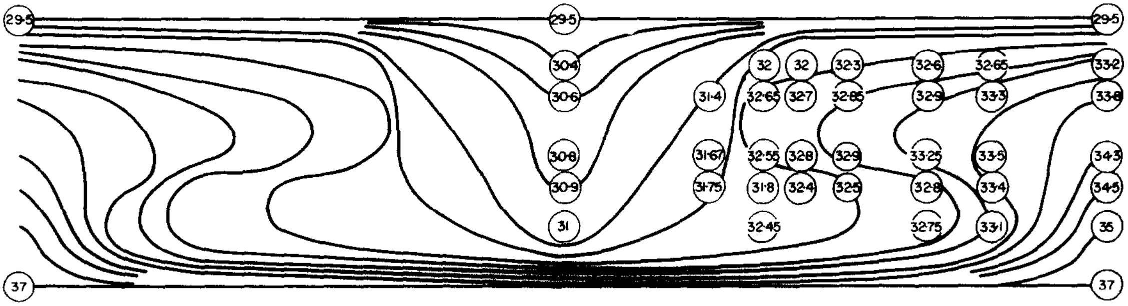

FIG. 6. Cell isotherms; height of layer, 4 mm; Ra = 41 000; 31, experimental points.

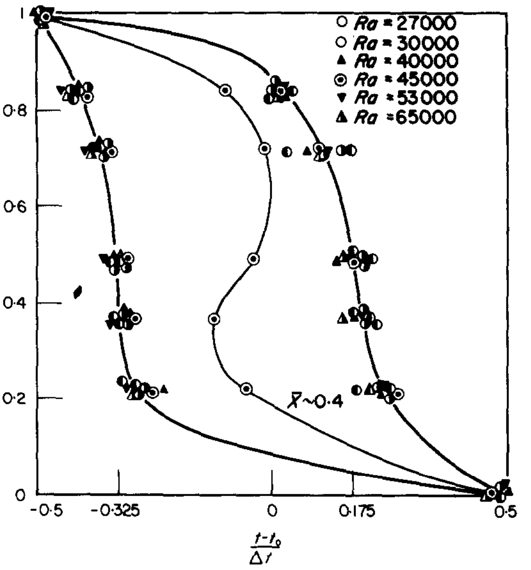

FIG. 7. Relative temperature change in downflow ($\bar{x} = 1$) and upflow ($\bar{x} = 0$) along the height of the liquid bed ($l = 4$ mm).

zontal solid surface. In the first case cooling of the free liquid surface proceeded as the result of evaporation. Ethyl alcohol vapours condensed on the surface (1) (Fig. 1).

In the second case the liquid was in contact with heat exchanger (1) (Fig. 1).

The process of cooling the liquid layer was rather slow and for the time of the temperature measurement could be considered stationary.

The Rayleigh number was determined from the temperature difference between the heat-transfer surface temperature and the temperature in the volume of the liquid over the surface and which could be considered constant over the layer height. The temperature of the free heat-transfer surface was determined as the mean between the temperature indicated by the thermocouples placed above the surface and those in the liquid with the distance of 0·5 mm between their heights. Within the temperature measurement the flow patterns were photographed (Fig. 8a) with the known photographing scale.

The height of the eddy layer was determined as follows. According to the experimental data (Fig. 4) the ratio $a/l \approx 1$ in the region of stability loss and $a/l \approx 2$ in the region of $Ra > Ra_{cr}$. In the first case the height of the eddy layer was assumed $l = a$. In the second, $l = a/2$ which corresponds to the region of $Ra > Ra_{cr}$.

In various experiments the height of the eddy layer was 2–3 mm. The change of temperature was measured mainly over the height of the eddy layer. The experimental value of $Ra_{\text{h.l.}}$ for the free horizontal heat-transfer surface in various experiments was measured within the range 800–1600. $Ra_{\text{h.l.}}$ for the layer bounded with the solid heat-transfer surface was found to be ~3100 ± 30.

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Abstract—Experimental study has been made of the hydrodynamic liquid flow patterns in horizontal layers up to $Ra = 1{\cdot}5 \times 10^6$; the temperature profiles over the cell volume and of cell sizes at various Ra and heights of bed.

It is shown that near the horizontal heat-transfer surface with natural convection in a large volume an eddy cell flow exists. *Ra* number calculated based on the height of the cellular layer near the heat-transfer surface is experimentally determined for various boundary conditions.

For various boundary conditions the Rayleigh number has been experimentally determined, based on the height of the cellular layer which exists close to the heat-transfer surface.

Résumé—Les configurations d'écoulement hydrodynamique d'un liquide en couche horizontale ont été étudiées expérimentalement jusqu'à $Ra = 1,5 \times 10^6$ ainsi que les profils de température dans le volume des cellules et les tailles de celles-ci pour divers *Ra* et hauteurs de la couche.

On montre que près de la surface horizontale de transport de chaleur, avec convection naturelle dans un grand volume, il existe un écoulement à tourvillons cellulaires. Le nombre *Ra* calculé en se basant près de la surface de transport de chaleur est déterminé expérimentalement pour diverses conditions aux limites.

Zusammenfassung—Hydrodynamische Strömungsmuster in waagerechten Flüssigkeitsschichten, Temperaturprofile innerhalb einer Zelle und Zellgrössen bei verschiedenen Ra-Zahlen und verschiedenen Höhen wurden für *Ra* bis zu $1,5 \cdot 10^6$ experimentell untersucht.

Es wird gezeigt, dass nahe der waagerechten Wärmeübergangsfläche mit natürlicher Konvektion in einem grossen Raum eine Zellströmung mit Wirbeln auftritt.

Für verschiedene Randbedingungen wurde die Rayleigh-Zahl experimentell bestimmt, wobei als charakteristische Länge die Höhe der Zellschicht nahe der Wärmeübergangsfläche verwendet wird.