EXPERIMENTAL INVESTIGATION OF CONVECTION IN THE CASE OF HEATING FROM ABOVE

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UDC 536.25

We have observed and studied experimentally cellular structure of flow in a horizontal cavity, on excitation of convection by heating from above.

Systematic studies have been undertaken in the numerous references dealing with free convection which is generated on heating from below or from the side [1-10]. In [11] our attention is drawn to the possibility of generating convection through heating from above. It is also pointed out in this reference that there is a need for a thorough study of the structure of the flow, the temperature field, and the heat transfer in a strictly horizontal in the case of heating from above.

Here we give the results from an experimental investigation, primarily into the structure of steady flow in a horizontal rectangular cavity, with nonuniform heating from above.

The investigations were carried out with the cavity formed by two horizontal brass plates (200 × 90 × 3 mm), side walls made of optical glass, the ends being made of a plastic with a thickness of 10.26 ± 0.01 mm. The surfaces of the plates were polished to a finish of $\nabla 7$. Visual observation of the flow patterns was maintained through the side walls, through which the pattern was photographed. The cavity was maintained at a maximum width for the selected procedure of filming the flow. Thirty (30) copper–constantan thermocouples were fixed to the horizontal and end walls of the cavity to determine the temperature distribution through the walls.

The horizontal position of the installation was maintained with a leveling device accurate to 0.08 mm per 1 m.

To achieve convection in the cavity by heating from above, the temperature along the upper horizontal plate must be nonuniform. The nonuniform temperature distribution is achieved by circulating thermostated water through the segmented jacket on the outside of the plate. The water temperature is maintained to within ±0.02°C by means of NBE-type thermostats.

The temperature of the cold bottom plate is kept constant by intensive pumping of the thermostated water through the multisegmented jacket. In all of the tests the deviations from the average wall temperature did not exceed 0.15°C.

From among the tremendous number of diverse laws governing heating, we chose several fundamentally different possibilities: the periodic distribution of temperature, δ-shaped distribution, and an approximate-linear distribution

1. To study convection with a periodic heating law we were able, experimentally, to achieve a distribution which – correct to 10% – can be regarded as cosinusoidal, with the difference between the maximum and minimum temperatures amounting to $\Delta t_L = 12°C$ (Fig. 1).

2. In the case of a δ-shaped distribution we established experimentally the temperature distribution which is approximated by the function

$$T = Ae^{-\alpha(x-0.07)^2} + B(0.07-x)^2,$$

Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzherno-Fizicheskii Zhurnal, Vol. 16, No. 6, pp. 972-976, June, 1969. Original article submitted February 12, 1969.

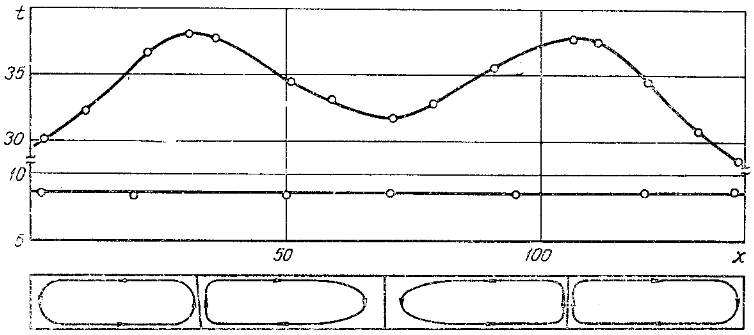

Fig. 1. Structure of the flow in a cavity for periodic temperature distribution at the upper walls, and with a constant temperature distribution at the bottom walls of the cavity: t, °C) the temperature of the upper and lower walls of the cavity; x, mm) cavity length.

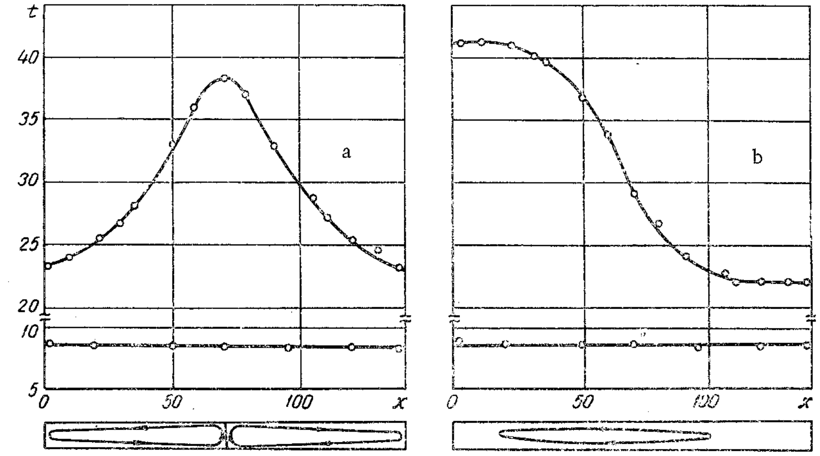

Fig. 2. Flow structure in the cavity for a δ-shaped temperature distribution at the upper cavity wall (a) and an approximate-linear distribution (b). The temperature of the bottom wall is constant (t and x – see Fig. 1).

where x is the coordinate along the length of the cavity, m; $0 \le x \le 0.14$; A, B, and α are coefficients, $30 \le A \le 50$, $2700 \le B \le 3700$, $300 \le \alpha \le 400$, accurate to 7% at a maximum temperature difference $\Delta t_L = 22$°C (Fig. 2a).

3. Convection with an approximate-linear variation in temperature ($25 < x < 100$) was investigated with the distribution described by the function

$$T = -A\,\mathrm{th}\,\frac{x-0.065}{\alpha} + B$$

with an accuracy up to 3.6%, with the nonuniformity of the temperature up to $\Delta t_L = 38.6$°C (Fig. 2b), $2 \le A \le 20$, $21.4 \le B \le 42.4$, $0.03 \le \alpha \le 0.05$.

Investigation of the flow structure through the width of the cavity and measurement of the temperature by means of a moveable copper–constantan thermocouple demonstrated that – in the central portion making up 11% of the cavity width of z = 90 mm – we have two-dimensional flow with identical velocities of motion and cell dimensions. On approach to the leading and trailing walls the dimensions of the cells diminished, with the velocity of motion dropping off to zero.

All of the measurements were subsequently carried out in the zebra/2 plane.

We performed two groups of tests: a hydrodynamic group, and a thermal group which was preliminary in nature.

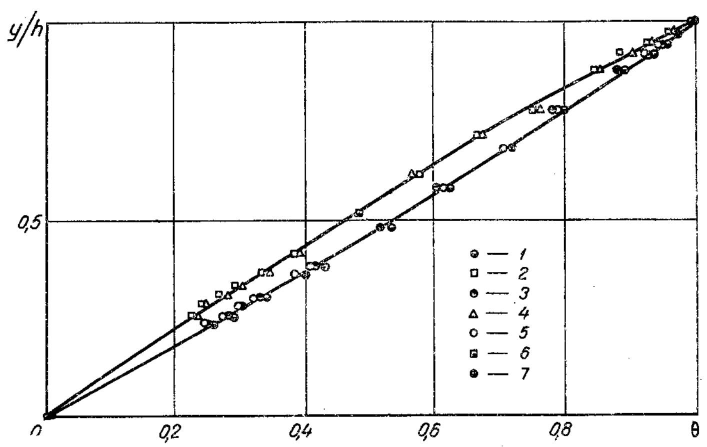

Fig. 3. Dimensionless temperature profile $\theta = (T - T_0) / (T_h - T_0)$ in descending and ascending flows of cells with periodic heating of the upper wall: 1) temperature at the section at a distance of 5 mm; 2) 35 mm; 3) 75 mm; 4) 110 mm; 5) 135 mm; 6) coincidence of measurements in ascending layers; 7) coincidence of measurements in descending layers.

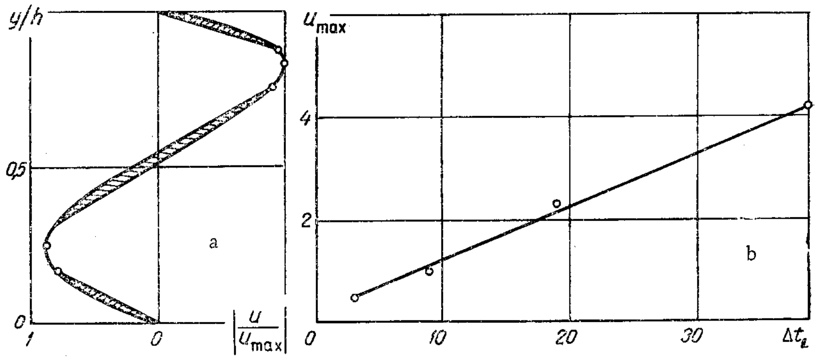

Fig. 4. Flow velocities in the cell with nonuniform heating from above: a) velocity profile in central vertical cross sections for all four cells with periodic heating from above. (The points on the curve denote coincidence of measurements and the cross-hatched sections denote the region of experimental points;) b) maximum velocity u_{max} (mm/sec) as a function of the temperature difference for the case shown in Fig. 2b.

The working fluid in this series of tests was air.

The cavity, filled with particles of tobacco smoke, was illuminated from the end. An OKG-11 gas laser served as the light source. The velocity of the convection was determined visually by measuring the time required for the passage of one particle between fixed markers on the micrometer eyepiece of a moveable binocular microscope. Each measurement was backed up by filming the flow pattern with a known exposure time; the magnitude of the tracks in this case is proportional to the velocity. The filming was carried out in reflected light. The camera was focused on the midplane of the slit and it could be moved to photograph the various parts of this plane.

The results of each test represent the averaging of 3-4 measurements, differing from each other by no more than 2-3%.

Figures 1, 2a, and 2b show the flow patterns for the forms of temperature nonuniformities at the upper cavity wall which we have investigated here.

In a number of the tests, the working fluid was distilled water with suspensions of light-scattering particles of aluminum dust. The flow structure always remained qualitatively the same, but the velocity of liquid motion in the cells diminished sharply. For example, for the pattern shown in Fig. 2a, with $\Delta t_L = 15.6$°C, $u_{max} = 0.33$ mm/sec, as opposed to $u_{max} = 1.7$ mm/sec in air.

The temperature field in the slit was measured with a moveable copper–constantan thermocouple 0.06 mm in diameter. The presence of the thermocouple resulted in no noticeable perturbations of the flow.

Figure 3 shows the curve of the relative temperature in the descending and ascending flows of four cells for the pattern which corresponds to Fig. 1.

The velocity profiles are shown for this same regime in the central vertical cross sections of all four cells (Fig. 4a). The velocity profiles in the various cells are virtually coincident and exhibit clearly delineated asymmetry. The maximum velocity, as was to be expected, is found in the upper half of the cavity. The velocity maximum in the lower half of the cavity is located farther from the cold wall than u_{max} from the upper hot plate. The zero velocity is also shifted upward, away from the center of the cavity.

If we number the cells sequentially in the positive direction of the x-axis, the experimentally derived cell lengths are the following:

y, mm	l_1, mm	l_2, mm	l_3, mm	l_4, mm
0	33,0	34,0	36,5	36,5
h	32,0	37,0	36,0	35,0

We also measured the angles of inclination for the boundaries separating the cells in the indicated regime, i.e.,

$$\varphi_{12} = 95°, \ \varphi_{34} = 87°, \ \varphi_{23} = 91°,$$

where φ_{12}, φ_{23}, and φ_{34} are the angles of inclination for the boundaries between the first and second cells, the second and third cells, the third and fourth cells, respectively, calculated from the positive direction of the x-axis in a counterclockwise direction.

For the investigated interval of nonuniformities $\Delta t_L = 2.95$-38.6°C the value of u_{max} varies in proportion to the magnitude of the temperature nonuniformity at the upper wall (Fig. 4b).

We noted a pronounced dependence of the circulation velocity in the cells on the mean integral temperature difference Δt_h between the hot and cold walls. Thus, for the scheme shown in Fig. 2a, when $\Delta t_h = 20.4$°C, $u_{max} = 2.78$ mm/sec, while for $\Delta t_h = 13.6$°C, we have $u_{max} = 3.7$ mm/sec.

The nonuniformity in the temperature in both cases amounted to $\Delta t_L = 26.6$°C. At a specified magnitude for the nonuniformity, the circulation velocity increases with a drop in Δt_h.

On the other hand, to evaluate the effect of the temperature nonuniformity, we have to maintain a constant difference Δt_{hmin}. In plotting the curve in Fig. 4b we kept the difference between the minimum temperature of the hot wall and the temperature of the cold wall constant, i.e., $\Delta t_{hmin} = 12.1$°C.

We can draw the following conclusions with regard to the structure of this kind of convection from the above-examined cases of free convection in the case of nonuniform heating from above:

1) the flow exhibits a clearly delineated cellular character;

2) each extremum in the distribution of the temperatures at the upper wall forms a boundary of separation between the cells;

3) the shape of the boundary separating the cells depends on the shape of the profile for the temperatures near the extremum;

4) the direction of motion in each cell near the upper wall is opposite to the temperature gradient at the wall;

5) the cell occupies the entire height of the cavity, and through the length of the cavity it is concentrated at a distance equal to the characteristic dimension of the temperature nonuniformity.

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