THE FREE CONVECTION OF A FLUID WITH AN INITIAL VERTICAL DENSITY GRADIENT AND LATERAL HEATING

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Some results are given of an experimental investigation into the free convection in solutions with density which is nonuniform with height. It is shown that convective motion in solutions with a vertical density gradient and lateral heating is cellular in nature. The height of the cells is determined as a function of the temperature head and the density gradient.

It is known that in certain cases the free convection of a fluid involves the formation of cells. It was observed in [1] that when there is heating from below the fluid moves between horizontal surfaces in six-sided cells. Cells are also formed when there is fluid convection in a narrow vertical slot [2]. Analytic investigation of the convective stability of a fluid in narrow vertical slots also indicates the formation of cells vertically [3, 4]. Convection with nonuniform heating from above was investigated in [5]. In this case the motion is also cellular. A cell fills a complete strip in height and in length it extends to a distance equal to the typical dimension of the temperature inhomogeneity.

Transparent plastic vessels in the form of parallelepipeds with dimensions $600 \times 400 \times 200$ mm^3 were made for the experiments. Lateral heating was provided by an electric heater in the form of a flat copper plate of width equal to that of the vessel, so that the heater could be moved inside the vessel, thus changing the working section of the volume. The heater power was varied by changing the supply voltage using an LATR-1 autotransformer.

Ten thermocouples were positioned on the surface of the plate along the vertical axis. Thermocouples were set in a thin wooden stand at the same heights as those in the plate in order to measure the fluid temperature. The stand with its thermocouples was placed in a vertical position outside the boundary layer far from the heater. Copper-constantan thermocouples were used. The thermo-electromotive force of the thermocouples was measured by the compensation method using a PP-63 potentiometer of class 0.05.

The experiments were made with solutions of glycerin in water. A solution with vertical density gradient was prepared in the vessel. Then the solution was sampled at 5-6 points over the height to determine the density. The density of fluid samples was determined by weighing in a pycnometer of volume 2 cm^3 to an accuracy of four decimal places. A graph of the density distribution with height was constructed from the measurements. The initial density distribution with height in the various experiments followed various laws: exponential, straight line, and a more complicated law. In the experiments the initial average solution density varied from 1.0010 to 1.0200 g/cm^3 at 20°C, while the density gradient varied from 0.0001 to 0.0025 g/cm^4.

Before heating started the fluid temperature was the same throughout its volume. After the solution had been prepared and had settled in the vessel the heater was switched on. The temperatures of the surface of the plate and in the fluid volume were measured during heating. The temperatures were measured every half hour or hour, depending on the rate of heating. In each series of experiments not less than 5-6 measurements were made. The experiments were repeated at various heater powers.

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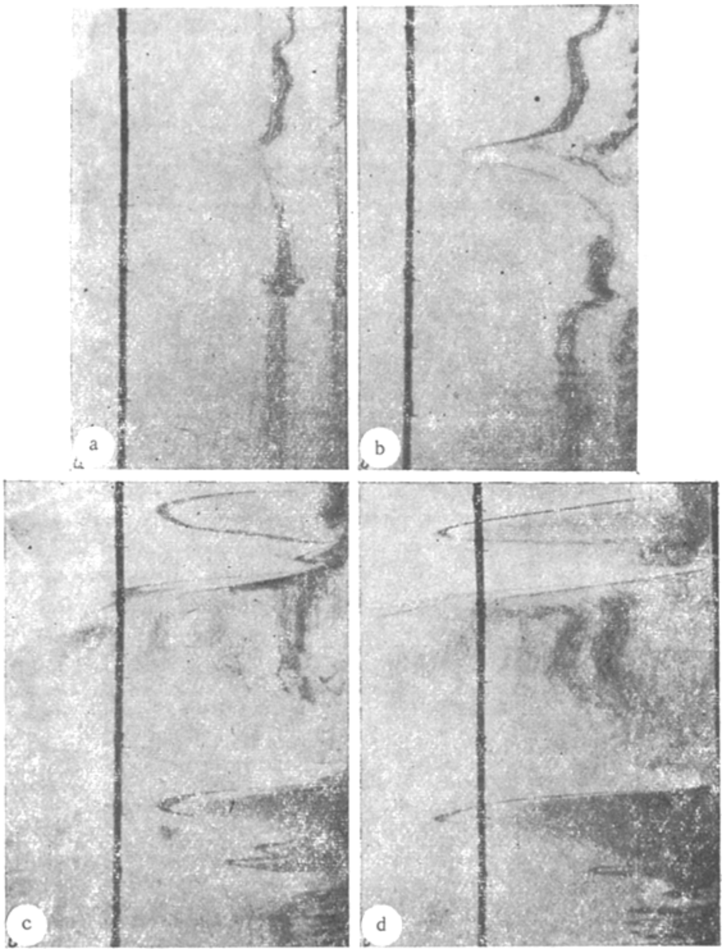

Fig. 1

The temperature head (the temperature difference between the heater wall and the fluid outside the boundary layer) varied between 2 and 7°C. Over the duration of the experiment (3-4 h) the local fluid temperature varied between 20 and 43°C, the temperature of the wall between 20 and 50°C, the maximum temperature drop with height being 10°C in the fluid and 7°C at the wall.

Convective motion was observed visually in the vessel. The motion was visualized by introducing into the fluid a colored vertical "cord" which, when inserted, formed fine wet particles of potassium permanganate.

The colored trace of the particles remained motionless in the vertical position in the motionless fluid. When motion began,the trace was carried away by the flow, making the velocity profile of the fluid stand out to be recorded photographically. The convective motion of the fluid occurred when it was heated by the vertical plate.

At the beginning of the process tongues appeared at the hot wall forming wedges through the thickness of the fluid (Fig. 1). As the heating continued, these tongues extended and reached the cold wall. In Fig. 1 frames a, b, c, and d correspond to sequential stages in the movement through the thickness of the fluid. Photographs were taken at intervals of 1, 7, and 8 min. Eventually a stable cellular motion was established. The time taken for the penetration of the cellular flow from the heated plate to the opposite wall depended on the distance between them and the fluid velocity. The maximum velocity in a cell was observed in the boundary layer at the hot wall, which gradually fell along the upper boundary of the cell and then along the direction of the motion.

The frames of Fig. 2 show the cellular convective motion when the height of the solution in the vessel is 360 mm. Photographs a and c correspond to different initial solution density gradients. The fine cells correspond to the larger density gradient and smaller temperature head. In Fig. 2 are also given shadow

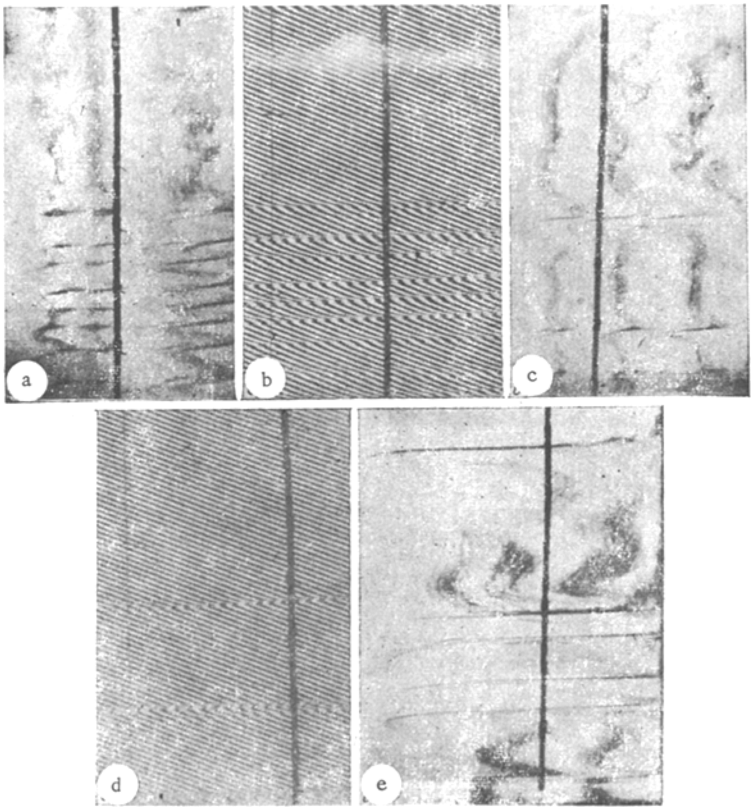

Fig. 2

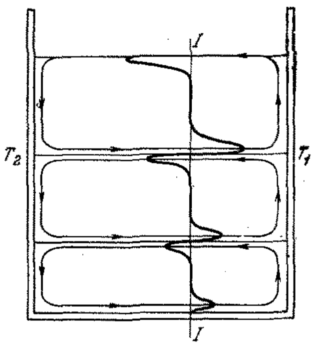

Fig. 3

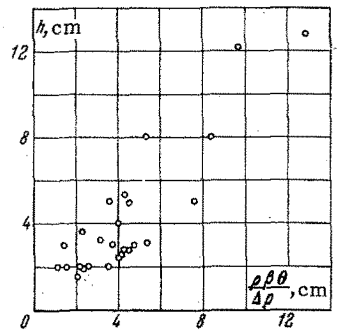

Fig. 4

photographs (b, d) of the inhomogeneity in the solution of photographs a and c due to the convective motion. The shadow photographs were obtained by photographing a rectangular grating through a layer of the solution under investigation with a telephoto lens when light was passed through the solution. Refraction of the lines of the grating corresponded to a sharp change in the solution density gradient. These photographs showed that such a change occurs at the edges of neighboring cells.

Figure 2a, b corresponds to the following experimental conditions: temperature heat θ = 2.9°C, density gradient approximately the same throughout the height of the cells $\nabla\rho$ = 0.0004 g/cm^4, mean volume temperature of the fluid 26°C. Figure 2d, c was obtained with θ = 2.1°C; density gradients

$$\begin{array}{ll} h = 1.5 \text{ mm} & \nabla\rho = 0.0037 \text{ g/cm}^4 \\ h = 62 \text{ mm} & \nabla\rho = 0.0004 \text{ g/cm}^4 \\ h = 112 \text{ mm} & \nabla\rho = 0.0001 \text{ g/cm}^4 \end{array}$$

mean volume temperature of the fluid 39°C.

Figure 2e clearly shows the motion inside the cells and at the walls inside the vessel. The photographs show that the motion in the cells occurs in a thin boundary layer near the vessel walls and at the edges of the cells. When the height of a cell is greater than twice the thickness of the boundary layer a kernel region appears in which the fluid is virtually in a state of rest. Figure 3 gives a schematic representation of cells and a typical velocity profile at the section 1-1. The fluid in a cell at the hot wall rises and at the cold wall falls.

Observations showed that the height of an individual cell depends on the temperature head and the initial solution density gradient. Experimental results on the heights of the cells as a function of $\rho\beta\theta/\nabla\rho$ are given in Fig. 4. Here ρ, β, $\nabla\rho$ are, respectively, the density, the thermal coefficient of volume expansion, and the initial solution density gradient; θ is the temperature head.

It must be noted that the density does not flatten out between the cells with time, but its distribution when established is discontinuous. Due to the convective motion the density in the various cells rapidly evens out.

The formation of cells when there is free convection of the fluid is to be expected in many practical problems. A density gradient can occur under natural conditions even in fluids usually assumed to be homogeneous, due to mechanical impurities, dissolved salts, or stratification of a multicomponent fluid (petroleum products). Under suitable thermal conditions when the fluid column height is sufficiently large, cells may be formed in such fluids which can significantly affect the industrial processes.

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