# EXPERIMENTAL INVESTIGATION OF THERMOCONVECTIVE WAVES IN HORIZONTAL GAS LAYERS

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Thermoconvective waves have been experimentally detected and studied in horizontal air layers uniformly heated from below.

Transverse waves and thermal waves are strongly attenuated in a layer of fluid having uniform density [1, 2]. The amplitude of these waves drops by roughly a factor of 540 over a wavelength, and it is essentially impossible to speak of a wave process in the propagation of temperature fluctuations.

Internal waves produced by a negative vertical-density gradient [3] propagate in a fluid that is in mechanical equilibrium in a gravitational field. The limits of existence of internal gravitational waves have been investigated in [4], while it has been shown in [5, 6] that in a fluid having a positive density gradient heating from below may cause the propagation of weakly attenuated thermoconvective waves. The conditions for propagation of such waves in fluids having various properties have been studied in [7-9], where thermoconvective waves were considered in a semi-infinite layer with no allowance for the influence of the boundaries. The problem of thermoconvective wave propagation in a layer with free boundaries has been analyzed in [10].

Here we report the results of an experimental investigation of thermoconvective waves in horizontal air layers of finite dimensions in the presence of solid walls. The experiments were carried out on a horizontal air layer heated uniformly from below, with height 11.7 mm and width 50 mm. The linear dimensions of the layer were chosen so as to produce a stable convective structure in the supercritical region, taking the form of rollers having axes parallel to the shorter side of the cavity [11-12]. It was found in experimental studies [13, 14] that the polygonal flows appearing after loss of mechanical equilibrium by the layer are unstable; there is drift and alternation of the convective structures over the layer of fluid. This process imposes parasitic oscillations of the local temperature in the layer, owing, as it were, to the arbitrary drift of the descending and ascending streams. In narrow layers, which are defined in [11] as layers having a short side greater than the depth and a long side more than twice the short side, the clear orientation of the axes of the roller-like convective motion eliminates disorderly temperature fluctuations at individual points of the cavity.

The layer was bounded from below by a copper plate having a nichrome heater. The upper boundary was formed by a heat exchanger consisting of two bonded sheets of Plexiglas; thermostated water circulated in the gap between the sheets.

A five-mm diameter copper tube was sealed into one of the short walls; water from the thermostat was pumped through it to produce periodic temperature fluctuations at the side boundary. The temperature of this water varied in time in accordance with a prescribed law, and this determined the temperature regime of the side boundary. Periodic modulation of the water temperature was provided by supplying the thermostat electric heater through a relay controlled by signals from two contact thermometers installed in the thermostat and set to the extremum values of temperature fluctuations. An overflow device was used to maintain constant water flow rate through the thermostat cooling coil. In this way we obtained

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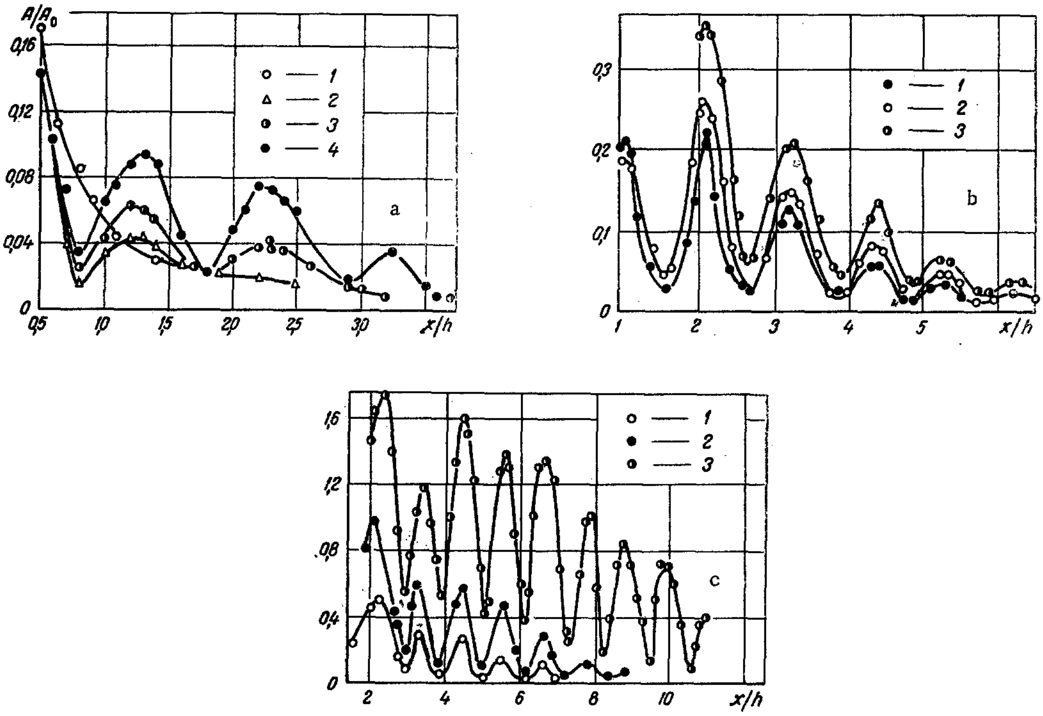


Fig. 1. Distribution of oscillation amplitudes over layer length: a) $\omega = 1 \cdot 10^{-2}$ sec$^{-1}$: 1) Ra = 0; 2) Ra = 1200; 3) Ra = 1500; 4) Ra = 1660; b) 1 − $\omega = 1 \cdot 10^{-2}$ sec$^{-1}$, Ra = 1800; 2) $\omega = 1 \cdot 10^{-2}$ sec$^{-1}$, Ra = 2400; 3) $\omega = 8 \cdot 10^{-3}$ sec$^{-1}$, Ra = 2400; c) Ra = 3400: 1) $\omega = 1 \cdot 10^{-2}$ sec$^{-1}$; 2) $\omega = 8 \cdot 10^{-3}$ sec$^{-1}$; 3) $\omega = 2.1 \cdot 10^{-3}$ sec$^{-1}$.

sinusoidal modulation of the temperature at the side boundary with an angular frequency of $\omega = 10^{-1} \cdot 10^{-4}$ sec$^{-1}$.

The temperature-measurement system included the following: a) measurement of the temperatures at the horizontal boundaries of the layer; b) recording of the time-modulated temperature at the side wall; c) recording of the temperature oscillations propagating in the layer.

Twenty-four copper-constantan thermocouples (0.1-mm diameter wire) were used to measure the temperature distribution at the horizontal boundaries of the layer and to check on uniformity of heating. In all the experiments the deviations from the mean temperature did not exceed 2%. The nature of side-boundary temperature modulation was registered by five copper–constantan thermocouples mounted uniformly along the height of the wall. A set of seven copper–constantan microthermocouples (0.05 mm-diameter wire), located at the center of the layer height, served as the sensor for registration of temperature oscillations. The sensor was moved by a micrometer screw. The thermocouple readings were recorded by a type EPP-09 multichannel potentiometer which simultaneously registered the modulated temperature of the side wall.

The structure of convective motion was observed visually and photographed through the upper transparent heat exchanger. The convective structures were visulaized with the aid of particles of an aerosol (tobacco smoke); this gave a contrasting flow pattern under illumination by a helium-neon laser. A special electromagnetic device was used to sweep the laser beam over the width of the cavity at 50 Hz in any horizontal cross section of the layer.

Let us consider the results of experiments for a 150 mm long layer. Under isothermal conditions the temperatures oscillations excited in the layer are strongly attenuated, and at distance of 1.25 h from the side wall the amplitude is reduced by more than a factor of 25 compared with $A_0$ (Fig. 1a). With a temperature drop corresponding to Ra = 1200 established between the horizontal layers of the boundary the amplitude curve changed shape: a minimum was observed a distance of ~0.8 h from the side boundary of the layer with a peak a distance ~ 1.25 h away. The temperature oscillations in the region of the peak are out of phase with the temperature oscillations at the side boundary. Heating of the lower boundary to

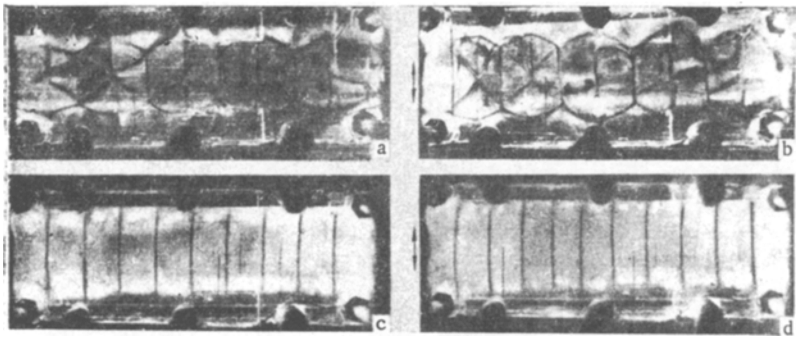

Fig. 2. Top view of convective structures in the layer for extremum values of modulated temperature (the arrow indicates the boundary having the variable temperature): a, b) Ra = 2300, $\omega = 8 \cdot 10^{-3}$ sec$^{-1}$; c, d) Ra = 3400, $\omega = 2.1 \cdot 10^{-3}$ sec$^{-1}$.

Ra = 1500 corresponds to an amplitude curve having two peaks and minima; the temperature oscillations at the next peak, at distance ~2.25 h away from the side boundary, are in phase with the oscillations at the wall. With a further increase in the temperature gradient (Ra = 1660) the amplitude curve exhibits three pairs of extremum values of oscillation amplitude. They increased by roughly a factor of 4 at the peaks in this case, as compared with the isothermal regime. The change in the frequency of the temperature oscillations at the side boundary does not affect the amplitude in the layer for the subcritical range of Rayleigh numbers.

There is a sharp increase in the amplitudes of the oscillations in the layer upon passage through the critical temperature gradient (Ra = 1708) (Fig. 1b). We define the depth of penetration of temperature oscillations as the distance from the temperature-modulated side-boundary at which $A/A_0 = 0, 1$, (i.e., the amplitude in the layer has decreased by a factor of 10 as compared with the amplitude at the wall). In the Ra = 1708-2400 region, the depth of penetration is 4.5-5 h. A decrease in the frequency of side-boundary temperature-modulation corresponds to a significant increase of the oscillation amplitudes in the layer. For the same temperature-oscillation frequency further heating of the lower boundary has almost no influence on the distribution of amplitudes over the length. As in the preceding modes, at even peaks (counting from the side boundary) the temperature fluctuations are in phase with those at the wall, while they are of opposite phase at odd peaks. In the region of minimum amplitudes the amplitude curve exhibits temperature oscillations at twice the frequency, $2\omega$.

The most interesting experimental results were obtained for Ra > 2400 beginning at which a threshold increase in oscillation amplitudes was observed at all points in the layer (Fig. 1c). Here the side-boundary temperature modulation frequency determines the magnitude of the oscillation amplitudes and the penetration depth. For a modulation frequency $\omega = 10^{-2}$ sec$^{-1}$ the penetration depth is 7.5 h. With a decrease in $\omega$ to $8 \cdot 10^{-3}$ sec$^{-1}$ the penetration depth goes up to 8 h, while at a distance of ~2 h the temperature oscillations have the amplitudes of those at the wall. When $\omega = 2.1 \cdot 10^{-3}$ sec$^{-1}$ the penetration depth equals the length of the layer, while the oscillation amplitudes at the peak exceed the amplitudes at the wall up to a distance of 8 h.

Let us consider the features of thermoconvective-wave propagation using the results of temperature measurements and visual observations of the structure in the layer. For the $1200 \le Ra < 1708$ range, with subcritical temperature gradients in the layer, temperature modulation at the boundary disrupts hydrodynamic stability in the region adjacent to the side wall. The value of vertical temperature drop determines the width of this region, the number of convection structures formed, and, accordingly, the peaks and minima on the amplitude curve (Fig. 1a). The two-dimensional convective rollers that have been formed reverse direction in synchronism with the temperature oscillations at the side boundary. A change in the sign of the vertical velocity component at a frequency equal to the frequency at which the side-wall temperature is modulated produces local periodic temperature oscillations in the layer. The extrema on the amplitude curve are accounted for by the fact that the velocities of the resulting convective motions and the temperature field are periodic over the length of the layer. The maximum oscillation amplitudes are registered at distances that are a multiple of the diameters of the rollers that have been formed, while the minima occur at distances of 0.5, 1.5, and 2.5 times the roller diameter away from the side wall.

In the Ra = 1708—2400 range, the layer exhibits stable convective motion in the form of roller-like cells (Fig. 2a). If the side-wall temperature modulation amplitude does not exceed 10% of the vertical temperature drop, then at one of the extremum values of temperature at the boundary an additional roller forms that shifts the convective cells into the layer (Fig. 2b). The roller that forms rotates in a direction opposite to that of the convective motion in the cell that had been next to the side wall. The ordinary convection structure returns (Fig. 2a) at the opposite extremum value of the modulated temperature. The periodic formation of an additional convective roller produces oscillatory motion in the x direction, and this determines the propagation of temperature—velocity perturbations in the layer. The greatest changes in the vertical velocity component of convective motion correspond to the peaks of the temperature oscillations in the layer.

For Rayleigh numbers exceeding Ra = 2400 the convective-motion structure takes the form of two-directional convective rollers with axes parallel to the short wall of the layer; they are stable in the Ra = 2400-8000 range. The process of thermoconvective wave propagation is of the same nature as it is for the roller-like cells. Figure 2c, d shows the structure of convective motion for the extremum values of wall-temperature modulation. As the temperature-modulation frequency decreases, the amplitudes of the thermoconvective waves rise, since the time during which velocity perturbations form becomes greater. If the frequency drops below $2.1 \cdot 10^{-3}$ sec$^{-1}$ for Ra = 3400, there are no changes in the characteristics of the thermoconvective waves (i.e., $\omega = 2.1 \cdot 10^{-3}$ sec$^{-1}$ is the frequency limit for the given temperature mode).

Analysis of the results of numerous experiments aimed at studying the characteristics and peculiarities of thermoconvective waves has yielded the following expression for describing the investigated wave process:

$$T = B \exp(-\delta x)[c + \cos k_1 x] \cos(k_2 x - \omega t).$$

The exponential factor characterizes the attenuation of temperature oscillations with length. The propagation of a thermoconvective wave may be interpreted as follows: it is a travelling wave $\cos(k_2 x - \omega t)$, whose amplitude is harmonically modulated in accordance with the law $B[c + \cos k_1 x]$.

## NOTATION

$\omega$ is the angular frequency of the oscillations, sec$^{-1}$; Ra is the Rayleigh number; h is the layer height; x/h is the dimensionless-horizontal coordinate; T is the deviation of the temperature from the stationary temperature distribution in the layer; B, c are constants; A, $A_0$ are the amplitudes of temperature oscilations in the layer and at the center of the height of the side boundary, respectively.

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