of the compression wave and beyond its front; ρ_0 and ρ_1, fluid density ahead of the compression wave and beyond its front; U_0 and U_1, fluid velocities in the coordinate system of the compression wave front; S_0, initial area of the tube; ΔS_0, increment in area.

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DIELECTRIC VISUALIZATION OF THE CONVECTIVE INSTABILITY IN NONPOLAR NONVISCOUS FLUIDS

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The dielectric method is used to study the convective instability in nonpolar nonviscous fluids "heated from below" at different temperature gradients (0.1-0.005 K/cm). Different types of resonant cavities are used as measuring cells; their specific feature is the pronounced nonuniformity of the electromagnetic field which has become a decisive factor in convective flow detection.

Heat convection in a heated fluid layer is the simplest case of hydrodynamic instability and, at the same time, is a striking example of how a system disturbed from a thermodynamic equilibrium state can change to a highly ordered state. In hydrodynamics, convective instability is "one of the most curious and difficult problems of classical physics" [1]. Benard's effect is the most striking example of the convective instability. It manifests itself in forming a regular cellular structure of the fluid heated from below under certain conditions. As these processes are fundamental in nature, Benard's convection has become the subject of many theoretical and experimental studies.

At present the experimental methods of studying convective flows have attained certain success. The traditional methods (such as hot-wire, photo visualization, acoustic, interferometric) continue to improve. The high effective laser Doppler method of measuring spatial and time parameters of flows [1-5] has been developed.

The measured parameters of natural convection are small in magnitude and require special recording facilities. Great difficulties spring up when determining the spatial-time temperature, pressure, and velocity fields of a test medium in closed volumes. Hence, further improvement of the visualization methods of convective flows remains urgent and expedient.

The ability to investigate hydrodynamic processes by the dielectric method is based on the close relationship between the dielectric properties of the substance and its molecular density [6]. The matter equations of electrodynamics contain the dielectric permeability (DP) which refers to the specific characteristics of the substance and depends on the mass density and, hence, on the flow and heat transfer parameters of this substance. In a more general form, this relationship may be given as [6]

$$F(\varepsilon) = \frac{4\pi\alpha\rho}{\mu}, \tag{1}$$

where $F(\varepsilon)$ is the dielectric function representing some structure composed of static ε_s and quasioptic ε_∞ dielectric permeabilities and the number coefficients; α is the polarizability of molecules; μ is the molar mass; ρ is the substance density.

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The dielectric method of recording convective flows is characteristic of such a sequence of transforming the quantities: $v \rightarrow \rho(P, T) \rightarrow \varepsilon(\rho) \rightarrow k(\varepsilon)$, where v is the flow velocity; T and P are the temperature and pressure in the region where the disturbance is localized; k is the wave number of an electromagnetic field which characterizes the measuring circuit or the signal parameters [6]. In a given circuit, of significance is how correctly the measured electric or electromagnetic parameter k is chosen, which directly depends on the type of a measuring cell.

Use of a resonant cavity as a measuring cell has become decisive for dielectric detection and visualization of the convective instability. The nonuniformity of the spatial structure of an electric field in the resonant cavity provides, in principle, the ability to record relative changes in the density of the medium which fills this cavity. For a relatively small disturbance of the medium, the changes of its frequency f are assigned by the equation [6]

$$\frac{\Delta f}{f} = \frac{\int\limits_{\Delta V} \Delta\varepsilon EE^* dV}{2\int\limits_{V} \varepsilon EE^* dV}, \tag{2}$$

where ΔV is the disturbed volume; $\Delta\varepsilon$ is the change of the medium DP in the region ΔV; E is the electric field strength.

When the total amount of substance is kept invariable in the cavity, the only fact that disturbs the frequency of this cavity is the density change of this substance. This means that for the known space distribution of electric fields in the cavity it is possible to establish reliable correlations between the changes of the cavity frequency f and the substance density and, hence, the convective flow velocity.

The relationship between DP and the density, ρ, of nonpolar media is sufficiently well studied. For them the dielectric functions $F(\varepsilon)$ in (1) have the simplest form. Nonpolar fluids have small dielectric losses and allow the inner resonant cavity chamber to be filled, thus providing the highest sensitivity $\Delta\varepsilon - \Delta f$. If conditions in this cavity are created which provide the onset of convective flows, then according to the transformations in the sequence $v \rightarrow \Delta p \rightarrow \Delta\varepsilon \rightarrow \Delta f$ it is possible to observe the corresponding frequency changes of this cavity. Their intensity and time behavior will be uniquely determined by the nature of the hydrodynamic processes. For example, when Benard's cells are observed it may be assumed that the closed fluid flow intersects the regions having different electric field strength E, causing cavity frequency changes according to (2). Another necessary condition to observe Bernard's cells is the flow modulation with respect to the density as the result of the spatial nonuniformity of the flow and its time periodicity.

When the cavity is filled with a fluid under small losses, Eq. (2) may be reduced to the form

$$\frac{\Delta f}{f} = -\frac{\Delta\varepsilon\xi m}{2\varepsilon}, \tag{3}$$

where $\Delta\varepsilon = \varepsilon(t)$; m is the coefficient allowing for the size ratio of the fluid flow and effective (in the electrodynamic sense) cross section of the cavity where the fluid flow extends; ξ is the medium asymmetry coefficient of the ascending and descending flow parts with respect to the electric field strength distribution in the cavity.

Equation (3) is basic for describing the processes observed in experiment. Different-type cavity cells have been used to prove the method. Their design features alone determine the conditions for the convective instability to originate. Figure 1 shows the schematic of the resonant cavity with the oscillations H_{011}, on the basis of which the measuring cell was designed. The cavity is composed of body 1 with cylindrical chamber and end covers 5. Upper cover 5 is detachable; in studies it may be replaced to assign different boundary conditions and the fluid-column temperature gradient variation. The cavity is connected with the measuring SHF section by means of waveguides 2 via coupling slot 4, whose sealing is provided by Teflon gaskets 6. The body and covers are brass-made. The cavity covers have vertical and horizontal channels to provide conditions for bubble-free filling of the inner chambers of the cavities with the test fluid. For this, an angular gap, which at the same time serves as the filter of the nonbasic types of the cavity oscillations, is between the cover and the side surface of the cavity. This and other cells are detailed in [7].

To record the relative cavity frequency changes the high-resolution dielcometer with continuous recording of current frequency values [6] has been used. The dielcometer has been designed in a differential circuit using reference and measuring cavities. Each of the cavities is used to stabilize the frequency of the corresponding generator, and the difference of their frequencies is the output signal measured by the ordinary frequency meter and recorded by the self-recorder. The working frequency of the dielcometer is ≈ 10 GHz, and the sensitivity with respect to DP is up to 10^{-8}.

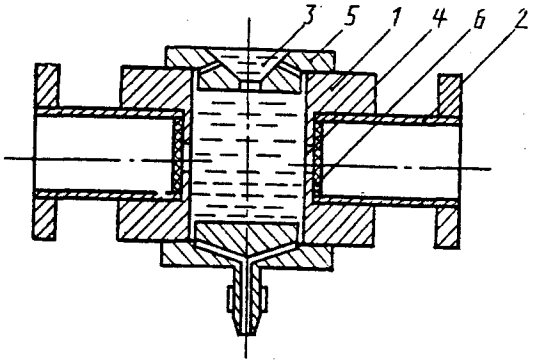

Fig. 1. Cavity used as a part of the device for detecting convective flows.

This equipment has allowed studies of transient and convective processes to be made. In particular, the generation of "dielectric oscillations" has been observed in cyclohexane, hexane, and other nonviscous nonpolar fluids in a closed volume (in a cavity) in the presence of a temperature gradient ("heating from below") within 0.005-0.5 K/cm.

Under these conditions there arises the stable generation of oscillations (for many hours) with an amplitude of 10^{-7}-10^{-5} unit DP and with an oscillation period from 3 min to 10-15 sec. It may be assumed that the observed oscillations reflect the convective instability which is the result of the simultaneous action of the upward convective and downward gravitational forces upon the solvent molecules of the Langevin fluctuation source. Apparently, there appear diametrally antisymmetric flows with a pronounced space–time structure in the cavity chamber [8]. This hypothesis is supported by experiment where increasing the fluid-column temperature gradient has resulted in a regular growth of the amplitude and frequency of the dielectric oscillations, and the sign change of the temperature gradient has destroyed these oscillations [7]. There are no other directed forces and/or the nonuniformity sources in the cavity chamber which would participate in forming the space-periodic processes.

As an example, Fig. 2, I shows the typical record of the cyclohexane DP behavior, displaying the development of the vibrational process from the stable state (diagram fragment $a-a'$, the output signal stability is not worse than 10^{-7} unit DP) to the periodic regime. In addition, the periodic process $a'-a''$ steady in the system can naturally continue for many hours. Apparently, the observed dielectric oscillations are the result of forming Benard's cells in the closed chamber of the cavity. In this case, the temperature gradient develops due to cyclohexane evaporation from the cavity surface (see Fig. 1) and does not exceed 0.01 K/cm.

Figure 2, II illustrates the transition of the system from the periodic regime to its stable nonconvective state. This transition is caused by decreasing the temperature gradient up to a value below the critical one. Processes 2, I and II are interreversible and easily-controlled and support the thermogravitational nature of the phenomenon.

Figure 2, III and IV illustrates the periodic oscillations generated at elevated temperature gradients (about 0.1 K/cm) which greatly differ from the harmonic ones. These oscillations are recorded by using the cavity E_{010}, for which the "direct heating from below" regime has been realized. The dielectrograms are obtained for heptane at a temperature of 40 (Fig. 2, III) and 60°C (Fig. 2, IV).

Studies of a free fluid surface on the cover of the cavity H_{011} have supported the substantial role of the temperature gradient in forming the conditions for stable oscillation generation [7]. At the same time, the temperature gradient is also affected by the fluid-scattered SHF energy that enters the cavity from the SHF generator and is the internal heat source. This assumption has been checked by a cavity E_{010}-based cell [7]. In this case, the test fluid is in a vessel made from a Teflon 4 mm ID tube. For this design of the cavity the sensitivity decreases up to 10^{-7}.

Figure 3a shows the recording fragments of pentane DP oscillations obtained at different levels of energy supplied to the cavity. It is interesting that in this case, the transition from the almost harmonic DP oscillations to the cycle doubling is observed. Here the SHF energy levels are consistent to the voltages U which are recorded at the cavity outlet (on a crystal detector) and, to a first approximation, are proportional to the changes in the energy supplied to the cavity inlet. These studies have shown that the energy levels necessary to excite the DR oscillations in the fluid can differ greatly. In the case of pentane the excitation starts at U = 0.6 V (which corresponds to an energy of about 1 mV supplied to the cavity inlet) and in the case of hexane, at U = 0.75 V [7]. The increase in the hexane excitation threshold is attributed to its greater viscosity

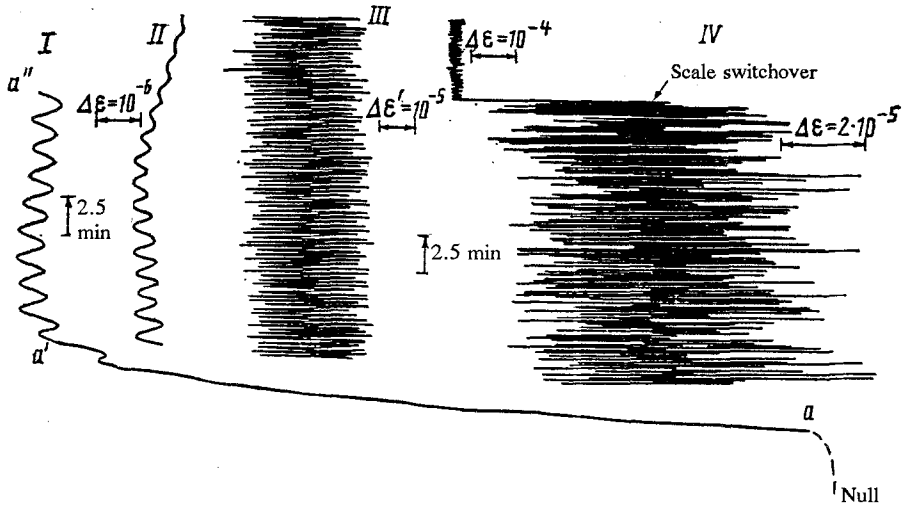

Fig. 2. Dielectrograms of periodic oscillations in the resonant cavity in the presence of the temperature gradient: I, convective instability evolution in cyclohexane in the cavity (null, moment of the temperature gradient superposition, ≈ 0.01 K/cm); II, system return to the stable state (after dissolving of nitrobenzene in heptane); III and IV, convective instability in heptane at elevated temperature gradients obtained in the cavities E_{010}.

as compared to pentane. This means that the convective stability of hexane starts at a temperature gradient which is larger than that for pentane. In this cell, success has not been attained in exciting DP oscillations in alkanes (heptane and octane), nor in benzene and dioxane. However, the oscillations in carbon tetrachloride [7] which are kept over the entire range of the energies supplied to the cavity have high stability. Evidently, this property of carbon tetrachloride is attributed to its low thermal conductivity, thus yielding a larger Rayleigh number as compared to other fluids.

The temperature gradient for the test fluid was assigned by different methods. The method based on fluid cooling at molecule evaporation from its surface proved to be most simple and natural. Figure 1 shows the cell, in which the used fluid can be poured to different levels of funnel 3 cut in upper cover 5. Varying the funnel fluid level can control the evaporation intensity, thus the fluid surface cooling depth. The temperature gradient is removed by a cork that stops up the throat of funnel 3 so that greater temperature gradients could be assigned, we used a thermoelectric microrefrigerator which was fastened to the upper or lower cover. Use of the microrefrigerator provided the smooth control of the gradient and possible sign change of the gradient (simply switching the voltage polarity). Also, the direct "heating from below" method was adopted.

Analysis of the possible mechanisms of low-frequency modulation of the cavity frequency and of the available experimental data [7] allows the unique conclusion to be made that the observed dielectric oscillations appear due to the onset of the convective instability of the fluid heated from below. It is therefore natural to assume that the nature of the observed effect is the cause of the convective Benard-type instability. Its unusualness is that it is observed in the nonviscous fluid at very small temperature gradients. The viscosity of all fluids we tested is very small ($\nu \gtrsim 10^{-2}$ cm^2/sec). Therefore, for the Rayleigh number to be close to the critical one ($R \gtrsim R_{cr}$) the temperature gradient must be indeed small (of the order of 10^{-1}-10^{-3} deg/cm). In substituting $g \approx 10^3$ cm/sec^2, $\beta \approx 1 \cdot 10^{-3}$ 1/K, $A = 10^{-2}$ K/cm, $L = 1$ cm, $\nu \approx 1.5 \cdot 10^{-2}$ cm^2/sec, and $\chi = 6 \cdot 10^{-4}$ cm^2/sec into the expression for the Rayleigh number [8]

$$R = \frac{g\beta AL^4}{\nu\chi} \tag{4}$$

(g is the acceleration of gravity; β is the thermal expansion coefficient; A is the equilibrium temperature gradient; L is the characteristic size of the chamber where unstable flow is observed; ν is the kinematic viscosity coefficient; χ is the thermal conductivity), we have $R \approx 10^3$-10^4. The uncertainty of the obtained Rayleigh number is associated with that of the spatial structure of convective flows which, in its turn, is bound up with the uncertainty of the solid boundaries that predetermine the temperature gradient. In principle, the design of the cavity H_{011} used realizes a semi-infinite layer of the fluid cooled and bounded by the metal surface from above. At the same time, the spatial configuration of convective flows is apparently much

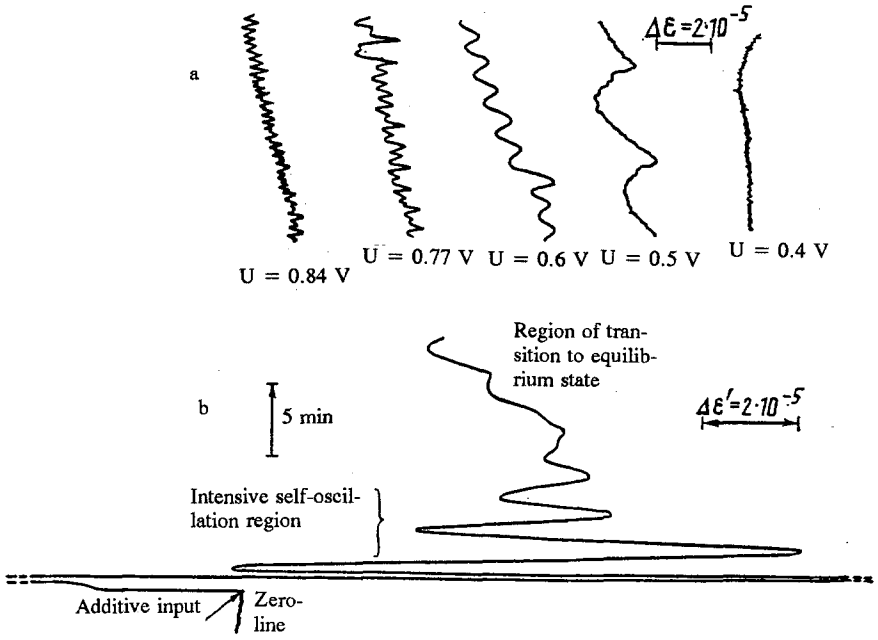

Fig. 3. Character of "dielectric" oscillations at different levels of SHF energy supplied to the cavity E_{010} partially filled with pentane (a) and the dielectrogram of "giant" oscillations observed when dissolving the polar additive (butanol, 5 ml) in cyclohexane (30 ml) obtained on the cavity H_{011} (b).

distorted by the presence of the side surface formed by the cavity body. Therefore, in calculating the Rayleigh number, the uncertainty associated with that of the knowledge of the quantities A and L is included. The obtained result can be compared with the calculated lower critical Rayleigh number for the appropriate closed circular cylinder. For the assigned geometry it is $R_{cr} \approx 10^3$ [8, p. 126], although in such a comparison it should be borne in mind that the real system is close to the semi-infinite cylinder.

At $A > 0$, the Rayleigh number is positive. In this case, the element of the volume of the fluid heated from below is shifted upwards due to disturbances. Being cooled through heat conduction it will have a higher temperature than the surrounding fluid. Therefore, the convective force acting upon it will be directed upwards, and the element will continue to rise, thereby overcoming the viscous resistance. Will this motion damp or develop – it depends on the relationship between the temperature gradient and the dissipation parameters. Nevertheless, this disturbance is monotonic in nature because of the absence of the "restoring" force. Under certain conditions, in the closed volume there appear harmonic oscillations with the frequency [9]

$$\omega^2 = \frac{\chi\nu}{S^2} + \beta g A. \tag{5}$$

Assume $\chi \approx 6 \cdot 10^{-4}$ cm^2/sec, $\nu \approx 1.5 \cdot 10^{-2}$ cm^2/sec, $\beta = 10^{-3}$ 1/K, $A = 10^{-2}$ K/cm, $g = 10^3$ cm/sec^2. Sizes of the cross section S of the convective flow must be substantially smaller than the cross-sectional area S_p of the resonant cavity; therefore, to a first approximation, $S \lesssim S_p/10 \approx 0.1$ cm^2. In this case, Eq. (5) yields $\omega/2\pi = f \approx 10^{-2}-3 \cdot 10^{-2}$ 1/sec, whence the self-oscillation period $T \approx$ 100-30 sec $\approx$ 0.5-1.6 min follows, which qualitatively agrees with the obtained experimental results.

Effects typical of the convective processes are also revealed in another run of experiments. In the cell (Fig. 1), while studying the dielectric properties of the diluted polar–nonpolar solutions, the dielectric oscillations are found which appear under diffusion at intensive evaporation of one of the components of this solution. In this effect, there is much in common with the above-considered phenomena. But the diffusion processes are an attribute of this effect. The phenomenon of "rolling cells" caused by diffusion [10, p. 99] can be considered to be closer to the phenomenon found. The corresponding dielectrograms are cited in [7].

One more variety of the convective instability is revealed in the processes of dissolving polar substances in nonpolar solvents. The pattern characteristic of the solution is found to manifest itself in strong dielectric oscillations immediately after

the polar component is added to the nonpolar solvent. Slow damping of these oscillations continues occurring for 5 to 15 min (for different solutions). This effect has been supported by many polar-nonpolar solutions [7], for which the dielectrograms are obtained. The specific features of this phenomenon are shown in Fig. 3b.

The oscillating nature of dissolving is peculiar not only to polar-nonpolar systems. It has appeared that dissolving nonpolar fluids in nonpolar dissolvents can also cause time-damping oscillations [7].

It should be supposed that the mechanism being the basis for appearing damping oscillations is stipulated by thermodynamic (to a first approximation, structureless) processes. Apparently, the dielectric oscillations revealed are the result of more general principles that establish the relations between the order and disorder in nonequilibrium systems in the presence of fluctuations [10]. In the generality of the observed phenomenon it is possible to see the manifestation of the same mechanism of the convective instability which acts under quasistatic conditions like Benard's structure systems. It may be assumed that the oscillating nature of dissolving is the cause of the mixing heat to release at this time. Together with the diffusional flow the mixing heat provides "fluid heating from below" and forms the spatial structure observed in experiment.

Analysis and experimental studies show that the dielectric method can be worthy among the modern ones for analyzing the hydrodynamic instability. The dielectric method enables one to extend the scope of studies of the hydrodynamic instability processes because of its specific features: inertialess measurement, high sensitivity, possible time "visualization," simple design of the measuring cell, conversion into an electric (frequency) signal that does not destroy the convective flow structure, recording of small flow velocities (of the order of cm/min), study of processes in closed volumes. A possible continuous recording of DP of kinematic processes permits one to investigate the evolution and dynamics of phase transitions of the order-disorder type in fluids and solutions under nonequilibrium conditions at small disturbances.

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