AN INVESTIGATION OF THE MOTION OF HOMOGENEOUS AND STRATIFIED LIQUIDS IN RECTANGULAR CAVITIES BY THE METHOD OF PHOTOCHROMIC VISUALIZATION

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A method of photochromic visualization has been developed for investigating thermogravitational flows in homogeneous and stratified fluids in a closed volume.

The method of photochromic visualization (PV) has been used in epxeriments for investigating velocity fields in viscous liquids [1-3]. The method is based on creating a colored tracer in a special photochromic solution by means of laser radiation and subsequently recording the motion of the tracer. The method appears to be very effective for studying hindered flow in a tube [3] and also for studying the structure of a flow after an obstruction [2]. In these problems the mean velocity of the flow was of the order of 20-40 cm/sec, and the time for which the tracer existed amounted to several seconds. The short time for which the tracer exists made it impossible to use the PV method for investigating low velocity flows, and in particular, for recording the slow thermoconvective motions of liquids in closed volumes.

In connection with the great interest in carrying out laboratory investigations of thermoconvective motions in homogeneous and stratified liquids and the special features of the PV method, which include the introduction of the tracer without disturbing the flow and the ability to make a non-contacting recording of the structure of the flow, a modification of the method has been developed which makes it possible to carry out the recording of velocity fields in low-velocity streams corresponding to the conditions for carrying out laboratory investigations of convection in stratified and homogeneous liquids [4]. This objective has been achieved through the selection of the concentration of the photochromic material, by introducing a thermal filter in the recording system, and by increasing the energy of the activating radiation.

The present paper describes the experimental equipment and the results of an investigation of the thermoconvective motion of a liquid by the PV method in a rectangular cavity heated at the sides filled with a homogeneous liquid, and in some cases with a density-stratified liquid. The experiments confirmed the possibility of using the method for investigating convection currents both in homogeneous liquids and in media with density stratification. Experiments carried out earlier to invetigate convection currents in homogeneous photochromic media [5] showed that with an energy for photoactivation of 0.01-0.05 J in the pulse it was possible to obtain tracers of lengths 3-4 cm and lifetimes of 20-30 seconds in aqueous photochromic solutions of indoline spiropyrans. It was found that during the investigation of the convection in homogeneous liquids in rectangular cavities the colored lines of tracer material deformed strongly in the course of motion and their optical density fell off, which made it impossible to reliably record the tracer more than 10 seconds after photoactivation. The equipment which has been developed for investigating rapid flows by the PV method made it possible to obtain an energy of UV radiation of 0.2 J in the pulse, but nevertheless this did not make it possible to invetigate the thermoconvective flow of a liquid in a rectangular cavity becauseo of the rapid fall-off in the optical density of the colored tracer during the deformation of the tracer as a result of the motion of the liquid in the cavity and the inadequate lifetime of the tracer [3].

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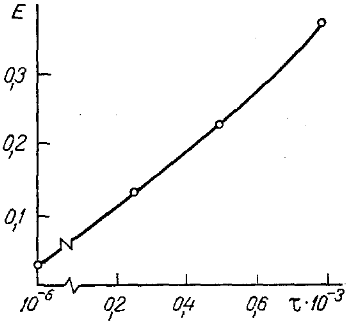

Fig. 1. Dependence of the UV radiation energy on the duration of the pulse. E is given in Joules and τ in seconds.

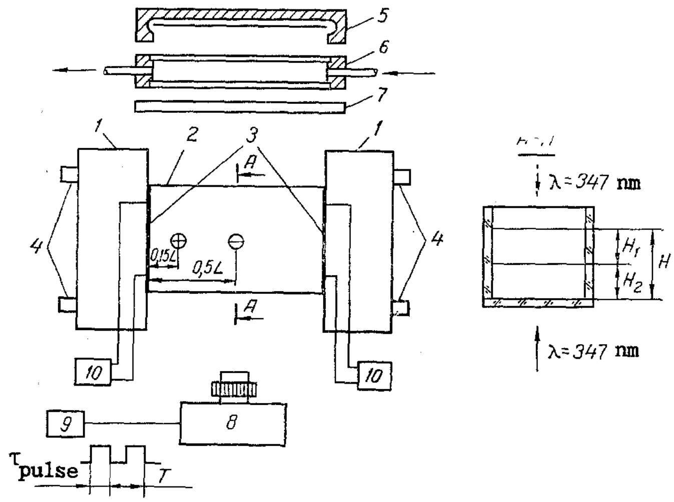

Fig. 2. Sketch of experimental equipment: 1) massive copper heat exchangers; 2) rectangular cavity made from transparent plastic; 3) film thermoresistor thermometers with positive temperature coefficients; 4) inlet and outlet nozzles; 5) ciné illuminator; 6) thermal filter; matte dispersing screen; 8) recording camera; 9) pulse generator; 10) voltammeter.

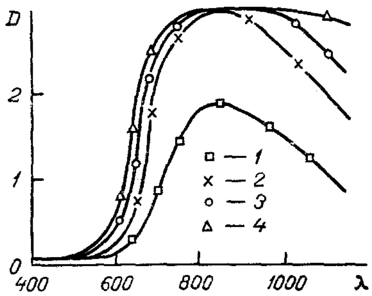

Fig. 3. Dependence of the optical density of thermal filter as a function of the wave length of the radiation for $CuSO_4 \cdot 5H_2O$ concentrations of: 0.16 mole/liter (line 1); 0.32 mole/liter (line 2); 0.48 mole/liter (line 3); 0.64 mole/liter (line 4). The wave length λ is given in nm.

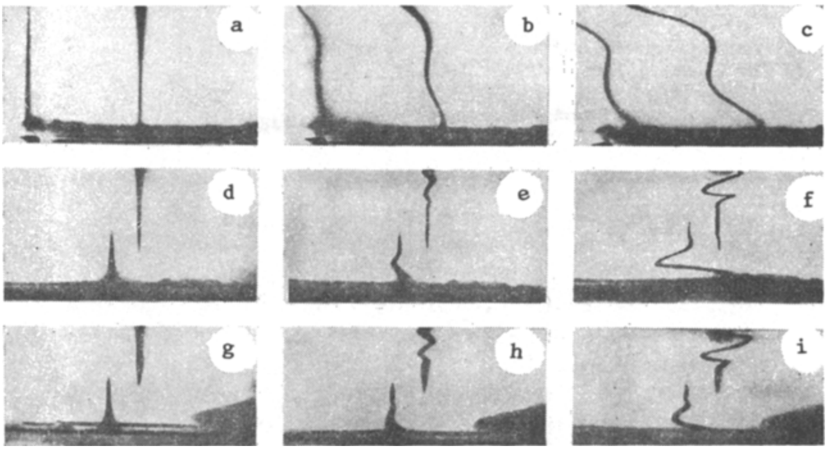

Fig. 4. Photographs of the flow visualization in rectangular cavities: a, b, c) flow of homogeneous liquid, t = 0, 4.1, and 12.2 seconds; d, e, f) flow in bilayer liquid, t = 0, 3.7, and 24.5 seconds; g, h, i) flow in three-layer liquid, t = 0, 10, and 33 seconds.

1. Description of the Experimental Equipment for Investigating Low-Velocity Thermoconvective Flows. In order to apply the PV method in experiments with low-velocity thermoconvective flows in stratified and homogeneous liquid special equipment was set up where in the photoactivation channels the duration of the initiating pulse was increased to 10^{-4} seconds, which led to an increase in the total energy of the pulse and made it possible to increase the density of the colored tracer. In addition, in the recording section a continuous regime of photography was recplaced by a discrete system, which made it possible to considerably decrese the thermal effect of the light flux for illumination on the photochromic solution. Simultaneously, the contrast of the colored tracer was increased by a suitable choice of the light filter in the illumination system. The equipment for investigating low-velocity flows, which is protected by an Inventor's Certificate [USSR Patent], made it possible to increase the lifetime of the colored tracer to 3-5 minutes [6]. The graph in Fig. 1 shows the change in the energy of the UV radiation as a function of the duration of the pulse. As the radiation source use was made of a solid ruby laser with modulation of the Q-factor, and the base radiation was converted into UV in non-linear KDP crystals [3, 7]. A sketch of the experimental equipment in which the thermogravitational flows of homogeneous and stratified liquids in rectangular cavities were investigated is shown in Fig. 2. Water with a specified temperature from a thermostat was pumped into the reservoirs of the heat exchanger. The readings of the thermoresistors, which were calibrated in advance, were recorded using an F-30 digital voltammeter. The temperature on the side walls of the rectangular cavity were determined to an accuracy of ±0.25°C. After the equipment reached a stabilized temperature regime (40-55 min), linear colored tracers were set up using the second harmonics of two ruby lasers (λ = 347 nm) at two cross-sections simultaneously as shown by the arrows in Fig. 2. At the moment that the tracers were formed the recording camera (type RFK-5) was switched on; in the film channel of the camera was placed a photodiode which reacted to the light flux passing through the films from the external source at the moment that the film gate opened. The recording camera operated on a frequency cycle with a filming rate of 10 frames per second.

In the initial position the film gate of the camera is open. After the controlling command pulse entered the camera the film gate closed, the ciné film was wound on by one frame, and the film gate opened again. Under these conditions the exposure was determined by the interval between the incoming command pulses from the G5-35 generator after deducting the time for transferring the film (≈0.05 seconds).

Thus the exposure time was $T_e T - \tau - 0.05$, where τ = 25-45 milliseconds. The RFK-5 recording camera made it possible to vary the exposure time from 4×10^{-3} to 10^{-1} seconds.

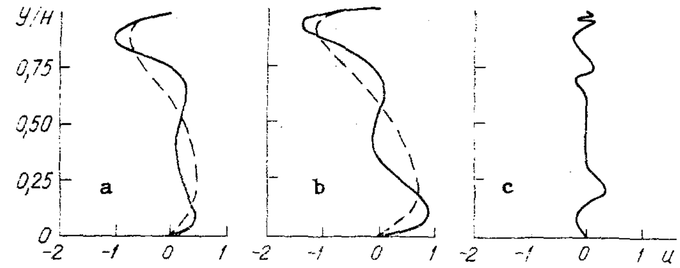

Fig. 5. Profiles of the horizontal velocity component in a rectangular cavity: a, b) in a homogeneous liquid at x = 0.14 L and 0.5L (solid lines are for $Gr = 0.92 \cdot 10^5$ and dashed lines are for $Gr = 0.24 \cdot 10^5$); c) in two-layered liquid. The value of is given in mm/sec.

TABLE 1. Characteristics of the Layers in Cases with Stratified Liquids

Number of layers	Layer	Depth of layer, mm	Concn. of salt in layer, g/liter	Concn. of photochromic material, 10^{-5} mole/liter
2	1	16	200	1,4
	2	16	100	0,7
3	1	10	200	1,4
	2	10	100	0,7
	3	5	0	52

In order to increase the lifetime of the photoinduced tracer it was necessry to reduce the thermal radiation from the ciné-illuminator, so the concentration of the copper sulfate $CuSO_4 \cdot 5H_2O$ in distilled water which was pumped through the thermal filter was increased. Figure 3 shows the relationship between the optical density of the filter which was used and the wave length of the radiation for various concentrations of $CuSO_4 \cdot 5H_2O$ in distilled water for a layer thickness of 10 mm. The maximum optical density of the colored tracer on Mikrat-200 film was obtained at the concentration of 0.64 mole/liter, which was therefore used during the investigations of slow flows of homogeneous and stratified liquids arising in rectangular cavities in the presence of temperature differences on the side walls.

2. Investigation of Convective Flow in Rectangular Cavities Filled with a Homogeneous Photochromic Solution. In investigating thermoconvective flows in aqueous photochromic solutions it is necessary to take into account that in preparing these solutions surface active materials (SAMs) are added which significantly alter the surface tension coefficient of the aqueous photochromic soltuion. In order to check the effect of the SAM on the value of the surface tension, measurements of the surface tension were carried out by the method of detaching a ring from the liquid surface. In the aqueous photochromic solutions which were used for the hydrodynamic investigations the concentration of SAM amounted to 6-8 mg/liter. At these concentrations of SAM the coefficient of surface tension appeared to be considerably smaller than in the case of water, and amounted to $(42\text{-}48) \cdot 10^{-3}$ N/m at a temperature of 20°C. It must be borne in mind that the decrease of the surface tension as a result of the effect of the SAM can be completely hidden by the effect of "congealing" the free surface of the aqueous photochromic solution caused by contamination of the surface by various impurities adsorbed form the air.

The experiments on visualization of the convective currents in a rectangular cavity were carried out at various values of the height of the liquid layer and at various temperatures on the vertical side walls of the cavity. Two parallel colored tracers were created simultaneously at the middle of the longitudinal vertical cross-section of the cavity, and the motions of these were recorded by the ciné-camera. From the negatives of the ciné-frames of the successive positions of the tracers the profiles of the horizontal components of the velocity of the solution were determined approximately assuming that they are close to uniform

[7]. This assumption is well satisfied at a sufficient distance from the side walls of the cavity. The evaluation of the Grashof number was carried out from the formula $Gr = (\beta g/\nu^2)\Delta T H^3$, where g = 981 cm/sec². Figures 4a, b, and c show characteristic photographs from the visualization of the convective flow in a homogeneous aqueous photochromic solution when the temperature on the left wall is T_1 is 23.6°C and that on the right wall is T_2 = 27.6°C. These photographs are typical examples of frames of the ciné-photographs which fix the positions of the two vertical linear colored tracers at successive moments of time. At the initial moment both tracers represent sections of two parallel straight lines located in the central longitudinal vertical cross-section of the cell. It is clear that with time a circulatory motion of the liquid develops in a coutner-clockwise direction. By carrying out the experiment at various values of the temperature difference between the side walls of the cavity it was possible to obtain information on the development of the thermoconvective motion at different Grashof numbers. In spite of the fact that the addition of the photochromic material led to a reduction of the surface tension coefficient of the water, the adsorptive properties of surface played a decisive part [9, 10]. The experiments showed that contamination of the water led to complete suppression of the thermocapillary effect, so that only thermogravitational flow occurred in the cavity.

In all of the experiments carried out at Grashof numbers $Gr = (0.24\text{-}0.92)\cdot 10^5$ the surface of the distilled water was immobile. At $Gr = 0.24\cdot 10^5$ a single-circulating flow arose, directed counter-clockwise, in the cavity with the aqueous solution, and a point of inflection occurred at a height 0.58H from the bottom in the cross-section 0.5L. On approaching the left wall, in the cross-section 0.14L from the left side wall, the point of inflection was shifted upwards a little. The deviation from a symmetrical profile led to an increase in the maximum velocity in the upper layers. At $Gr = 0.92\cdot 10^5$ a second circulating flow directed counter-clockwise appeared in the cavity. Figures 5a and b show velocity profiles for various Grashof numbers and different distances form the left wall which illustrate the conclusions reached above.

3. Investigation of Thermoconvective Flow in Stratified Liquids. For investigating the flow of stratified liquids in a rectangular cavity the density stratification was set up by using solutions with various salt concentrations in the different layers. Preliminary experiments shows that the addition of common salt to the aqueous photochromic solution led to a reduction of 10-15% in the density of the colored tracer in the solution compared with the aqueous photochromic solution without the salt. For investigating convective flows in media with density stratifications which are set up by means of dissolving common salt the concentration of the photochromic material was therefore increased. The intensity of the initiating radiation was also increased by 20-40%.

Two or three layers with appreciably different concentrations of salt and of the photochromic material were set up in the cell. The use of different concentrations of the dissolved photochromic material in the layers with different salt concentrations with the same level of the activation energy led to the situation that the optical densities of the tracer were different in the different layers. The formation of a tracer which was nonuniform in density across the layers made it possible to check the constancy of the thickness of the layers with various salt concentrations during the course of the experiment.

Examples of the successive positions of the colored tracers during thermoconvective flow of the liquid in two- and three-layered stepwise stratification are shown in Fig. 4. The method made it possible to record liquid velocities of the order of 10^{-3} cm/sec with at total recording time of up to several minutes. Analyses of the series of photographs for various experimental conditions made it possible to obtain information on the structures of the thermoconvective motion of stratified liquids.

In experiments with two layers, the parameters of which are given in Table 1, the structure of the flow as investigated with a temperature difference beween the right and left side walls of 10 and 18°C. At the temperature difference of 10°C an intense circulating flow in a clockwise direction was observed in the lower layer at a height of $2H_2/3$ from the bottom. In the upper layer a circulating flow almost twice smaller in intensity in a counter-clockwise direction was observed at a depth of $H_1/2$ from the upper boundary of the layer. At the interface between the layers of different densities up to distances into the layers equal to $\sim H_1/3$ and $\sim H_2/3$ there was no motion. Figure 5c shows velocity profiles with a temperature difference of 10°C. With a temperature difference of 18°C between the vertical walls a deposition of salt was noted in the lower layer at the warm wall. An unstable flow arose in the upper layer at a depth of $H_1/3$ from the upper surface of the layer; at the interface between the layers within the the layers up to distances $H_1/4$ and $H_2/4$ a feeble circulating flow was observed.

In the experiments with three layers (see Figs. 4g, h, and i) use was made of an unsteady-state process of the liquid motion at the middle cross-section of the cavity. The parameters of the layers are given in Table 1. At the initial moment the temperature at the side walls was equal to the room temperature, and then the heating was switched on in the thermostat from which water was pumped to the right hand cavity. Photographs of the motion of the colored tracers were made at various temperature differences between the side walls. The rate of increase of temperature in the thermostat was in the range of 0.15°C per second, which made it possible to oberve in the cavity a complex but close to quasi-steady-state picture of the development of the thermoconvective motion in the stratified liquid. It was found that the thermal convection in the layers of different densities led to liquid motions of different intensities with clearly marked individual structures of the flows in each of the layers. The nature of the flow in the cavity varied gradually as the temperature difference between the walls increased. Thus, at $\Delta T = 10°C$ an intensive circulating flow was observed in the upper layer in a clockwise direction, while the flow in the lower layer was found to circulate in a counter-clockwise direction, and the middle layer remained practically stationary for a considerable time.

When the temperature difference reached 25°C the circulating flow in the upper layer became disordered. An increase in the intensity of the counter-clockwise circulating flow in the lower layer was observed.

A deposition of cyrstalline salt was noted at the warm wall such that the shape of the outer boundary of the layer was close to the shape of the velocity profile for the liquid motion in the layer.

The experiments which have been carried out showed that the use of the photochromic visualization method for investigating the thermoconvective motions of liquids in systems with density stratification and also in the case of homogeneous liquids makes it possible to record the instantaneous structure of the velocity fields, register the important features of the flow (for example, vortex formation), and determine the location and size of mixing zones. It appears to be particularly effective to use the method in combination with Schlieren methods.

NOTATION

T_e, exposure time; T, succession period of command pulses; τ, duration of command pulse; Gr, Grashof number; β, ν, coefficients of temperature expansion and kinematic viscosity; $\Delta T = T_2 - T_1$, temperature difference between the vertical ends of the cavity; H, height of layer of homogeneous liqud in cavity; H_1, H_2, H_3, heights of layers of liquid with various salt contents; L, width of cavity; x, distance from left wall of cavity.

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