Thermal Convection under Conditions of Unsteady Wall Heating

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***Abstract*— Based on the using of the optical method of holographic interferometry, the occurrence and development of convective flows in liquids with various thermophysical characteristics in the process of unsteady conductive wall heating has been experimentally investigated. A difference in the structures of the emerging thermal convection flows for different liquids is found. The dependence of the convection initiation time on the value of the heating is established.**

***Keywords*— unsteady heat flux; flow visualization; thermal; convection**

I. Introduction

A large number of experimental and theoretical studies have been devoted to the problem of the appearance and development of thermogravitational convective flows, for example [1, 2]. This is due to the wide practical interest to the phenomena that arise when liquid or gaseous media are heated. Knowledge of the structure of the convective flows makes it possible to determine the efficiency of heat transfer from a source of heat to a liquid medium [3, 4] and, vice versa, the possibility of increasing the thermal insulation properties of elements of technical constructions [5]. Convective motions of the gas when it is heated near the earth's surface are important for predicting the dynamics of numerous atmospheric and technogenetic processes [6, 7].

Physically, the appearance of convection when the liquid is heated from below is associated with the development of thermocapillary and/or thermogravitational phenomena. In the first case, convective motions arise on the free surface due to the forces connected with the temperature dependence of the surface tension. In the second case, they arise due to the volume forces, when a lighter heated liquid is emerging in the surrounding cool and dense medium [8]. There are numerous models of thermogravitational convection in a closed fluid volume, taking into account various factors that affect the shape of convective currents, their intensity, and the time of their appearance. For example, such factors include: the shape of the cavity with the heated liquid [9], the thermal properties of the heated medium [10], the presence of heat transfer through the walls [11].

Visualization [12, 13] is an effective method of experimental study of thermogravitational convection for optically transparent media. Since this method is non-contact, its application does not distort the natural dynamics of the heat transfer process. The method of holographic interferometry is of particular interest, and with its help it is possible to obtain in real time information about the density distribution in a transfer medium. For example, it has been successfully used to study the temporal and spatial dynamics of the distribution of concentration fields in a liquid during the chemisorption of carbon dioxide with aqueous alkali solutions [14]. Since the density of the liquid depends on the temperature, this method can also be used effectively to study the dynamics of the temperature field propagation in a liquid upon its heating [15]. The use of special immersion liquids makes it possible to significantly expand the capabilities of the method and extend it to unique heat transfer conditions in cavities between optically transparent glass spheres [16].

In the present paper, using the method of holographic interferometry, experimental data on the features of the temporal and spatial dynamics of the development of convective currents in liquids with various properties during their unsteady heating through the wall are obtained. Specificity of measurements consisted in the use of a special gradient heat flow sensor, which allows determining with a high accuracy the amount of heat transferred to the liquid heating. At a fixed thermal load, the time of occurrence of thermo convection for various liquid media is determined.

II. Experimental Setup

An investigation of the appearance and development of free-convective currents in the conditions of unsteady heating of liquids with different thermophysical properties is performed by holographic interferometry. The scheme of the experimental setup is given and described in detail in [16].

The measuring section on which the investigation was performed is a cuvette made from optical glass. The general view of the measuring section is shown in Fig. 1. The cuvette is divided into two sections. In the experiments, one section was used with dimensions of 5 × 10 mm, a height of 20 mm.

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Fig. 1. Measuring section of the experimental setup.

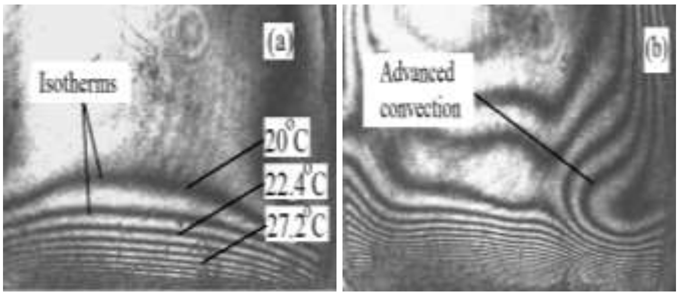

Fig. 2. The development of free convection in a cuvette with water under unsteady wall heating: (a) warming up layer near the wall; (b) the appearance of convection.

The cuvette was installed on a special holder, in the lower part of which, on the outside, layer-by-layer heat and electrical insulation, a heater and a gradient heat flow sensor were installed. The heating element was made in the form of a plate of nichrome brand X20N80 with dimensions 5 × 10 mm, thickness 0.06 mm. To prevent heat losses, the heat element was deepened to its own thickness in the layer of thermal insulation from the textolite. Thermal insulation thickness of 8 mm tightly pressed the heating element in the holder.

The measuring cuvette was filled with the test liquid. In the lower part, the heat was supplied by an electric heater with a controlled supply of heat load power. The value of the thermal load was equal to the power set at the current source and varied in the range from 4 to 30 W. To measure the value of the heat flux density, a gradient heat flux sensor was used on the lower surface of the cuvette with the liquid to be studied. Fluid temperature was measured by electronic devices Fluke 287 and CENTER-309 with the ability to determine up to four temperatures simultaneously thermocouples such as chromel-alumel and chromel-copel.

The gradient heat sensor is a heterogeneous anisotropic thermoelement made of a layered composition of metals: nickel and steel of brand 12X18N9T. Due to the anisotropy of heat and electrical conductivity in the sensor sections located normally to the external heat flux vector, a transverse temperature difference arises and the thermal-electric driving force proportional to this difference is generated.

The registration of the unsteady thermal processes taking place was carried out using a Fast Video-500M high-speed video camera. Holographic images were displayed on the computer screen in real time from the beginning to the end of the heating. The resolution of the video camera with a “global” shutter at a nominal recording rate of 500 frames per second was 1280 × 1024 pixels.

III. Measurement of Temperature Fields

The measurement of the temperature fields in the liquids under investigation was carried out as follows. On the basis of high-speed video recording of the process of unsteady heating of the liquid, interference patterns of the process of occurrence of convection were obtained. Interference patterns are special images of liquid heating, on which lines of equal temperatures (isotherms) are fixed for the certain time.

For interpretation of the isotherms, it is necessary to have a temperature value of at least one point in the volume of the studding liquid and the gradient of the change in the refractive index of the liquid from temperature. In the experiments, the initial temperature of the liquids was measured by the contact method using thermocouples and was 20°C. The values of the temperature dependences of the refractive index for various liquids are standard reference values.

In Fig. 2 as an example, video images of the temperature fields in water under conditions of unsteady heating from below at 5 and 30 seconds from the start of heating are presented. The thermal load, established with using a current source, was N = 10 W.

As shown in Fig. 2 (a) on initial stage of heat transfer the isotherms are parallel heating surfaces and correspond to the regime of classical unsteady thermal conductivity. Here, as an example, a scale with restored temperature values is given. For water, the temperature change between two interference bands with an initial temperature T = 20°C at a helium-neon laser wavelength of λ = 0.63 μm and a beam length L passing through a cuvette of 5×10^{-3} m was ΔT = 1.28°C.

As a result of heating the bottom wall of the cuvette the temperature field is distorted, in which the density vector of the heat flux ceases to be collinear with the temperature gradient vector, which subsequently leads to a curvature of the parallel isotherms. As can be seen in Fig. 2 (b), after 30 seconds from the beginning of the heating of the liquid, there are curvatures of the isotherms, which indicate the development of the regime of non-stationary convection. In experiments, the characteristic time at which the parallel isotherms are crooked with respect to the heating surface was identified with the time of occurrence of thermal convection.

IV. Experimental Results

Using the above-described measuring complex realizing the method of holographic interferometry, an experimental study of the occurrence and development of convective flows in the process of unsteady heating of the bottom wall of a cuvette was carried out. As working fluids was used: distilled water deaerated by pre-boiling, as well as chemically pure isopropyl alcohol and methylene chloride. The experiments were carried out at atmospheric pressure. The thermal load N varied from 4 to 30 W. The ambient temperature was kept constant and corresponded to an initial temperature of 20°C.

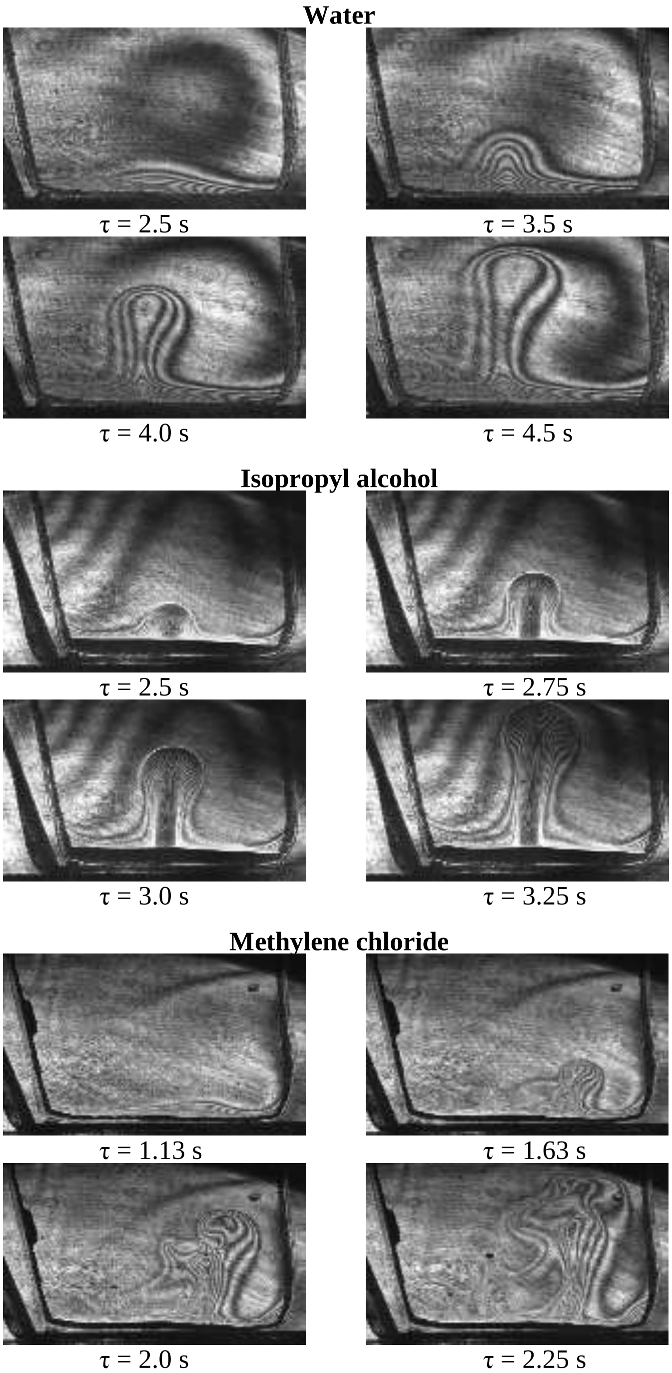

Fig. 3. The occurrence and development of natural convection, depending on the heating time for various liquids with a thermal load N = 30 W.

In Fig. 3 presents experimental results on the occurrence and dynamics of the development of convective currents in a cuvette with an established thermal load N = 30 W. The given video frames allow to determine the time of occurrence of free convection. As can be seen, in the experiment with water up to the time 2.5 s from the start of heating, the classical non-stationary thermal conductivity regime is observed, since isotherms are practically parallel to the heating surface. For isopropyl alcohol after 2.5 s there is a noticeable deformation of the temperature field. For comparison, convection in water occurs only after 3.5 seconds from the start of heating.

Among the fluids studied, the maximum value of the delay time at which an appreciable deformation of parallel isotherms starts and convection reaches the upper interface of the liquid-gas phases corresponds to water. Thus, under identical experimental conditions, the parameters for determination the onset of convection in homogeneous pure liquids are its thermophysical properties.

The method of holographic interferometry, which has high sensitivity, makes it possible to visualize local regions of the appearance of free convection. When heating was carried out in the lower part of the cuvette and there was a subsequent heating of the liquid, a thermal ("thermal spot") was formed. In all liquids, except methylene chloride, the thermal spots have a classical symmetrical appearance and retain it until the upper interface of the gas-liquid phases is reached. However, for methylene chloride the thermal develops asymmetrically throughout the volume of the liquid. Such deformation of the heat spot in methylene chloride intensifies the development of free convection throughout the cuvette which ensures more efficient heat transfer.

V. Discussion

The characteristic times of the appearance of free convection for the investigated liquids are determined from the experimental data. They are presented in Fig. 4 in the form of the dependence of the Fourier criterion **Fo** on the power of the thermal load N, set on the current source. The Fourier number was determined from the relation

$$\mathbf{Fo} = a\tau/L^2,$$

where a is the coefficient of thermal diffusivity. The Fourier number was calculated for times τ, at which the regime of unsteady thermal conductivity was replaced by the regime of free convection. The characteristic linear dimension L, entering into the criterion **Fo**, was assumed equal to the height of the liquid layer – 15 mm.

As follows from Fig. 4 the convection occurs earlier in methylene chloride and isopropyl alcohol, and in water the time of its occurrence is 2-3 times upward. It can be seen that for heating powers of 15 W and higher, the time for the appearance of convection varies insignificantly.

As can be seen from interferograms in Fig. 3, the temperature of the liquid rapidly increases with time in the bottom of the cuvette near the heater and remains constant and equal to the initial in the upper part until the loss of stability of the system. According to the available theoretical notions of one-dimensional unsteady heat transfer in a stationary liquid medium heated from below by a constant-power heat source N, the dependence of the maximum temperature difference ΔT for the layer height L on time t can be estimated starting from the solution of the second boundary-value problem for the heat equation on a semi-infinite region, see, for example, [17]: $\Delta T \sim N\sqrt{t}$.

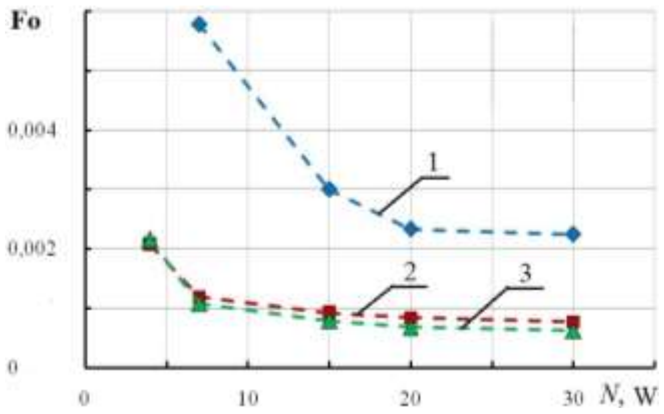

Fig. 4. Dependence of the Fourier criterion **Fo**, determined from the convection start time, on the thermal load *N* of the heater: 1 - water, 2 - isopropyl alcohol, 3 - methylene chloride.

The estimate obtained above makes it possible to calculate the instantaneous local value of the Rayleigh number. Achieving a local Rayleigh number at $t = \tau$ of critical value is a necessary condition for the occurrence of spontaneous thermal convection. The problem of thermal convective instability realized in the experiment differs from the classical problem [18, 19] in that in the problem under consideration, not the temperature difference over the height of the liquid layer but the heat flux at the lower boundary are taken into account. For the classical problem of thermal convection, according to [19], the critical value of the Rayleigh number

$$\mathbf{R}_{cr} = gL^3\beta\Delta T/(\nu a) = 1700 \pm 51,$$

where g is the acceleration due to gravity, β is the thermal expansion coefficient of the liquid, ν is the kinematic viscosity.

As the characteristic scale of the length L for the local Rayleigh number, it is necessary to choose the depth of the heating region of the liquid layer before the appearance of convection. Proceeding from the assumption of the self-similarity of the temperature profile, according to [17], the depth of thermal penetration is estimated by the relation $L \sim \sqrt{4a\tau}$.

Substitution of the characteristics of the liquid heating region ΔT and L into the expression for the local critical Rayleigh number, taking into account its value corresponding to the condition for the appearance of convection, makes it possible to approximately estimate the dependence of the time of occurrence of thermal convection on the heating power as $\tau \sim (N)^{-0.5}$. The obtained relation qualitatively corresponds to the dependences shown in Fig. 4, but requires further refinement in order to take into account the physicochemical and thermal properties of the heated liquids.

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