POSSIBILITY OF USING HOLOGRAPHIC INTERFEROMETRY FOR STUDY OF MASS-TRANSFER PROCESSES

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A method is proposed for measuring the redistribution of density of liquid in a closed basin during laboratory model studies of isothermal two-dimensional mass-transfer processes.

As the process of isothermal turbulent mass transfer in a closed basin decays, the relative shift of interference fringes can be determined from the condition that the mean density of stratified liquid in any vertical section remains invariant, i.e., the same before and after decay of the process.

At the present time an intensive development of optical contactless laboratory methods for study of mass transfer in stratified media is taking place. The study of phase nonhomogeneity by such methods involves measurement of the space distribution of the refractive index, which is determined by the space distribution of density of the liquid. Under the conditions of an oceanological laboratory experiment, for instance, the density of the liquid can vary as a result of salinity or temperature variation, while in an isothermal experiment it can vary only because of varying salt concentration in the water. Inasmuch as in laboratory basins stratification is usually produced by dissolution of sodium chloride in water, the $\rho = \rho(s)$ relation is known [1].

The method of determining the space distribution of density (refractive index) by holographic interferometry has already been considered [2]. The measured quantity is here the shift of interference fringes. The number k is proportional to the phase lead $\Delta\varphi$ which the probing wave acquires upon single passage through the object [2]

$$k = c\frac{\Delta\varphi}{2\pi} = \frac{c}{\lambda}\int\limits_{Z_1}^{Z}(n - n_0)\,dz.$$

In two-beam interferometry the coefficient c is unity [2]. In this case, if the object is homogeneous along the line of vision, i.e., the refractive index is a function of coordinates X and Z only (not a function of the Y-coordinate),

$$k(X, Z) = \frac{\Delta\varphi}{2\pi} = \frac{l}{\lambda}[n(X, Z) - n_0].$$

From here we have

$$n(X, Z) = \frac{k(X, Z)\lambda}{l} + n_0.$$

Fringes are counted from a point in the field at which the refractive index (density) is known. In the study of mass-transfer processes in objects with a phase constitution it is not possible to track the shift of a fringe after one has been initially recorded at some instant of time, because perturbations induced in the medium will rupture it. In such a case of fringe rupture, i.e., of turbulence in a stratified liquid, the most typical and scientifically important situation, extraction of quantitative data from holograms will contribute to the solution of many problems. Such a pattern prevails, for instance, in a stratified liquid during spread of a turbulized patch. After the process of spreading has ended, there follows a restoration of a stationary pattern of interference fringes corresponding to the final space distribution of density with distinctly visible elements of the fine structure. The space distribution of density of a liquid after perturbations have decayed was never measured quantitatively, however, because of the impossibility of determining the relative shift of interference fringes appearing before and after the experiment.

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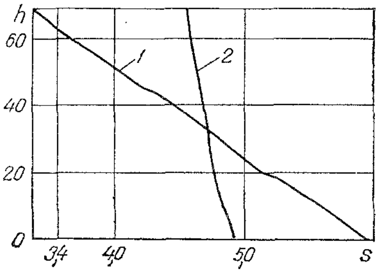

Fig. 1. Distribution of salinity of liquid in basin: interference fringes 1 and 2 correspond to salinity distribution in liquid in initial static state and in final static state, respectively; h (mm), s (‰).

The gist of the proposed method of measuring the space distribution of density of liquid in closed basins during laboratory simulation of isothermal two-dimensional mass-transfer processes is determining the relative shift of interference fringes from the condition that the mean density of a stratified liquid in any vertical section remains invariant, i.e., the same before and after decay of the mass-transfer process, which implies equality of the areas in both initial and final static states bounded by orthogonal axes, the free surface of the liquid, and the interference fringe which corresponds to the density distribution in the respective static state.

We will illustrate this with an example. Processing of interferograms with fringes of finite width involves calculation of the area bounded by axes of coordinates parallel to the basin generatrices and curve 1 representing the interference fringe must pass through a point where the density is known. Since the static interferogram constitutes an array of parallel lines, one can select any interference fringe corresponding to the density distribution in the liquid in the final static state. Its characteristic point (e.g., at the bottom or at the surface) is selected as the origin of coordinates, whereupon one determines the area of the figure bounded by the given interference fringe and the axes of coordinates. The position of the interference fringe which corresponds to the density distribution in the basin in the final static state, relative to the initial density distribution, is determined from the condition of equality of respective areas.

Earlier it was not possible to evaluate such experiments quantitatively. Only after fringes have been tied together, furthermore, is it now possible to quantitatively evaluate the dynamics of mass transfer from the instant when fringes become restored following their rupture to the instant when the liquid in the basin reaches its final static state. It is exactly during this time that a collapsing patch of mixed liquid in a stratified basin generates internal waves, which subsequently evolve and decay, while also a fine brine structure forms, i.e., processes occur whose nature has not yet been properly explored.

As an example, holographic interferograms with fringes of finite width in both initial static states of a stratified liquid in an experimental closed basin under isothermal conditions without intake and drain of liquid were examined.

The interference pattern was produced by means of a standard two-beam optical system suitable for holographic interferometry. Measurements were made in real time, with the varying interference pattern recorded on moving film.

In a 1650 × 150 × 350 mm large laboratory basin, with the aid of a stratifier, an initial vertical salinity profile in the liquid corresponding to position 1 of an interference fringe in Fig. 1 (curve 1) was produced. A specially designed mixer at half-depth in the basin mixed a 1-cm-thick layer of liquid. Interference fringe 2 in Fig. 1 corresponded to the salinity profile in the final static state, namely after perturbations produced by mass-transfer processes in the liquid have decayed.

From the shift of curve 2 relative to curve 1 changes in the refractive index and then the absolute density of liquid in each horizontal section were determined. The values thus obtained are given in Table 1.

A specific feature characterizing the spread of a mixed layer in a stratified liquid is formation of a fine vertical structure of its density (salinity) field which varies little in the horizontal direction but has a rather large vertical density gradient, on the order of 10^{-3} g/cm^4, and a characteristic thickness on the order of 1 cm. Interferograms of objects with phase constitution are usually decoded without refraction taken into account, refraction causing a shift of the interference pattern relative to the line of vision, and without the additional phase shift due to different lengths of the deflected light beam and of the line of vision taken into account. The effect of refraction is known to have been estimated in the case of objects having a phase constitution with axial symmetry and parabolic distribution of the refractive index. It has been demonstrated that refraction is negligible when the maximum change in the refractive index along the axis of an object does not exceed 5% [3]. Let us then estimate the errors which the optical system used in the experiment introduces into the

TABLE 1. Changes in Refractive Index and in Salt Concentration in Water at Various Depths in Basin

Layer No.	Distance of layer from bottom, mm	s_1, ‰	$(n-n_0)\cdot 10^{-5}$	s_2, ‰	Layer No.	Distance of layer from bottom, mm	s_1, ‰	$(n-n_0)\cdot 10^{-5}$	s_2, ‰
1	0	5,91	18,2	4,92	9	40	4,50	2,2	4,52
2	5	5,70	14,9	4,89	10	45	4,28	5,9	4,60
3	10	5,58	14,2	4,81	11	50	4,12	8,5	4,58
4	15	5,42	11,7	4,77	12	55	3,94	11,2	4,55
5	20	5,18	6,5	4,72	13	60	3,76	14,0	4,52
6	25	5,01	5,7	4,70	14	65	3,53	17,8	4,50
7	30	4,85	3,9	4,65	15	70	3,40	19,9	4,48
8	35	4,68	0,7	4,64					

interference pattern recorded by a movie camera. The screen was located 45 cm away from the basin, the line of vision in the basin was 15 cm long.

The angle Θ by which the light beam is deflected because of refraction in a layer with a constant density gradient of approximately 10^{-3} g/cm^4 (gradient of the refractive index $\Delta n/\Delta z \sim 10^{-4}$ cm^{-1}) is, with an observation base of length l, is $\Theta = (l/n_0)\Delta n/\Delta z$. With $l = 15$ cm and $n_0 = 1.34$, we have $\Theta_{\max} \sim 10^{-3}$.

The maximum shift of the light beam from the line of vision on the interferogram will be of the order of $L\Theta \sim 0.6\cdot 10^{-1}$ cm, where $L = 60$ cm. Then the maximum possible lengthening of the deflected light beam relative to the line of vision will be $\sim L\Theta^{\lambda} \sim 0.6\cdot 10^{-3}$ mm $\sim \lambda$.

The holograms were analyzed in 15 selected horizontal sections 5 mm apart from one another. The maximum possible shift of the light beam from the line of vision was $\sim$ 0.6 mm, comparable with the thickness of the boundary line between sections, and the resulting error (10%) was, therefore, discounted. In the layer with the maximum density gradient, where the deflected light beam was lengthened by an amount on the order of λ, the recorded phase shift was equivalent to 16λ and the error in that case was $\approx 6\%$. These estimates thus indicate that the optical system yields results accurate within 15%.

NOTATION

s (10^{-3} g/cm^3), salt concentration in the liquid; ρ (g/cm^3), density of the liquid; c, a coefficient characterizing the sensitivity of the method; k, number of fringes through which an interference fringe has shifted; $\Delta\varphi$, phase lead of the probing wave produced by passage through a test object; λ (μm), wavelength of the probing wave; n, refractive index of the liquid with nonhomogeneity; and n_0, refractive index of the liquid without nonhomogeneity.

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