Marek Jerzy Matczak, Zbigniew Kraska**

An Application of the Holographic Interferometry to Visualize Thermodynamical Processes

This paper presents holograms of thermodynamical processes in the transparent regions obtained with the help of holographic methods. It also includes a mathematical description of the creation of an interference field during the holographic registration of phase changes in transmissive objects illuminated by a plane wave. Possibilities of temperature gradient determination by means of the holographic interferometry is described.

1. Introduction

The stormy development of holography in recent years is linked to large extent with the employment of holographic interferometry methods in many fields of science and technology.

Examinations of displacements and strains in solid body samples [1], vibration analysis [2, 6], investigation of the thermodynamical processes as well as shock waves [3, 5] have to be mentioned among many other applications of these methods. The holographic methods exhibit many essential advantages when compared with classical interferometric methods. In particular: no high accuracy is required for the optical elements of the system, no restrictions concerning the shape of the object to be examined is imposed, the possibility of determining of both the deformation and displacement of the diffusing objects, which can not be examined by means of classical interferometric methods is offered. Besides, the holographic interferometers exhibit the property of three-dimentional imaging of the interference fringe system, which may enable an analysis of the processes in their three-dimentional description.

An examination of thermodynamical processes with the holographic interferometric method may be realized in two different ways. In the first method two successive holograms of a transmissive object taken at different moments of the thermodynamical process are registered on the same plate. The system of fringes recorded on the interferogram contains information about the difference between the two registered thermodynamical states of the investigated object. An application of the pulsing lasers allows to shorten the exposure time sufficiently, which is indispensable when investigating quick nonstationary processes. The other method enables a continous observation of the process to be examined. The real time holographic interferometry is employed here [4]. The interference pattern appears as a result of the interference of the wavefront emerging from the hologram with that coming directly from the object. Thus, the interference pattern presents the actual state of the objects as compared with its state which was registered on the hologram previously.

2. Experimental Part

A scheme of the holographic system in which an interferogram of the transmissive object were produced is presented in Fig. 1. The system makes it possible to produce holograms by the double exposure method using a ruby laser ($\lambda = 694$ nm) or the real time observation of the processes using a He–Ne laser ($\lambda = 633$ nm). The examined object was perme-

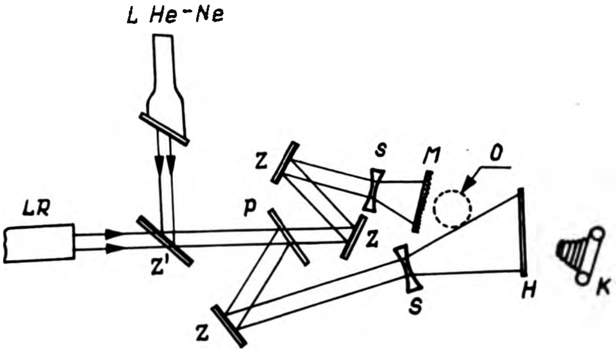


Fig. 1. Scheme of the holographic structure: LR — ruby laser, L He-Ne — He-Ne laser, M — matted plate, Z — mirrors, S — lenses, P — beam spliter, H — holographic plate, K — photographic camera, O — object to be examined

*) Military Technical Academy, Warsaw, Poland.

ated with a light diffused by a matted plate. To improve the coherence degree of the ruby laser beam a multi-plate mirror together with a diaphragm restricting the beam diameter were used. The holograms were produced on 10E75 Agfa-Gevaert photographic plates. The interferograms of the transmitting objects produced by the double exposure method, using a ruby laser, are presented in Figs. 2–6. Figs. 7 and 8 present interferograms of thermodynamical processes obtained by the real time holographic interferometry method using a He-Ne laser.

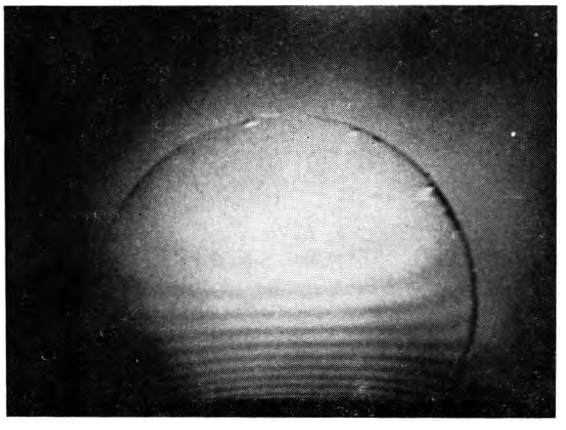


Fig. 2. An interferogram of the glass plate heated from the bottom

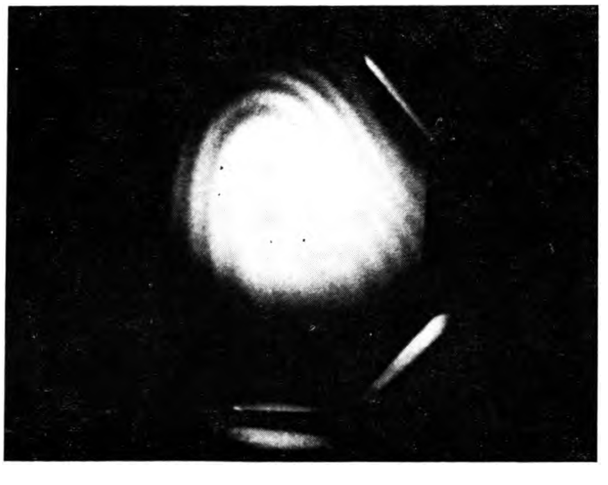


Fig. 3. An interferogram of the heated glass prism during the thermodynamical equilibrum settlement

3. Theoretical Part

The present work discusses the application of the holographic interferometry in registering of thermodynamical processes which take place in transparent solids, fluids and gases. In this instance the transparent object is understood as a medium of a non-zero transmission factor for the radiation used during examination. The lowest admissible value of the transmition factor for the medium investigated in the particular experiment depends on the radiation source power as well as on the sensitivity of the registering material.

The presented mechanism of the holographic registration of the thermodynamical process is based on a wave model of the coherent light and concerns the discription of the interferograms given in Figs. 7 and 8, which illustrate the processes appearing in the medium contained in a plain parallel container. In the course of this processes the differences in the refractive index occuring in the examined medium are of the order 10^{-5}–10^{-3}, which means that the propagation direction in front of the object and behind it is practically invariable. The thermodynamical processes change the refractive index distribution within the medium and thus modulate the phase of the radiation passing the object. Assuming that the object is permeated by a plane wave and defining the coordinate system so that the propagation direction is identical with the 0–z axis the complete phase increase may be written down in the following form

$$\varphi(x, y, z, t) = \frac{2\pi}{\lambda}\int_0^z n(x, y, z, t)\,dz, \qquad (1)$$

where λ is the wavelength of the used radiation, and $n(x, y, z, t)$ denotes the refractive index distribution.

After having holographically registered the examined object at two different moments of the thermodynamical process the hologram will reproduce — during the reconstruction process — two coherent wavefronts representing the registered states. The image obtained is described by a sum of amplitudes of the interfering wavefronts, which take the following form

$$A(x, y, z; t, t_0) = \exp[i\varphi(x, y, z, t_0)] \\ \{1+\exp[i(\varphi(x, y, z, t)-\varphi(x, y, z, t_0))]\} \qquad (2)$$

apart from a constant factor. Interference fringes may, therefore, occur in the places determined by the condition

$$\frac{2\pi}{\lambda}\int_0^z [n(x, y\ z, t)-n(x, y, z, t_0)]\,dz = (2m+1)\pi, \qquad (3)$$

where m denotes an integer.

Fig. 4. An interferogram of the match flame

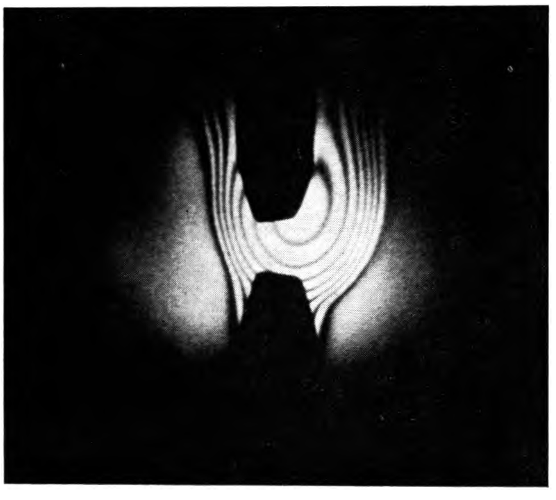


Fig. 5. An interferogram of the electrical arc

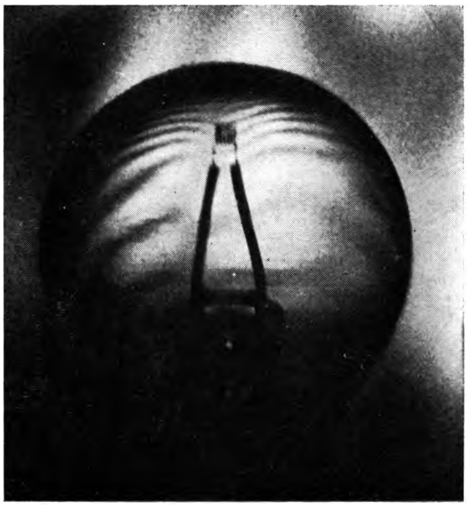


Fig. 6. An interferogram of a shining incadescent lamp

When examining thermodynamical processes one of the basic values sought is the temperature gradient as a function of time and position. The method of holographic interferometry working in real time enables to carry out current observation as well as the photographic registration of the tested process, which results in a temperature–time relation determination. The temperature gradient distribution as a function of position can be obtained for a given time point of the process from the condition (3) with the help of a properly designed experimental structure.

In our case this structure is represented by a plain-parallel container thin enough (small Δz) to assume that along the 0–z axis the value of the temperature gradient is equal to zero across the whole container. Thus the condition (3) takes the form

$$\frac{2\pi}{\lambda}\Delta z[n(x, y, t)-n(x, y, t_0)] = (2m+1)\pi. \quad (4)$$

Figs. 7 and 8 illustrate a process of pulse heating the water and a process of ice thawing in reference to the initial state of the processes registered on the hologram at the moment t_0 (which is a state of constant temperature within the container volume). A linear dependence of the refractive index on the temperature may be assumed for the temperature range occuring in the course of this processes.

$$\Delta n = \gamma\Delta T, \quad (5)$$

where the proportionality coefficient γ is equal to $-8\cdot 10^{-5}\,\mathrm{deg}^{-1}$ in the case of water. Thus, measuring the distance $|\Delta\vec{\varrho}|$ between the neighbouring fringes in the arbitrary direction $\Delta\vec{\varrho}$ in the plane $\{x, y\}$ the differential temperature gradient may be determined in the vicinity of the given point (x, y) by

$$\frac{\Delta T}{\Delta\vec{\varrho}} = \frac{\lambda}{\gamma\Delta z|\Delta\vec{\varrho}|^2}\Delta\vec{\varrho}. \quad (6)$$

4. Concluding Remarks

The method described above and its mathematical description preserve their validity for the examination of any object for which it is possible to find a coherent source of radiation sufficiently penetrating, and to which the wave treatement may be applied. In the present paper the theoretical description is based on the simplified assumption that the object is permeated by a plane wave, while experimental results have been obtained for diffused illumination. In the case of the

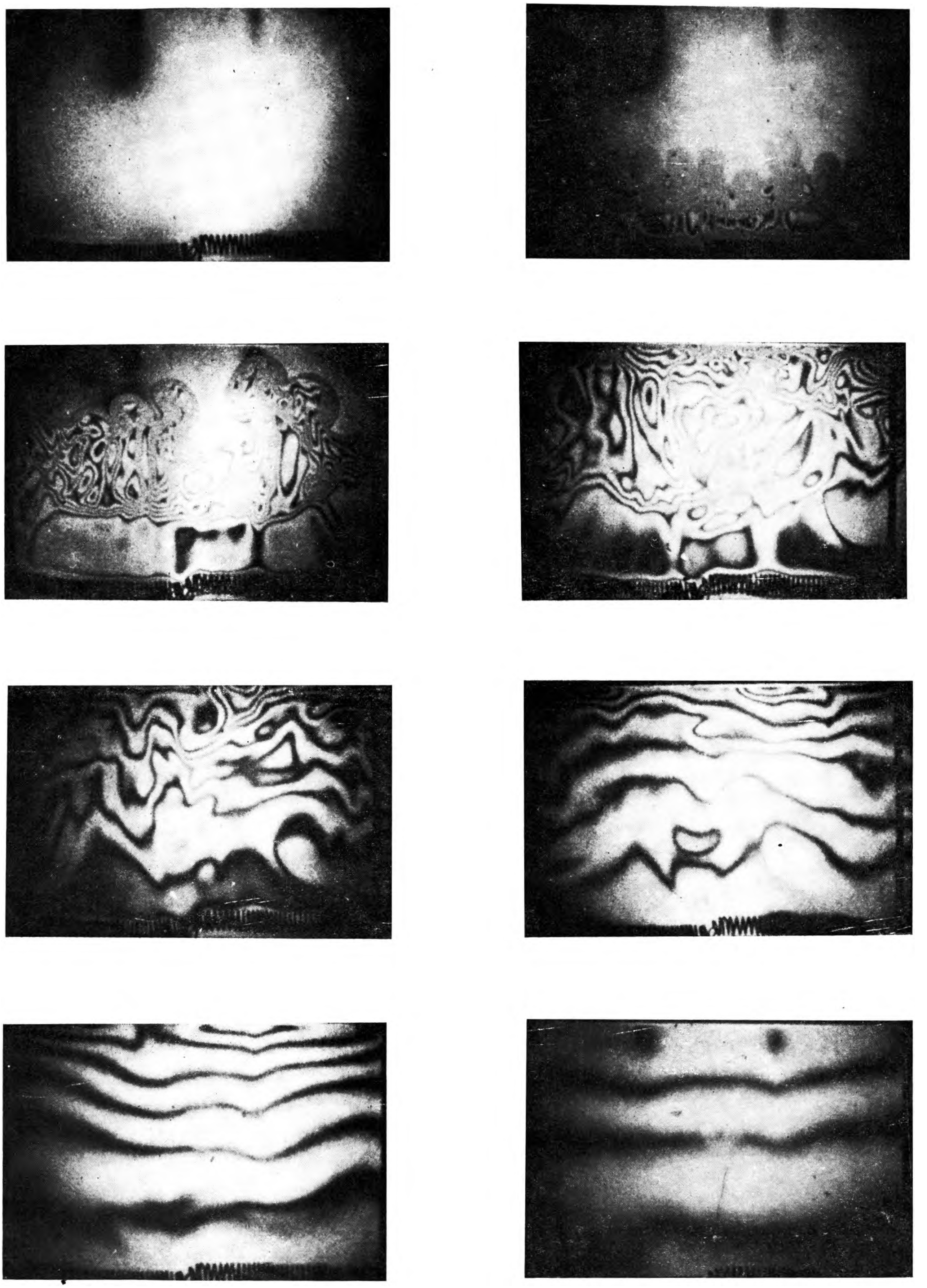
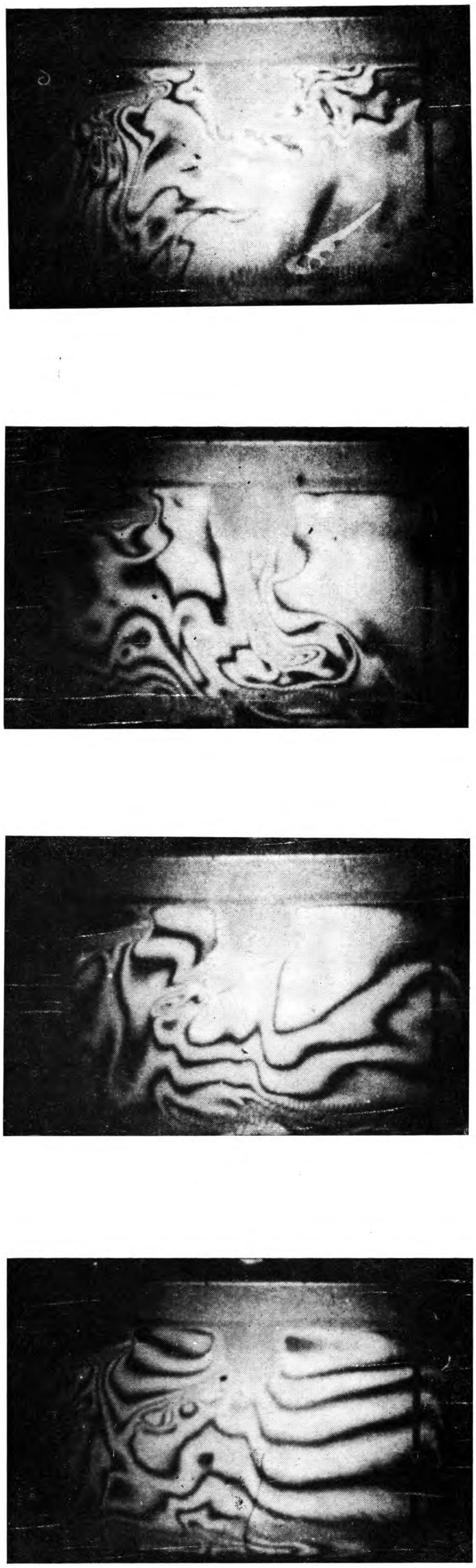


Fig. 7. Interferograms of a process of the pulse heating of water; the pictures reproduced from film tape



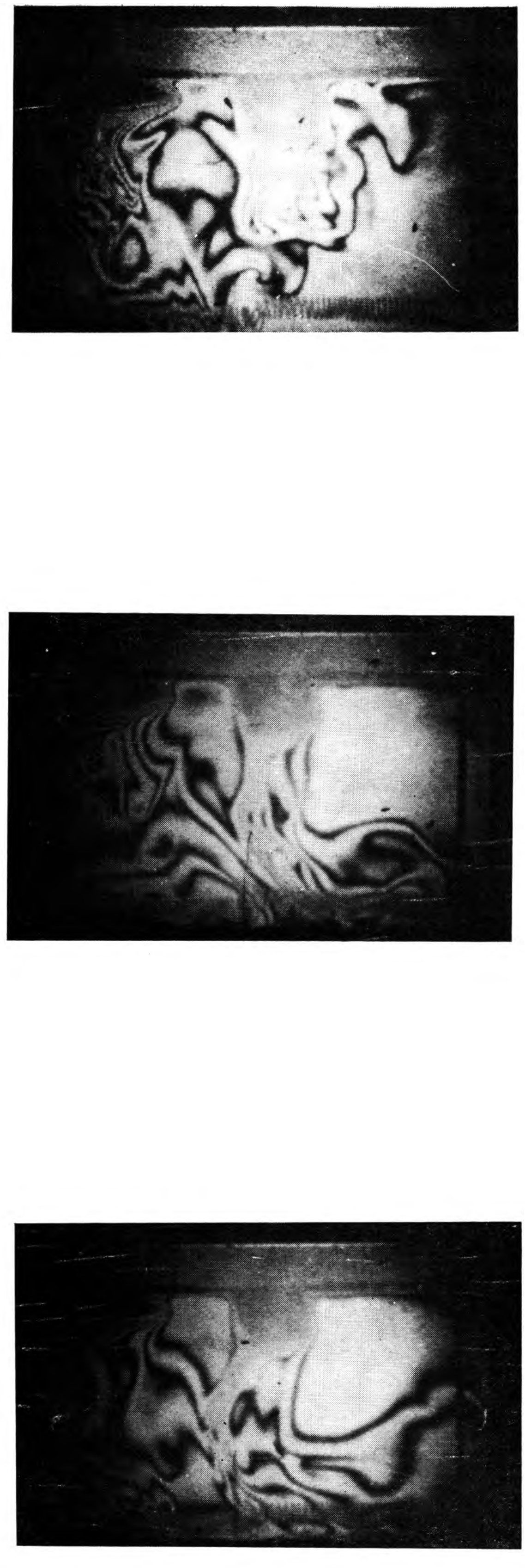


Fig. 8. Interferograms of aice thawing process; the pictures are reproduced from film tape

plane wave illumination an interference fringe pattern appears at any optical plane perpendicular to the direction of the wave propagation, while for the diffusing illumination the fringes are localized in one exactly determined optical plane, which is a plane virtual source of deformation of the incident wave. In this case the description of the phase-deformation for the informative wave is widened in such a way that it includes the acting of the space operator of the Fresnel transform type.

References

[1] ALEKSANDROV E. B., BONCZ-BRUJEWICZ A. M., ŻTF **37**, 360 (1967).

[2] ALEKSOFF C.C., Appl. Opt. **10**, 1329 (1971).

[3] BROOKS R., HEFLINGER L., WUERKER K., IEEE QE-**2**, 275 (1966).

[4] CASLER D. H., PRUETT H. D., Appl. Opt. **10**, 341 (1967).

[5] HEFLINGER L., WUERKER R., BROOKS R., J. Appl. Phys. **37**, 642 (1966).

[6] KRASKA Z., MATCZAK M. J., Biuletyn WAT, No. 7 (1972).