INTERFERENCE METHODS OF ANALYZING OPTICAL INHOMOGENEITIES WITH AN IAB-451 INSTRUMENT

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UDC 531.715.1:536.46

The application of interference methods is considered for analyzing optical inhomogeneities. The experimental data indicate that such methods can be successfully used for the analysis of stationary as well as fast processes.

Optical and interference methods have found wide applications in the study of diverse phenomena occurring in translucent media and related to local variations of the refractive index.

The optical instrument most often used nowadays is the IAB-451 shadowgraph. It is produced serially by a domestic manufacturing enterprise and is widely used for various studies. Many interference patterns can be achieved with it. We will consider the application of interference techniques with an IAB-451 instrument for the study of optical inhomogeneities.

There are three methods of analyzing optical inhomogeneities: the Tepler or Schlieren method, the shadow method, and the interference method. The ideas underlying all of them have been known for over 100 years now. Until the 1950s, however, these methods were used only for essentially qualitative studies. Monographs published at various times cover the state of the art in the respective periods. Among them one ought to mention the works by Maksutov [1, 2], Schardin [11, 12], Abrukov [3], Holder and North [13], and Vasil'ev [4].

The method of interference fringes in the Tepler device has been perfected more than any other for the study of flame structures, it permits the analysis to be carried up to numerical calculations.

Both theoretical [5] and experimental studies have shown that, in order to produce a pattern suitable for measurements, the filament diameter must be

$$D \leqslant 1.2\frac{f\lambda}{\pi d}. \quad (1)$$

If the focal lengths of the viewing tube objective and the collimator tube objective are equal, as they are in the IAB-451 instrument, the slit width must be somewhat smaller than the filament diameter. The instrument can be set up for fringes of either finite or infinite widths. In the first case, the interferogram is processed in terms of the measured shift of fringes. In order to produce an interferogram with a good contrast, one needs a narrow light source and, for this reason, the study of fast processes is fraught with difficulties due to an inadequate illumination of the screen.

In the slit-and-grating method the light source is a slit while a grating with the parameter $2a$ serves as the diaphragm. The grating lines must be parallel to the image of the illuminating slit. One positions the grating in such a way that the undeflected light rays are led back by its lines. Then the background will be dark and the image of an inhomogeneity will appear covered by dark and bright fringes along which the deflection of light rays is constant.

This procedure has served as the basis in the design of a diffraction interferometer with the IAB-451 shadowgraph, which offers certain advantages over the Schlieren-interference technique with a narrow slit and a thin filament: the screen is better illuminated, the interferograms are of higher quality, and the procedure is more reliable. It is necessary, however, to protect this interferometer against vibrations and one must avoid shaking the floor during recording.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 22, No. 2, pp. 267-274, February, 1972. Original article submitted May 19, 1971.

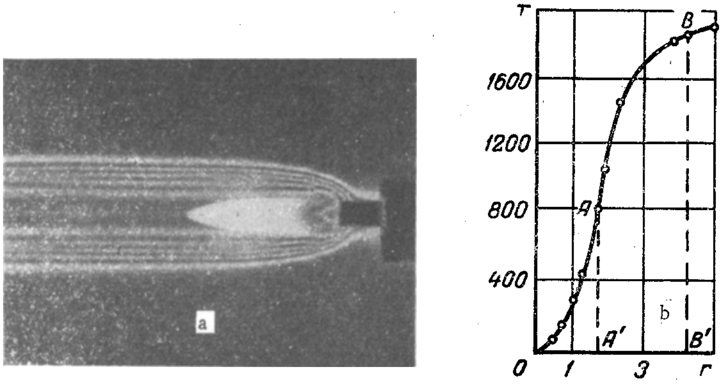

Fig. 1. Interferogram of a flame (a) and graph of the temperature distribution over a flame cross section (b). r) Distance from the flame edge, mm; A) nominal point on the boundary between the heating zone and the combustion zone; T, °C) temperature.

These interference methods are reliable for the analysis of steady flames. One can determine distributions of the refractive index and of the temperature in a flame, and to measure the flame temperature as well as the size of the combustion zone, of the heating zone, etc.

As an example, in Fig. 1 is shown the interferogram of a Bunsen burner flame, which has been by the slit-and-filament method, and the temperature distribution in the flame across one section of the stoichiometric CO + air mixture.

The light source here was a DRSh-250 lamp with a yellow filter. The interferogram was processed by the method shown in [6].

Polarization-type shift interferometers represent a new class of two-beam instruments [7-9]. Compared to a shadow-type instrument, they ensure a higher measurement accuracy. While generally less accurate than classical interferometers, shift interferometers excel the latter in some other aspects. They are easily adjusted and regulated, they are stable in operation, and the light-beam splitters and the compensators are small. Certain shift interferometers can also be designed with the IAB-451 shadowgraph.

Optical inhomogeneities are now most widely analyzed with the aid of lateral-shift interferometers, which can be classified into differential ones and ones with a large shift. Among the latter are those with a shift approximately equal to one half the radius of the collimator lenses or mirrors, and those with such a large shift that a separate set of optical components is required for each light beam. In differential interferometers the shift is much smaller than the transverse dimensions of the test object. Such interferometers can detect small gradients of optical thickness and are almost insensitive to vibrations. In differential interferometers it is easier to ensure an invariability of physical conditions along the path of the interfering beams, and a high-contrast interference pattern can be obtained.

Interferometers with polarized light operate on the principle that a double-refracting system (light-beam splitter) converts a plane-polarized wave into two waves: an ordinary one and an extraordinary one. These two waves are displaced from one another by the birefringency of the system. In an interferometer with fully separated light beams one of them passes through the test object and the other passes through an unperturbed field. From the interference pattern one can determine the distribution of the refractive index in the tested medium. The most commonly used light-beam splitter for polarization interferometers is a Wollaston prism, in which both outgoing beams are displaced symmetrically with respect to the incident beam.

A conversion of the IAB-451 instrument into a polarization interferometer is accomplished as follows. The illuminating slit in the collimator tube and the Foucault knife-edge in the viewing tube are replaced by identical double-refracting systems. For producing polarized light and viewing the interference pattern, one places a polarizer before the first prism and an analyzer behind the second prism. Polaroids mounted between two glass plates may be used as the polarizer and the analyzer. The polarizer is installed so that the incident light at its prism is polarized at 45° to the optical axes of the prism wedges. Depending on the purpose of the experiment and on the object under study, a polarization interferometer with the

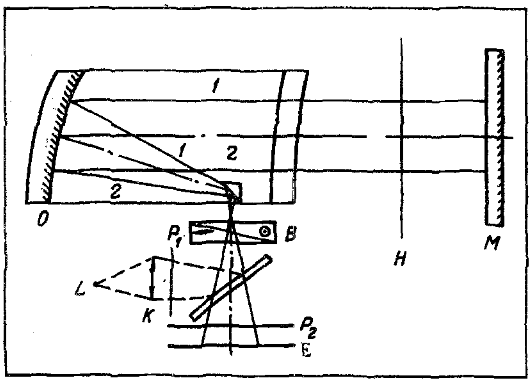

Fig. 2. Schematic diagram of a polarization interferometer with the IAB-451 instrument.

IAB-451 instrument can be set up so that the light beam will pass through the test piece twice and, in this way, the interferometer sensitivity will also be doubled. In this case one uses only the viewing tube of the IAB-451 instrument. The design of such an interferometer is shown in Fig. 2.

Light from source L passes through condenser K, polarizer P, and, after reflection at the semitranslucent plate D, forms an image of the source in the focal plane of the principal object O. In the Wollaston prism B the light beam splits into two (1 and 2). After reflection at the plane mirror M, the light beams return along the same path through prism B, the semitranslucent plate D, and analyzer P_2, and produce an interference pattern on screen E. The optical inhomogeneity under study is placed in the H plane.

The interferogram can be processed by various methods of measuring the optical thickness of the inhomogeneity. If the transverse dimensions of the latter are greater than the linear shift of the light beams, then the optical thickness of the inhomogeneity is measured indirectly: on the interferogram one determines directly either the additional path difference or the angular deviation ε_x.

In the case of complete double refraction, the interferogram is processed in a simple manner. If the test region is not wider than the birefringency, then the interferogram in the full birefringency range as well as the interferogram obtained with a Mach–Zender interferometer yields the distribution of path differences directly. An interferogram can be evaluated with the instrument set up for operation in the single-color mode or in the fringing mode. A quantitative evaluation with the instrument set up for finite-width fringes consists in measuring the displacements between interference fringes on the image of the inhomogeneity relative to its position in a free field with a known refractive index. The fringe width is used as the scale unit for measuring the displacement of fringes.

The sensitivity of a shift interferometer depends on the setup. Observations and photographs of inhomogeneities of known widths have shown that, with a setup for fringing and with the light beam crossing the inhomogeneity only once, one can detect changes in the optical thickness of the order of $0.01\,\lambda$. Under the same conditions (same optical system, same light source, etc.) the Tepler method is less sensitive than shift interferometry.

The just described polarization interferometer was used for studying the propagation of a flame along a closed tube [10].

A flame propagates along closed tubes under complex conditions, since it is accompanied by an increase in the pressure and in the temperature of the fresh mixture. Determining the time characteristics of these parameters is very important for calculations aimed at revealing the mechanism of oscillatory flame propagation.

The static pressure and the temperature were measured by slit scanning the interferograms. One of these interferograms is shown in Fig. 3. It was obtained for a tube 86 cm long and 20×20 mm^2 in cross section. The burning mixture was 48% CO + air.

In order to produce an interferogram, the reactor tube was positioned horizontally within the active range of the interferometer. The tube had a window covered on both sides with plane-parallel plates of optical glass. The window was further covered by an opaque screen with a narrow vertical slit. The interferometer was set up for horizontal fringing, and the system of interference fringes on the tube image was projected on a horizontally moving cymograph film. The time markers were produced by a neon tube supplied from a GZ-34 audiooscillator. The slit was approximately 1 mm wide. The ignition of a hot mixture and the turning on of the cymograph with the neon tube were synchronized so that the entire process of flame propagation was recorded on the interferogram.

In adjusting the interferometer properly for a clear interferogram, one must observe the following requirements:

1) The slit must have precisely cut straight edges.

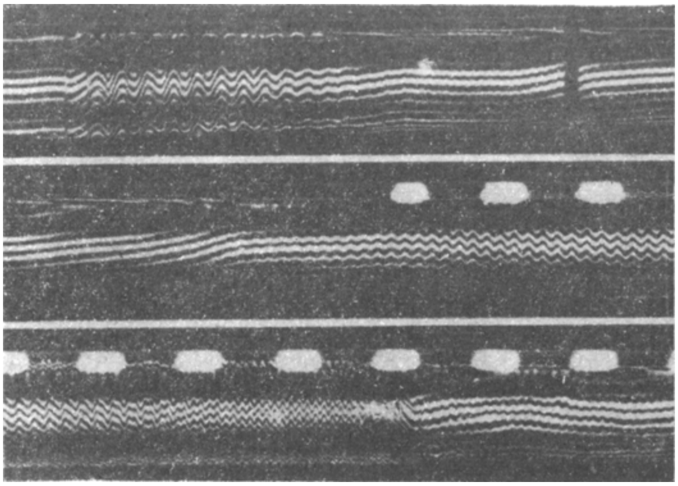

Fig. 3. Interferogram of flame propagation.

2) The light beams shifted in the Wollaston prism must lie in the same plane as the slit. (The slit should optimally be as narrow as possible. Diffraction effects make this difficult, especially as the slit is made narrower. For a good resolution of images of interference fringes, furthermore, the illumination of the field must be adequate.)

3) It is desirable that the apparatus be shielded from unavoidable vibrations in the laboratory. In our experiment the light source was an LG-75 optical quantum generator operating on the $\lambda = 6328$ Å wavelength. This, together with the twofold passage of the light beam through the test piece, improved the contrast of the interferograms.

A scan of the interferogram shows a change of state of the gas ahead of the flame front and shows recorded displacement of the interference fringes along the slit in distance–time coordinates. The flame propagated from the right to the left. The process can be tracked by scanning the interferogram.

The instant of sparking is represented on the interferogram (upper frame in Fig. 3) by a fine discontinuity in the interference fringes. A considerable jitter of the interference fringes is due to the generation of a weak compression wave by the spark. From the instant the mixture ignites, decaying acoustic vibrations are excited whose initial frequency is close to the fundamental tone of the tube. Later on one observes weak vibrations at a higher frequency. As the flame moves along the tube, the amplitude and the frequency of the acoustic vibrations change until harmonics appear. Thus, from the scanned interferograms one can quantitatively evaluate the changes in the frequency and the amplitude of the acoustic vibrations during an oscillatory propagation of a flame along a tube.

This is not all the information, however, which such a picture yields. An upward shift of the interference fringes corresponds to simultaneous increases in the density, the pressure, and the temperature of the initial mixture, which can be calculated from the interferogram. From an analysis of the process interferograms one can also conclude that the pressure and the temperature increase adiabatically. When there are no temperature gradients perpendicularly to the walls, then the interference fringes become parallel to the tube and their width remains constant. At a certain time after the mixture had ignited, at some distance from the wave front (center frame in Fig. 3) there appear large temperature gradients, which reflect a higher rate of heat transfer between the adiabatically heated gas and the tube walls. The heat-transfer rate increases during strong vibrations. Thus, the departure of the process from adiabaticity can be established by the appearance of temperature gradients at the walls. It is also noticeable that the width of the interference fringes is not the same at the upper and at the lower walls, which indicates that grad T is not the same. With active mixtures, which burn fast, large temperature gradients appear only at the end of the process. For this reason, the propagation of flames from such mixtures may be considered entirely adiabatic.

Considering the process adiabatic, from the scanned interferogram one can calculate the mean pressure and temperature of fresh mixture.

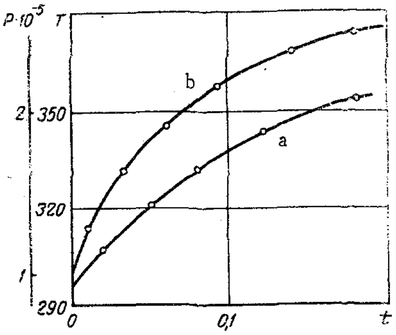

Fig. 4

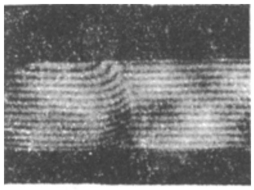

Fig. 5

Fig. 4. Graphs of: a) mixture pressure as a function of time; b) mixture temperature as a function of time. P, N / m^2; T, °K.

Fig. 5. Film frame taken on the polarization interferometer.

The optical difference between beams, one of which passes through the tube and the other passes through the surrounding medium, is

$$\delta = 2l(n - n_0) = k\lambda. \quad (2)$$

It follows from (2) that

$$n = n_0 + \frac{k\lambda}{2l}. \quad (3)$$

The following relations apply to an adiabatic process:

$$\frac{P}{P_0} = \left(\frac{\rho}{\rho_0}\right)^{\gamma} \text{ and } \frac{T}{T_0} = \left(\frac{\rho}{\rho_0}\right)^{\gamma - 1}. \quad (4)$$

From the Gladstock–Dahl law we have

$$\frac{n-1}{n_0 - 1} = \frac{\rho}{\rho_0}. \quad (5)$$

From Eqs. (3), (4), and (5) one can obtain expressions for determining the pressure and the temperature of the initial mixture:

$$P = P_0\left(1 + \frac{k\lambda}{2l(n_0 - 1)}\right)^{\gamma} \quad (6)$$

and

$$T = T_0\left(1 + \frac{k\lambda}{2l(n_0 - 1)}\right)^{\gamma - 1}. \quad (7)$$

Graphs representing both pressure and temperature changes of fresh mixture ahead of the flame front are shown in Fig. 4, based on the interferogram in Fig. 3. The measurement errors are $\Delta P = 5 \cdot 10^{-7}$ N/m^2 in the pressure and $\Delta T = 1°C$ in the temperature, at an accuracy of measuring the interference order of 0.03 the fringe width.

Analogously, after necessary transformations, we obtain a formula for determining the amplitude of acoustic vibrations generated during an oscillatory propagation of flames in tubes:

$$\Delta P_1 = P_0 \frac{\gamma k\lambda}{2l(n_0 - 1)}. \quad (8)$$

If the interference fringes at the flame front are resolved, then the temperature behind the flame front can be determined. The interferograms and the cinematograms show that this is entirely feasible with the appropriate interferometer setup and with a reduced initial mixture pressure in the tube.

In Fig. 5 we show film frames obtained on the interferometer for a 40% CO + air mixture at an initial pressure of $3.3 \cdot 10^4$ N/m^2.

NOTATION

f	is the focal length of the viewing tube objective;
λ	is the wavelength of the light;
d	is the dimension of the unperturbed field in the direction perpendicular to the filament;
P_0, T_0	are the initial pressure and temperature of the mixture in the tube;
k	is the interference order;
l	is the tube width;
$\gamma = c_p \; c_v$	is the ratio of constant-pressure to constant-volume specific heat;
n, ρ	are the refractive index and density of fresh mixture, both varying along the path of adiabatic compression;
n_0, ρ_0	are the refractive index and density of the mixture in the tube at P_0 and T_0.

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