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OPTIMAL METHOD FOR HEAT-FLOW REGISTRATION

M. P. Golubev, A. A. Pavlov,
Al. A. Pavlov, and A. N. Shiplyuk

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A new optical method for heat-flow registration is proposed. The sensor is a plane-parallel plate made of a transparent material. The form of the interference pattern resulting from superposition of waves reflected from the leading and trailing edges of the sensor varies in time depending on the distribution of heat flows. A relation for calculating heat flows by the shift of interference fringes is given. The measurements obtained by the optical method and by a certified thermocouple probe are compared. The results are in good agreement. The sensitivity and spatial resolution of the method are estimated.

Key words: *registration of heat flows, optical interferometry.*

1. Registration of heat flows is important in studying aerodynamic heating of the walls of flying vehicles and operation of gas turbines, compressors, aviation engines, heat exchangers, and other machinery [1]. Sometimes, heat-flow measurements offer additional information on the character of the flow near the walls of an aerodynamic model. In particular, the use of panoramic optical methods allows visualization of the boundary-layer transition from the laminar to the turbulent state, regions of flow separation and reattachment, streamwise vortex structures, and other features of the flow.

Most methods for heat-flow measurements are based on temperature registration in the surface region under study by thermocouples, thermistors, and other sensors. In solving various research and applied problems, such methods allow registration of heat flows with acceptable accuracy and within a comparatively small period of time. A significant drawback of these methods is the local character of measurements and the necessity of complicated preparation of the model. An alternative solution can be the use of optical methods of visualization and registration of surface temperature or directly heat flows, which include methods based on the use of temperature-sensitive coatings (temperature-sensitive dyes, melting indicators, and liquid-crystal coatings) and methods for temperature registration of the wetted surface by means of thermal imagers.

The merits of optical methods are the comparative simplicity of preparing the model surface and the possibility of registering the parameter of interest over a large area. At the same time, these methods have some drawbacks. For example, temperature-sensitive coatings on the basis of temperature-sensitive dyes and melting indicators drastically change their color when a certain value of temperature is reached and allow visualization of one or several isotherms. Liquid-crystal coatings, possessing high sensitivity, have a narrow dynamic range and, as a consequence, a narrow range of operating temperatures. Therefore, extension of the set of available metrological tools is an urgent problem and expands the possibilities of an aerophysical experiment.

The present paper describes a new optical method for registration of heat-flow fields [global interferometer heat flow (GIHF) meter] [2] and some results that validate the method workability and prospects.

2. The method is based on variation of the optical path length in the layer of a transparent substance, depending on temperature. The optical scheme is shown in Fig. 1a. A collimated beam of coherent light A_0 is incident onto a plane-parallel plate of thickness L, which is made of a transparent substance, for instance, glass. Part of light is reflected from the front face of the plate P_1, and the other part, being refracted and passing through the plate, is reflected from the back face P_2. Thus, the reflected light has two plane waves A_1 and A_2 interfering with each other. Under the action of the heat flow Q through the surface, the temperature in the glass volume

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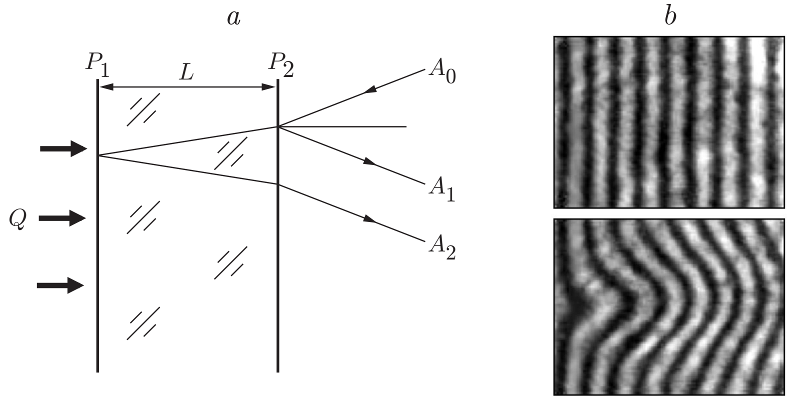


Fig. 1. Optical scheme of the method (a) and fragments of typical interferograms obtained during registration of heat-flow fields (b).

changes, which leads to thermal expansion and to a change in the refractive index. This, in turn, leads to a change in the optical path length of the light wave inside the plate and, thus, to a change in the interference pattern. On the basis of the shift of interference fringes on interferograms registered with a known period of time, one can determine the heat-flow value in the corresponding region of the surface. In deriving the relation that expresses the shift of interference fringes as a function of the heat flow, we used the following assumptions.

1. The temperature-induced changes in the refractive index do not alter the direction of propagation of the light wave inside the glass. This is a standard assumption used in optical interferometry. The angle of deviation $\delta\varepsilon$ of the beam passing in an inhomogeneous medium is determined by the gradient of the optical path length [3]. In our case, this quantity and, hence, $\delta\varepsilon$ did not exceed $5 \cdot 10^{-3}$, which allowed us to apply this condition.

2. A layout with an orthogonal direction of the probing beam with respect to the sensor surface is used. Obviously, the relations obtained below can be readily extended, if necessary, to the case of oblique incidence of the probing beam.

3. In determining the change in the optical path length as a function of temperature, we took into account only the temperature coefficient of the change in the refractive index $\beta = \partial n/\partial T$ and the temperature coefficient of linear expansion $\alpha = \partial L/L\partial T$. The influence of elasticity and piezooptical effects on the change in the optical path length was ignored.

4. Heat propagation along the sensor surface was ignored, i.e., a one-dimensional problem was solved.

With allowance for the above assumptions, the path-length difference of the interfering waves at the time t can be represented as

$$\Delta S_t = 2 \int\limits_L n(l, T_t)\, dl. \tag{1}$$

The path-length difference and the refractive index in Eq. (1) can be different for different points on the surface. Since a one-dimensional problem is solved, we further use simplified records of equations without clear indications on the functional dependences of the parameters used on surface coordinates.

In the presence of a heat flow, the temperature distribution inside the plate varies with time. The change in the differential of the optical-path difference $d\Delta S = 2n(l, T)\, dl$ during the time δt can be written as

$$\delta d\Delta S(l) = d\Delta S_{t1} - d\Delta S_{t0} = \frac{\partial d\Delta S}{\partial T}\, \delta T(l) = 2\delta T(l)(\beta + n\alpha)\, dl. \tag{2}$$

Relation (2) is written under the assumption that α and β are constant within the range of the maximum variation in temperature along the optical path. The factor $\beta + n\alpha$ can also be considered as a constant with second-order accuracy. As a result, we have the following relation for the change in the optical-path difference:

$$\delta\Delta S = 2(\beta + n\alpha) \int\limits_L \delta T(l)\, dl. \tag{3}$$

TABLE 1

Substance	n	$\beta \cdot 10^6$, K^{-1}	$\alpha \cdot 10^7$, K^{-1}	ρ, g/cm^3	C_p, $J/(g \cdot K)$	k, J/cm^2	$æ \cdot 10^3$, $W/(K \cdot cm)$
LK5	1.476	6.2	33.9	2.270	0.674	4.440	10
TF2	1.667	5.7	79.4	4.090	0.490	3.438	7.83
KRS5	2.564	251	600	7.370	0.126	0.074	4.605
Plexiglas	1.492	—	350	1.18	1.48	0.442	—
“Balzers”	—	—	—	—	—	5.155	—

Taking into account that the integral in the right side, with accuracy to the factor $\rho\sigma C_p$ (ρ is the density and C_p is the heat capacity at constant pressure), determines the amount of heat that passed through an elementary area σ, one can easily transform Eq. (3) to

$$Q(x,y) = k\,\frac{dN(x,y)}{dt}, \tag{4}$$

where Q is the heat flow, N is the number of the interference fringe, $k = \lambda\rho C_p/(2(\beta+n\alpha))$ is a coefficient depending on the properties of the substance used to make the sensor, and λ is the wavelength of probing light. Numerically, the coefficient k equals the amount of thermal energy passing through a unit area of the operating surface of the sensor, which is necessary to shift the interference pattern by one order.

Optical characteristics of some glasses and the KRS5 crystal for a wavelength $\lambda = 656.3$ nm [4, 5] and the coefficients k for $\lambda = 650$ nm calculated on the basis of these characteristics are listed in Table 1. Table 1 also contains the thermal conductivities æ. For Plexiglas and glass of the “Balzers” company, the coefficient k was obtained from experimental data. Of special interest are crystalline materials based on thallium halogenides, which possess a significantly higher sensitivity as compared to glasses. Thus, the expected sensitivity for KRS5 (solid solution of TlBr 42% + TlI 58%) is 60 times higher than that for LK5 glass. In addition, the thermal conductivity of such materials is lower than that of glasses, which is important for increasing spatial resolution of the optical sensor and decreasing its minimum possible thickness.

3. The most important characteristics of any method are its potential sensitivity and accuracy. In the technique considered, the directly measured quantities are the shift of interference fringes ΔN and the time period Δt. In our case, the error in determining Δt was lower than 10^{-6} sec, which had almost no effect on measurement accuracy. The random error of measuring ΔN is more significant. The accuracy of measurement of this quantity determines the sensitivity of the method and usually amounts to $\delta\Delta N \approx 0.05$. The absolute error in determining heat flows is

$$\delta Q(x,y) = k\,\frac{\delta\Delta N(x,y)}{\Delta t} = \frac{k}{20\Delta t}.$$

In a real experiment, the error in determining ΔN can be significantly greater if the step of interference fringes is comparable to the spatial resolution of the TV camera. In interferogram processing, the position of the maximum or minimum of the interference fringe is usually assigned to the coordinate of the center of a certain pixel in the image obtained. If the step of fringes is m pixels, then we have $\delta\Delta N \geqslant 1/m$.

More complicated things for analysis are the measurement errors related to processes ignored in deriving Eq. (4), namely, heat spreading along the sensor surface and effects of photoelasticity. The heat flows along the sensor surface can introduce significant errors in measurement results for $Q(x,y) \neq \text{const}$. Simultaneously, the error in registering the integral heat flow over the area can be small. The effect is mainly manifested in the errors in determining local values and worsens the spatial resolution. The measurement results depend not only on test conditions but also on spatial frequencies of heat-flow fields. We did not evaluate possible errors caused by heat spreading theoretically, but some experimental estimations of this effect are given below.

If heating is nonuniform over the sensor volume, elastic stresses arise, which can induce strains that are not taken into account by Eq. (4) and, hence, additional changes in the path-length difference of interfering waves. Mechanical stresses can also involve changes in the refractive index owing to the photoelasticity effect. The changes in components of the dielectric permeability tensor determining refractive indices are linearly related to the components of the stress and strain tensors via the tensors of elastooptical stresses and strains, respectively [3]. These effects are not considered in the present work. Nevertheless, in registering powerful heat flows distributed nonuniformly over the sensor area and leading to emergence of high temperature gradients and, as a consequence, strong elastic stresses

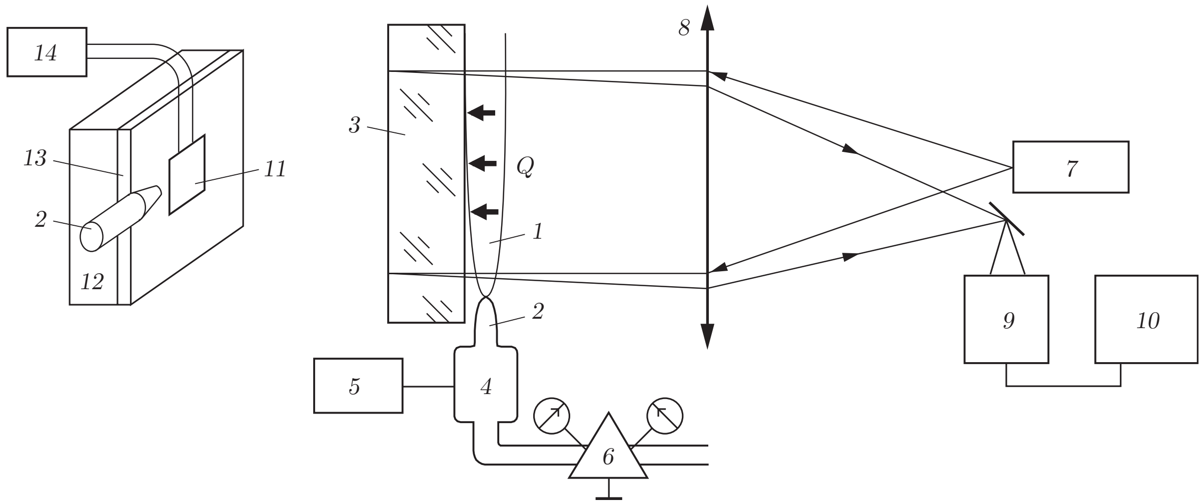


Fig. 2. Scheme of heat-flow registration: 1) jet; 2) nozzle; 3) sensor; 4) heater; 5) source of current; 6) reductor; 7) semiconductor laser; 8) lens; 9) TV camera; 10) computer; 11) thermocouple sensor; 12) thermostat; 13) protective coating; 14) digital voltmeter.

in the sensor volume, the influence of photoelasticity effects can be significant, and this issue requires additional theoretical and experimental studies.

In deriving Eq. (4), we assumed that the entire heat that entered the sensor remains inside the sensor volume. In a real experiment, the sensor is usually attached to the surface of the examined model, and this assumption can become invalid because of the heat flow through the back surface of the sensor. Using the solution of the heat-conduction equation for a semi-infinite body [6], we can show that, if a heat flow Q_1 is switched on at the time $t = 0$ and remains constant afterwards, passing through the operating surface of the sensor, the heat flow through the back surface of the sensor is

$$Q_2(t) = Q_1\Big[1 - \operatorname{erf}\Big(\sqrt{L^2/(4\eta t)}\Big)\Big]. \tag{5}$$

Here $\operatorname{erf}(\,\cdot\,)$ is the error integral, L is the sensor thickness, and η is the thermal diffusivity. The thermal diffusivity is assumed to be identical for the sensor and model materials. We have $Q_2 \to 0$ as $t \to 0$, $L \to \infty$, and low values of η. Vice versa, for thin layers and large registration times, Q_2 tends to the limiting value Q_1. The measurement errors can be represented as the ratio of the integral of the heat flow Q_2 with respect to time and the integral of the registered heat flow Q_1. With increasing thermal diffusivity of the substrate, the heat flow Q_2 is more intense, and vice versa. Relation (5) allows one to estimate the maximum possible time of registration and the minimum thickness of the sensor for ensuring specified accuracy.

Based on the above said, we can draw the following conclusions. To improve the sensitivity of the method, it is necessary to use TV cameras with low noise, maximum possible dynamic range, and high spatial resolution. Obtaining high-quality interferograms allows much more accurate determination of the shift of interference fringes. A decrease in the time interval of heat-flow registration worsens the sensitivity of the method. In this case, however, spatial resolution and measurement accuracy are improved, as in the case of increasing thickness of the operating layer of the sensor L. The reason is the attenuation of heat flows along the sensor surface and through its back surface contacting the model.

4. To verify the workability of the method, we measured the heat flow from a heated jet propagating along a flat surface (Fig. 2). The jet of a heated gas escaping from the nozzle propagates along the surface of the sensor, which is a flat plate 80 × 80 mm and 10 mm thick, made of LK5 glass. The degree of heating of the jet was determined by the heater power W. The flow rate of air was controlled by a reductor. The radiation of a semiconductor laser ($\lambda = 0.65$ μm) was formed into a plane-parallel beam by a lens with a focal distance of 500 mm. Interferograms in reflected light were registered by a TV camera and saved on a computer. To verify the reliability of results obtained by the optical method, we measured heat flows under the same parameters and jet position with respect to the operating plane by a certified thermocouple sensor (TS) with an operating area of 10 × 10 mm and sensitivity of 288 J/(mV · m^2). The TS was attached to a massive flat plate made of the D16T aluminum alloy,

TABLE 2

W, W	Q_{t}, mW/cm^2	Q_{opt}, mW/cm^2	$Q_{\mathrm{opt}}/Q_{\mathrm{t}}$
44.0	1238.4	1297.7	1.048
24.9	662.4	682.7	1.031

which also served as a thermostat. To insulate the thermostat from the heat flow induced by the jet escaping from the nozzle and to ensure a flat operating surface, a protective coating made of Plexiglas was applied. The sensor readings were registered by a digital voltmeter. The possibility of rapid introduction into the flow was provided both for the optical and for the thermocouple sensors.

The heat flows were registered successively by the thermocouple, optical, and again thermocouple sensors without changing the jet parameters. Since the TS registers the heat flow averaged over the area, the results of optical measurements were also averaged over the corresponding area. Figure 1b shows the typical interferograms obtained in test experiments. The results of heat-flow measurements by the thermocouple (Q_{t}) and optical (Q_{opt}) sensors, averaged over two series of experiments, for different powers of jet heating W are listed in Table 2. The agreement in measurement results within 5% confirms that it is possible to use Eq. (4) to process experimental data.

The calculations with the use of the tabulated data of [2, 4] show that the coefficients k for ordinary glasses differ by no more than two times. This significantly restricts the possibility of using the method for registration of low heat flows. The use of more sensitive materials, such as KRS5, is limited by their high cost and complexity of optical processing. It is known, however, that many plastics, including polymethyl methacrylate (Plexiglas), have a higher coefficient of thermal expansion and a stronger dependence of the refractive index on temperature as compared to usual optical glasses. This allows us to expect that these materials also have a higher sensitivity in heat-flow registration. The difficulty is that, for such substances, it is rather difficult to find all parameters necessary to calculate the coefficient k. Therefore, its value for Plexiglas was determined experimentally. For this purpose, measurements by a sensor made of Plexiglas were performed simultaneously with test measurements of heat flows by the TS and the optical sensor on the basis of LK5. The measurements performed show that the sensitivity of Plexiglas is ten times the sensitivity of LK5 (see Table 1).

5. One of the basic advantages of the method discussed is the possibility of obtaining information on the distribution of heat flows over a large area of the examined surface. Figure 3 shows the interferograms recorded in studying the jet flow around a cylinder 5 mm in diameter and 15 mm high, which was mounted vertically on a flat surface. It follows from Fig. 3 that Plexiglas has a much higher sensitivity than LK5 glass. For a less heated jet and during a smaller time, the shift of fringes ΔN for Plexiglas is significantly greater than for LK5. In addition, Plexiglas has a higher spatial resolution. The shift of interference fringes in regions with heat-flow gradients for Plexiglas is more pronounced. This is explained by the lower thermal diffusivity coefficient for Plexiglas as compared to LK5.

In our case, all interferograms were registered in finite fringes. The reason was the wedge angle between the sensor surfaces. Because the heat flow in Eq. (4) is independent of the sensor thickness, this does not alter the measurement results. Small variations around the base thickness ($\delta L/L \ll 1$) do not affect the accuracy of heat-flow determination either, if the errors caused by heat losses through the back surface of the sensor are taken into account. Indeed, to obtain 20 fringes over the interferogram field, one has to ensure the change in the path-length difference of the interfering beams equal to 20λ. For the refractive index of glass $n \approx 1.5$, the change in the sensor thickness δL is approximately 4 μm.

The main advantage of interferometry in finite fringes is rather simple processing of the results obtained. In our case, another advantage, which is not less important, is the possibility of using substance layers with surfaces that are not absolutely flat as sensors. The curvature of reflecting surfaces leads to the curvature of basic interference fringes. The measured parameter, however, is not the shape but the change in the order of the interference fringe passing through the given point, and the curvature of fringes does not affect the result (it is assumed that the curvature of surfaces is rather small to ensure registration of interferograms). This allows one to reduce the requirements to surface processing and, sometimes, eliminate the latter altogether. In particular, the interferograms shown in Fig. 3b were obtained by a sensor made of technical Plexiglas sheets 10 mm thick without additional processing of the surfaces.

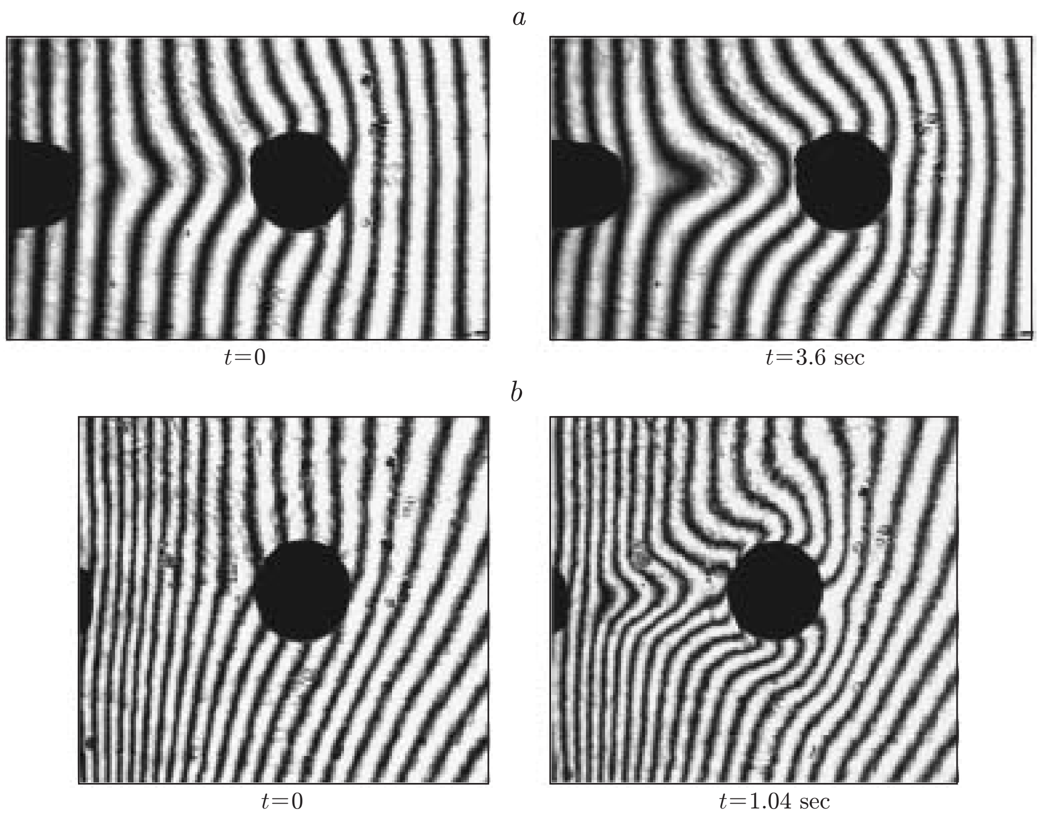


Fig. 3. Interferograms obtained in the flow around a cylinder ($D = 5$ mm and $H = 15$ mm) by a heated jet with the use of sensor on the basis of LK5 glass for $W = 44$ W (a) and Plexiglas sensor for $W = 24.9$ W (b).

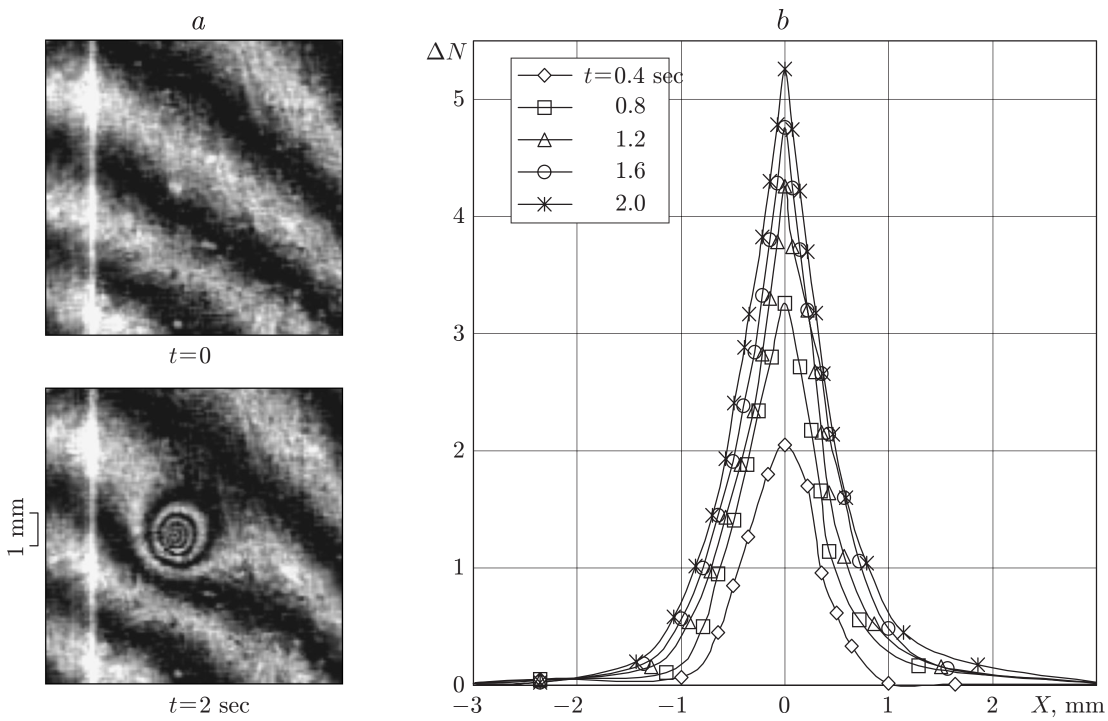


Fig. 4. Interferograms (a) and plots of the shift of interference fringes ΔN (b) illustrating spreading of the heat mark.

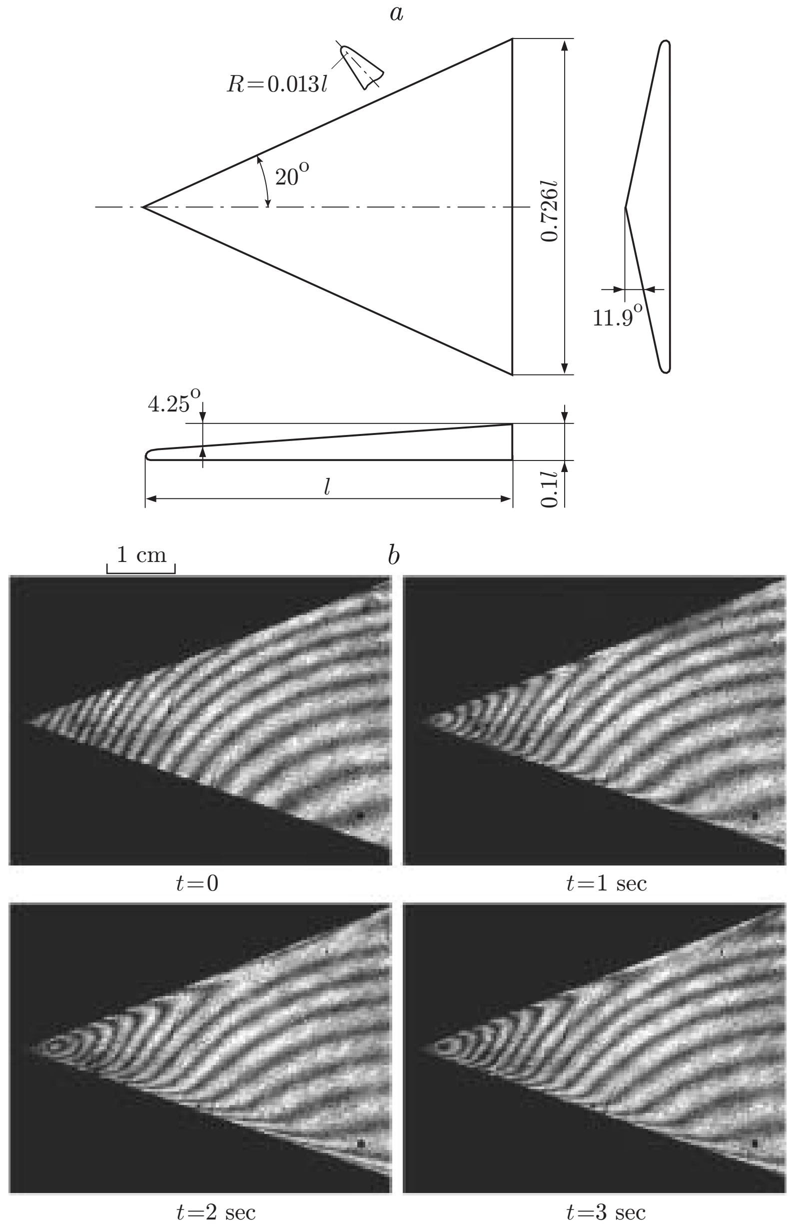
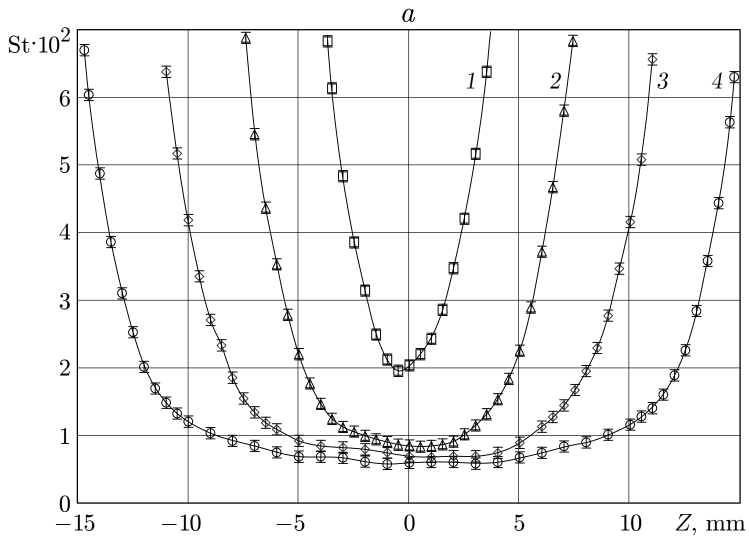


Fig. 5. Schematic of a delta wing (a) and typical interferograms obtained by registration of heat flows on the windward side of the wing (b).

6. To evaluate spatial resolution of the method, we considered spreading of a heat mark from a point source, which was the radiation of a semiconductor laser with a power of 25 mW focused onto the surface of the optical sensor. Better absorption of radiation was provided by applying a thin (approximately 0.2 μm thick) layer of black varnish onto the surface. Similar heat marks were used to estimate the depth of penetration of heat from a point source, which was necessary to choose the acceptable sensor thickness and measurement time.

Figure 4 shows the interferograms and plots of the shift of interference fringes for different times after the laser was switched on, which were obtained by a Plexiglas sensor for a single heat mark. During 0.8 sec, the energy of the heat source is mainly localized in a spot less than 1 mm in diameter. This indicates that spatial resolution for registration times smaller than 1 sec is approximately 1 mm. This is confirmed by the results obtained for two heat sources located at a distance of 1 mm from each other [2]. The experimental estimate of spatial resolution allows us to evaluate admissible intervals of measurement times and can be used in planning the experiment.



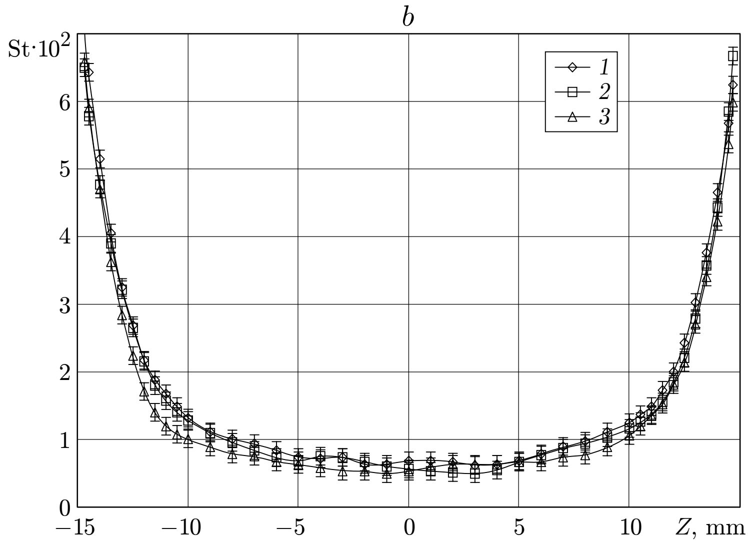


Fig. 6. Distribution of heat flows over the wing span: (a) $X = 10$ (1), 20 (2), 30 (3), and 40 mm (4); (b) experiment No. 1 (1), experiment No. 2 (2), and experiment No. 3 (3).

As was noted above, the measurements results can be significantly affected by the heat flow through the back surface of the sensor. Hence, information on the rate of heat penetration inside the sensor is important for choosing its thickness and measurement time. The experiments on registration of the heat-penetration depth versus time showed that the depth of noticeable propagation of the heat mark in Plexiglas does not exceed 1 mm during the time $\Delta t \approx 2$ sec [2].

7. The method was used to study the flow around the model in the T-327 hypersonic nitrogen wind tunnel of the Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences. The measurements were performed for a Mach number $\mathrm{M}_\infty = 21$, stagnation temperature $T_0 = 1700$ K, and stagnation pressure $P_0 = 84$ MPa. The wind tunnel is equipped by a graphite heater for the gas upstream of the plenum chamber, shock-starting device, and system for gas exhaustion into a vacuum tank. The shock-starting device provides a time of flow stabilization in the test section equal to $0.5 \cdot 10^{-3}$ sec. The maximum operation time of the wind tunnel is 240 sec.

The model was a 10-% delta wing (Fig. 5) with a sweep angle $\chi = 70°$ and blunted leading edges, which was made of AG-4V fiber-glass plastic [$æ = 0.453$ J/(m · sec · K) and $\eta = 0.231 \cdot 10^{-6}$ m²/sec]. The model length was 100 mm. An optical sensor 1.5 mm thick, made of glass produced by the "Balzers" company, was glued onto the flat upper surface of the model. The coefficient k for this glass was determined experimentally by the same technique as that used for Plexiglas.

The measurements were performed for angles of attack $\alpha = 0$, 5, and 10°. Figure 5 shows the typical interferograms obtained in the experiments with $\alpha = 5°$. The measurement time was 3 sec. Figure 6a shows the distributions of the Stanton number St over the wing span for cross sections located 10, 20, 30, and 40 mm from the model tip; the results are averaged over three experiments. Figure 6b shows the data for the cross section of 40 mm, which were obtained in different experiments. The graphs also contain the confidence interval calculated by the error in determining the shift of interference fringes, with allowance for the registration time and averaging. Results of different experiments are in good agreement. The scatter of heat-flow values obtained in different experiments is mainly within the confidence interval. The results obtained indicate the prospects of using the optical method for heat-flow registration in hypersonic flow regimes. To increase the measurement accuracy, however, it is necessary to use sensors made of more sensitive materials.

8. The method proposed, in the authors' opinion, significantly extends the possibilities of an experiment with registering heat-flow fields. The results of testing and using the technique in the T-327 hypersonic wind tunnel confirm its workability and prospects. Nevertheless, further development of the method requires additional theoretical and experimental studies. It is important to take into account the effects of heat spreading over the sensor surface and heat penetration into the sensor, as well as the effects caused by elasticity and photoelasticity of the materials used. It is necessary to perform more detailed studies to choose substances promising for this kind of measurements.

The method proposed can be used not only to obtain quantitative information but also to visualize heat-flow fields. Interesting results could be obtained by sensors that allow operation in fringes of infinite width. It is possible to significantly increase the sensitivity of the method as compared to its implementation in finite-width fringes. An important research direction on improving this technique is the extension of possibilities of using it on curvilinear, arbitrarily oriented surfaces. Obviously, it is possible to produce not only panoramic but also local sensors on the basis of the technology proposed.

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