MULTIDIRECTIONAL SPECKLE PHOTOGRAPHY OF DENSITY FIELDS IN GASDYNAMIC FLOWS

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Double-exposure speckle photography is employed experimentally to determine the fields of local density (temperature) values in a freely burning flame, as well as in the region of natural convection near a heated cylinder.

Introduction

Researchers have traditionally been attracted to optical methods of diagnostics to determine temperature fields in problems of heat and mass exchange because of the high level of information which these provide, as well as the fact that no physical contact is required, and the information is available without delay [1]. However, at the present time specialists lack a universal method of measuring a broad range of heat and mass exchange problems that are devoid of shortcomings and suitable for analysis, including turbulent flows. Thus, the methods based on the recording of scattered radiation (Raman, CARS) or laser-induced fluorescence (LIF), provide for information from a single measurement only at a single point in the flow, while mechanical systems must be used for spatial scanning in order to determine the distributions of the sought parameters.

It is possible to obtain instantaneous density distributions by interferometry methods (including holography), while the density gradient fields are usually obtained with Tepler circuits or by means of displacement interferometry [2, 3]. However, the former, as a rule, provide only qualitative information, while the latter are suitable only for laminar or slightly agitated flows, and require expensive high-quality optics that are sensitive to vibrations.

The majority of the optical methods provide information about the process being studied that is integral over the optical path. Determination of local parameters for axisymmetric processes in this case can be accomplished by utilization of the Abel transform on the basis of the measurement results obtained for a single direction, whereas the data are inadequate for arbitrary flows and simultaneous measurements are needed along several directions, and on the basis of the results from these measurements we can reproduce the local parameters by methods of computer-augmented tomography [4]. Particularly urgent in this case is the simplicity in the single-measurement circuit, the number of optical elements within the circuit, simplicity of justification, and the possibility of automating the processing of experimental data under conditions wherein massive amounts of information are generated.

Tomographic measurement circuits are presently being developed actively in conjunction with interferential methods, as well as methods based on the recording of resonance absorption or radiation in the infrared region of the spectrum (see, for example, [5]). At the same time, for such measurements we can utilize the simpler technology that is based on speckle photography [6]. It is significant that, as has been demonstrated in [7-9], unlike any type of interferometry, this technique makes it possible to obtain the required information even in the case of turbulent flows. This paper will illustrate the possibility of a new experimental technique — speckle photography — to determine the fields of local density (temperature) values within a flame and in the region of natural convection around a heated rod.

Double-Exposure Speckle-Photography Techniques

When coherent radiation is diffused through an object or when the radiation is reflected from a diffusing reflector as a consequence of three-dimensional interference, the scat-

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tered radiation takes on a grainy character. The dimension of the elementary radiation grain, the speckle, is independent of the properties of the diffuse scattering mechanism and is determined by the laws of diffraction [10]

$$\sigma = 1.22\lambda \frac{L}{D}. \qquad (1)$$

The characteristic dimensions of the speckle, when utilizing a laser where the radiation is within the visible region, are on the order of 10-100 μm.

The use of speckle techniques is based on the recording on a photographic plate of two identical speckle fields shifted relative to each other through a distance equal to several speckle diameters. When the developed photographic plate, i.e., the specklegram, is illuminated with the beam of a noncollimated restored laser on a screen positioned behind the specklegram, straight equidistant interference bands appear, and these are the same as in a Young interferometer with two slits which are positioned relative to each other at a distance equal to the magnitude of the speckle-field displacement. However, in this case the bands exhibit lower contrast than in the classical Young interferometer, but are described by the same relationships (see [10]):

$$I(\eta) = I_0 \cos^2\left(\frac{\pi\Delta n}{L_1\lambda_1}\right). \qquad (2)$$

Therefore, the magnitudes of speckle displacements at each point relative to the horizontal and vertical axes in the specklegram plane can be reproduced in single-valued fashion on the basis of the distance δ between the bands and from the angle of band inclination, for example, relative to the horizontal β axis:

$$\Delta = \sqrt{\Delta x^2 + \Delta y^2} = L_1\lambda_1/\delta, \qquad (3)$$

$$\Delta x = \Delta \sin\beta; \qquad (3a)$$

$$\Delta y = \Delta \cos\beta. \qquad (3b)$$

Utilization of such a technique offers great promise for the diagnosis of flows, including turbulent flows, streams of gases and liquids, of plasmas, as well as for the determination of the density-gradient fields, temperature fields, and velocity fields within these streams. Since the rays undergo distortion at the discontinuities of the gasdynamic flow being investigated, for purposes of determining the density-gradient field of the flow it is sufficient to produce two exposures of the speckle field on the photographic plate: one, without distortion of the speckle field by the nonuniformity of the phase object, and the other, the speckle field distorted by the flow being investigated. Two speckle fields displaced relative to each other will be recorded on the photographic plate, and the magnitude of the speckle displacement at each point on the specklegram will be determined by the magnitude of the density gradient or, strictly speaking, by the gradient of the refractive index of the object being investigated, along the corresponding trajectory of the beams forming the speckle:

$$\Delta x = L_2 \int_{z_1}^{z_2} \frac{1}{n} \frac{\partial n}{\partial x} dz \simeq L_2 K_{\lambda_2} \int_{z_1}^{z_2} \frac{\partial \rho}{\partial x} dz, \qquad (4)$$

$$\Delta y = L_2 \int_{z_1}^{z_2} \frac{1}{n} \frac{\partial n}{\partial y} dz \simeq L_2 K_{\lambda_2} \int_{z_1}^{z_2} \frac{\partial \rho}{\partial y} dz. \qquad (4a)$$

The sought density-gradient field in this process, with consideration of expressions (3) and (4), is determined by the distance between the Young interference bands on recovery of the double-exposed specklegram and the angle at which the bands are inclined to one of the coordinate axes:

$$\int_{z_1}^{z_2} \frac{\partial \rho}{\partial x} dz = \frac{\lambda_1 L_1 \sin\beta}{\delta L_2 K_{\lambda_2}}, \quad \int_{z_1}^{z_2} \frac{\partial \rho}{\partial y} dz = \frac{\lambda_1 L_1 \cos\beta}{\delta L_2 K_{\lambda_2}}. \qquad (5)$$

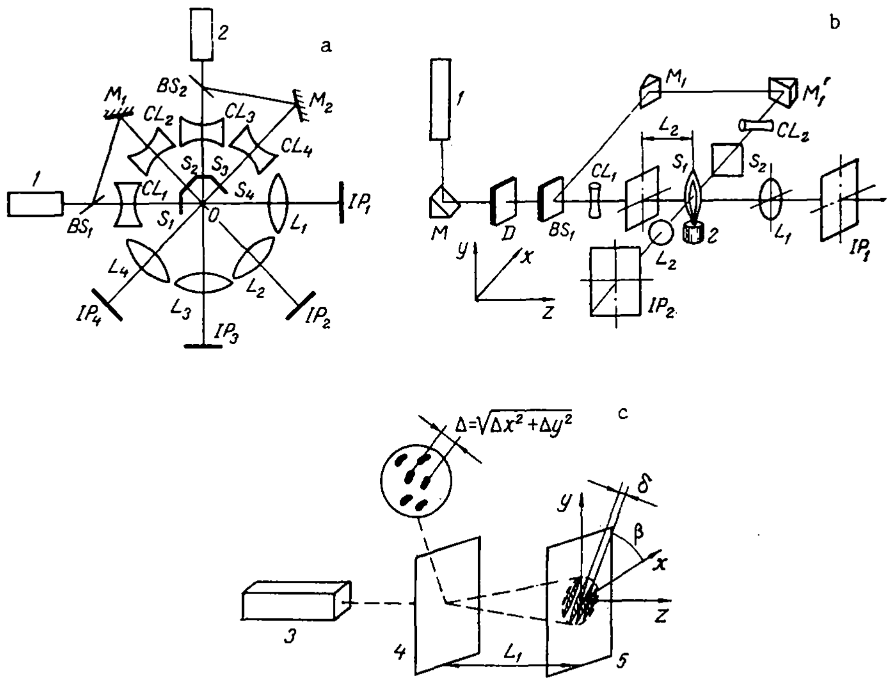

Fig. 1. Diagram of experimental installation. a) Multidirectional speckle-photography installation: 1, 2) pulsed laser; M_1, M_2) mirrors; BS_1, BS_2) separator plates; CL_1, ..., CL_4) the collimators; L_1, ..., L_4) the lenses which form the speckle field on the photographic plates in the image plane IP_1, ..., IP_4; S_1, ..., S_4) the speckle-field generators (mat plate); O) the object being studied. b) The bidirectional components of the installation: M) rotating mirror (prism); D) filter diaphragm; the remaining notation is the same as in Fig. 1a. c: 3) Continuous laser; 4) developed speckle photograph; 5) screen for observation of Young bands.

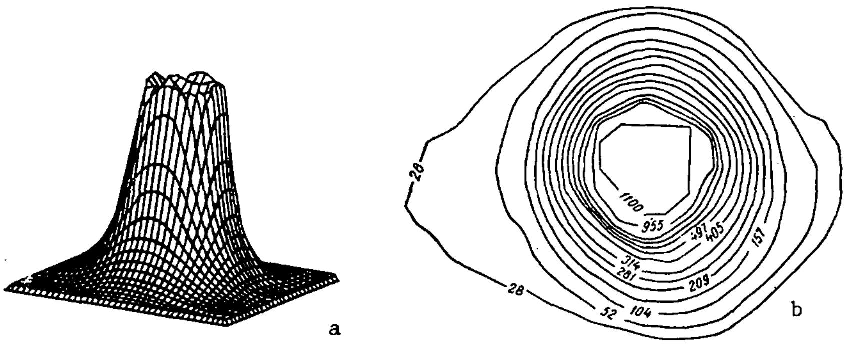

Fig. 2. Experimental data on the temperature fields in the flame: a) temperature distribution in one of the horizontal cross sections of the axisymmetric flame, with the maximum value of the temperature 1250 K, the temperature outside of the flame 300 K, and a coordinate spacing of 0.5 mm; b) isolines $T - T_\infty$ in one of the horizontal cross sections of an arbitrary flame, these lines plotted with the use of the Radon transform on the basis of data from four-angle speckle photography, with the central region of the flame corresponding to $T - T_\infty \geq 1100$ K.

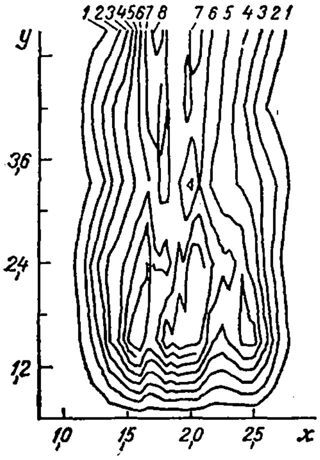

Fig. 3. Temperature isolines in one of the vertical cross sections of the axisymmetric flame shown in Fig. 2a: curves 1-8 correspond to temperatures of 400-1250 K. y, x, cm.

In order to calculate the distribution of the local values of the refractive index for the region under consideration in the case of axisymmetric flows for which the relationship n = n(r) is valid, we make use of the Abel transform:

$$\frac{n(r)-n_\infty}{n_\infty}=\frac{1}{\pi}\int_r^\infty \frac{\partial y}{\partial z}\,\frac{dy}{\sqrt{y^2-z^2}}. \tag{6}$$

With consideration of the Gladstone—Dale formula ($n - 1 = K\rho$), this relationship allows us to determine the density field, and with the pressure known it also allows us to determine the field of local temperature values. It is significant that the quantity $[\varepsilon_y(y) = \partial y/\partial z]$ in the Abel integrals in the speckle-photography method is determined directly as part of the experiment $[\varepsilon_y(y) = \lambda_1 L_1 \cos\beta/\delta]$, and not as a result of the differentiation of the preliminary data, as is the case in interferometry; in this case, the relationship between this quantity and the coordinate y can be determined at intervals considerably smaller than in interferometry, i.e., less than 10 μm. At the same time, we see from relationships (5) that unlike classical optical methods the speckle technique enables us to obtain quantitative information with regard to the magnitude of the density gradient along each of the beam trajectories, at each point on the x, y plane, independent of each other, since for the determination of the quantities δ and β at each point on the specklegram we need not know the values of these quantities at the adjacent points. This important unique feature of the speckle technique allows us to utilize it for purposes of investigating complex turbulent flows, as well as for purposes of analyzing conventional interference patterns which do not lend themselves to easy resolution because of the need to decipher them simultaneously over the entire field of the flow.

In reproducing the local values of the parameters in nonaxisymmetric objects, we probed the subject nonuniformity by means of a speckle field from various directions. Here we made use of the Radon transform:

$$\frac{n(x,\ y)-n_\infty}{n_\infty}=-\frac{1}{2\pi^2}\int_0^\pi J_0(P_0,\ \alpha)\,d\alpha,$$

where

$$J_0(P_0,\ \alpha)=-\int_{-\infty}^{\infty}\frac{\varphi(P,\ \alpha)\,dP}{P-P_0}. \tag{7}$$

The numerical application of this transform to problems of speckle tomography was carried out by M. N. Rolin on the basis of the TOPAS program group [4].

EXPERIMENTAL

Experiments on the application of the speckle technique to investigate dynamic flows were begun during the author's scientific research in the FRG, at Ruhr University, in 1983, in the laboratory of Prof. W. Merzkirch. During these experiments, the double-exposure speckle-photography method was used to determine the density-gradient fields in a turbulent jet of helium escaping into air [7-9]. Subsequently, work along these lines was continued both at the Merzkirch laboratory [11, 12], as well as at the Likov Institute of Heat and Mass Exchange of the Academy of Sciences of the Belorussian SSR [13-15].

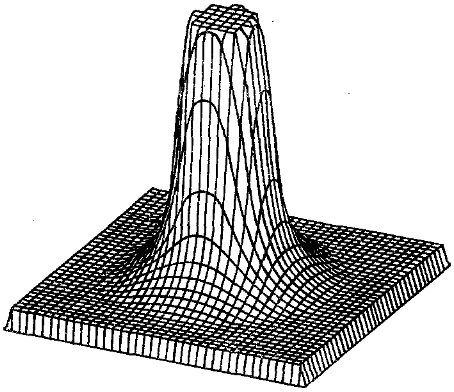

Fig. 4. Temperature distribution in the region of natural convection near the heated vertical cylinder; T_{max} = 450 K, T_∞ = 300 K, coordinate spacing, 2 mm.

The experimental results demonstrated the feasibility of the method and the possibility of its application to investigate a broad range of gasdynamic flows, including turbulent flows.

We will subsequently describe the results obtained at the Likov Institute of Heat and Mass Exchange, Academy of Sciences of the Belorussian SSR, on the temperature fields determined by this technique within flames and in natural-convection flows.

Figure 1 shows a diagram of the experimental installation used to study an object as it is illuminated from four directions simultaneously. This installation is based on the standard UIG-type holographic design. The laser beam is directed by means of a mirror or a prism through a diaphragm and collimator onto a scattering plate. The scattered emission passes through the object under investigation, forming a speckle pattern beyond the objective in the registration plane, this pattern carrying information with regard to the fields of the various quantities within the flame. To produce the speckle photography, we use a pulsed ruby laser with a wavelength of λ = 0.69 μm, a pulse energy of E ~ 0.5 J, and a pulse duration of τ ~ 0.5 msec. The specklegrams were reproduced by means of a continuous single-mode low-power laser.

The object being studied was positioned at a distance of ~50 mm from the scattering plate. VRL, FPGV, and Mikrat photographic plates and films with resolution of 300-1000 lines/mm were used to carry out the photography. We selected a speckle size on the order of 3 μm. The initial exposure of the speckle field included the object, while the object was removed during the second exposure. The Young interference bands which arise in the scanning of the double-exposed specklegram were projected onto a mat screen situated at a distance L_1 = 500 mm from the specklegram. Here the halo diameter on the screen was 140 mm. The specklegrams were scanned at intervals of 0.1-2 mm, depending on the type of flow being investigated.

The measurement circuitry requires no calibration, since the sought magnitudes of the density gradients are determined directly from the measured parameters δ and β. The circuit can be tested and the geometric parameters selected through a mechanical micrometric test displacement of the diffusion panel or the registering photoplate in any direction between the exposures. Displacement between exposures can be determined from the parameters δ and β with a high degree of accuracy, i.e., 3-5%, within a range of 2-1000 μm. Utilization of automated systems for the counting of Young interference bands, these systems based on television technology involving transmitter cameras with charge coupling (PZS matrix) and the processing of the derived bundles of data by means of computers allows us significantly to improve the process and the accuracy of determining δ and β, and concurrently the sought final parameters. In this operation we used a PTU-50 industrial television installation with KT-2 television cameras in which a TsM1200-type PZS matrix was used. The data were processed by means of an SM-4 computer. The temperature profiles were constructed with an EM 7042 graph plotter.

Examples of Utilization

Figure 2 shows data on the temperature distribution in the flame of a Stearin candle. The left-hand side of this figure shows the temperature profile in one of the sections of the natural-convection region above the flame, derived from the data of a unidirectional speckle photograph, involving the use of the Abel transform. Similar distributions can also be constructed on the basis of speckle photographs in the three remaining directions (see Fig. 1). Comparison of these distributions enables us to estimate the degree of flame asymmetry, which in this case did not exceed 10-15%.

The temperature isolines in one of the horizontal cross sections of the nonsymmetric flame are shown in the right-hand side of Fig. 2, and these were obtained from the four-angle speckle photographs and reproduced by means of the Radon transform. Model calculations of the transform showed that the error in the mathematical reproduction procedure for local parameters does not exceed 10% where the displacement measurement errors for the speckles is ≤10%. Figure 3 shows the temperature isolines calculated on the basis of the data in Fig. 2a in one of the vertical cross sections of the flame. We note that one specklegram includes information about the entire field of the flow, and where the flow is axisymmetric through the field we can reproduce the local parameters of interest to us at any point within the flow. In this case, the laser energy ~0.5 J is sufficient to illuminate objects with an area of 0.1×0.1 m^2.

Figure 4 shows the restoration of the temperature profile on the basis of a specklegram for the free-convective flow about a vertically heated cylinder. All of these data were also derived in the processing of a single specklegram. Let us also note that the exposure time for the specklegram was 0.5 msec, and the distributions that are presented are therefore instantaneous, rather than averaged over time.

CONCLUSIONS

The results of these studies show that the technique of laser speckle photography makes it possible to obtain reliable quantitative data on the density-gradient fields of the flows being investigated and on the basis of these data to reproduce the temperature distributions. In axisymmetric flows, the procedure of reproducing local values involves utilization of the Abel transform with respect to the data of a unidirectional speckle photograph. In the case of an arbitrary flow we must increase the number of observation angles. In this case, reproduction of the local values within the sought fields involves the utilization of the Radon transform.

We have demonstrated here the possibility of simultaneously determining the entire three-dimensional field of local temperature values by the methods of speckle photography. As examples of these flows we have chosen an axisymmetric and arbitrary flame, as well as the axisymmetric natural convective flow about a vertical heated rod. The model calculations have demonstrated that the mathematical procedure of reproducing the local parameter values on the basis of data from four-directional measurements for noncomplex flows introduced virtually no additional errors into the final results.

Thus, double-exposure speckle photography is a simple and effective engineering method of measuring the distributions of local temperature values in various gasdynamic flows and in the processes of heat and mass exchange. The measurement scheme is no more complex than in the case of optical methods, involves fewer expensive optical elements, and imposes fewer rigorous requirements on the resolution of the photographic equipment. This facilitates the realization of tomographic research procedures based on speckle photography.

NOTATION

D, the diameter of the illuminated portion of the reflector or the diameter of the objective, m; L, the distance to the point of observation or the focal distance of the lens, m; λ, the radiation wavelength, m; $I(\eta)$, the intensity of the light at a point with coordinate η, W/m^2; Δ, the shift in the speckle field at this given point, m; η, the coordinate in a direction parallel to the shift in the speckle field, m; λ_1, the wavelength of the "reproduction" laser, m; L_1, distance from the developed specklegram to the screen, m; J_0, the intensity of the light at the center of the Young band, W/m^2; δ, the distance between the bands, m; β, the angle at which the bands are inclined relative to the horizontal axis, rad; Δx and Δy) the shift in the speckle field at the given point along the corresponding coordinate axes, m; L_2, the distance from the object being investigated to the plane in which the speckle field is photographed, m; n, index of refraction; ρ, density, kg/m^3; $K_{\lambda 2}$, the Gladstone–Dale constant for the wavelength of the probing laser λ_2, m^3/kg; z_1 and z_2, the coordinates along the z axis of the beginning and the end of the region of gasdynamic nonuniformity being studied, m; P, the laser strength, W; E, the energy of the laser pulse, J; t, the duration of the laser pulse, sec; σ, size of the speckle, m.

LITERATURE CITED

1. W. Hauf and U. Grigul', Optical Methods in Heat Transfer [in Russian], Moscow (1973).
2. Yu. E. Nesterikhin and R. I. Soloukhin, High-Speed Measurement Methods in Gasdynamics and in the Physics of Plasmas [in Russian], Moscow (1967).
3. Merzkirch, in: Methods in Experimental Physics, Vol. 18A: Fluid Dynamics, R. J. Emrich (ed.), New York (1981), pp. 345-403.
4. V. V. Pikalov and N. G. Preobrazhenskii, Reconstructive Tomography in Gasdynamics and in the Physics of Plasmas [in Russian], Novosibirsk (1987).
5. T. O. McCay and J. A. Roux (eds.), Combustion Diagnostics by Nonintrusive Methods, New York (1983).
6. U. Köpf, Opt. Commun., 5, 347-350 (1972).
7. U. Werneking, W. Merzkirch, and N. A. Fomin, 7th All-Union Conference on Heat and Mass Exchange, Minsk, May, 1984. Minsk (1984), Vol. 3, pp. 45-53.
8. N. A. Fomin, U. Werneking, and W. Merzkirch, "Optical methods in dynamics of fluids and solids," in: Proc. IUTAM Symp., Liblice, Czechoslovakia, 1984, M. Pichal (ed.), Berlin (1985), pp. 159-165.
9. U. Werneking, W. Merzkirch, and N. A. Fomin, Experiments in Fluids, 3, 206-208 (1985).
10. R. Jones and C. Wykes, Holographic and Speckle Interferometry, 2nd edn., Cambridge University Press.
11. U. Werneking and W. Merzkirch, Proc. 8th Int. Heat-Transfer Conf., San Francisco, Hemisphere, Washington (1986), pp. 100-105.
12. R. Erbeck and W. Merzkirch, Proc. 1st Symp. on Turbulence, Univ. of Missouri at Rolla (1986), pp. 1-17.
13. G. N. Blinkov, R. I. Soloukhin, and N. A. Fomin, Problems of Heat and Mass Exchange, 1986 [in Russian], Minsk (1986), pp. 92-97.
14. G. N. Blinkov, D. É. Vitkin, and N. A. Fomin, "Contemporary experimental methods of research into the processes of heat and mass exchange," in: Proceedings of the International School Seminar (Minsk, May, 1987), Minsk (1987), Ch. 1, pp. 28-35.
15. G. N. Blinkov, D. É. Vitkin, R. I. Soloukhin, and N. A. Fomin, Dokl. Akad. Nauk BSSR, 31, No. 10, 895-898 (1987).

FLOW IN THE INITIAL SEGMENT OF A TUBE WITH A SHARP INLET EDGE. COMPARATIVE ANALYSIS

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When flow becomes detached in the inlet segments of tubes and channels with sharp leading edges and where the Reynolds numbers exceed $75 \cdot 10^3$, the displacement of the maximum of the local heat transfer is in agreement with the onset of secondary laminar flow.

The detached flow model proposed in [1] can be compared with experimental heat-exchange and friction data applicable to the initial segments of tubes and channels with sharp inlet edges; this comparison is carried out on the basis of direct measurements of the surface static pressures and on the basis of the results from studies into local heat exchange, which can be found in [2-5].

For purposes of determining surface static pressures on a bench, such as that used in experiments to achieve flow visualization [1], we mounted a one-piece initial segment 80 mm in length ($X/d_{eq} = 2.22$) with a system of drainage orifices whose inside diameter was 0.5 mm. The curve of the changes in surface statistical pressure along the longitudinal coordinate for $Re_{d_{eq}} = 78 \cdot 10^3$ is shown in Fig. 1. The figure shows the positions of the

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