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HOLOGRAPHIC STUDY OF FLOWS WITH PHOTOCHROMIC VISUALIZATION

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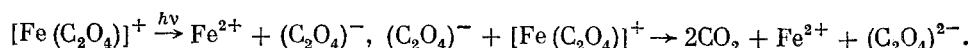
To measure the velocity and temperature profiles in a fluid flow, we chose two nondisturbing optical methods: the method of interferometry [1] to measure the temperature profile; the method of a holographic photochromic fluid to measure the velocity profile. Certain changes were made to the latter method in order to allow the two methods to be used together. These changes were specifically dictated by the fact that the photochromic liquid chosen in [2] was an alcohol solution of a substance, belonging to the class of spiropyrans, which changes color from transparent to red under the influence of ultraviolet radiation. However, the colored marking has a low contrast and requires special bias lighting, i.e., it is necessary to choose the wavelength of the bias light source.

The use of such a photochromic liquid for studies in a boundary layer is generally complicated by the fact that with magnification of the colored part of the liquid by the optical system, such as a microscope, contrast is lost at the boundary of the marking. This loss of contrast continues up to a magnification of about 50, when the marking disappears altogether. This leads to errors in the measurement of the coordinates of the colored wake and, thus, in the measurement of velocity in the boundary layer. We should also note the high cost of spiropyrans and the complexity of preparing aqueous solutions of the photochromic liquid. Moreover, a photochromic reaction of this type is reversible, and the colored marking exists for only a limited time. To avoid these problems and, more important, to permit recording of the colored marker against a background of red laser radiation — necessary to simultaneously study the temperature field — we used an aqueous solution of potassium ferrioxalate as the photochromic liquid.

This allowed us to obtain a highly contrasting colored marking noticeable against the entire visible spectrum. This in turn made it possible to use radiation from a helium—neon or ruby laser as the bias lighting. In addition, the contrast of the marking does not diminish with an increase in the magnification of the optical system, which means that it is possible to conduct investigations in boundary layers. In contrast to spiropyrans, dissolvable only in organic liquids, the ability of potassium ferrioxalate to dissolve in water permits simplification of the process of preparing aqueous solutions of the photochromic liquid and allows its viscosity to be varied through the addition of glycerin or sugar. Other important advantages of this method are the availability and low cost of the chemical components of the photochromic liquid when potassium ferrioxalate is used.

A working solution of the photochromic liquid was prepared by dissolving potassium ferrioxalate in water with an addition of sulfuric acid. In an acid solution, ferrioxalate ions dissociate into mono- and dioxalate complexes. Exposure to light produces ions of bivalent iron:
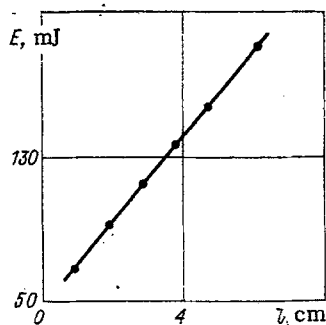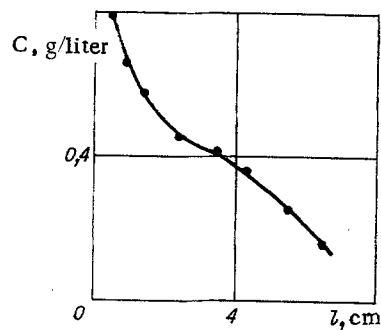
$$[\text{Fe}(\text{C}_2\text{O}_4)]^+ \xrightarrow{h\nu} \text{Fe}^{2+} + (\text{C}_2\text{O}_4)^-, \quad (\text{C}_2\text{O}_4)^- + [\text{Fe}(\text{C}_2\text{O}_4)]^+ \rightarrow 2\text{CO}_2 + \text{Fe}^{2+} + (\text{C}_2\text{O}_4)^{2-}.$$

Fig. 1

Fig. 2

As the indicator reacting to the production of ions of bivalent iron, we used potassium ferricyanide, also added in solution: $3Fe^{2+} + 2[Fe(CN)_6]^{3-} = Fe_3[Fe(CN)_6]_2$.

Exposure of the above solution to a narrow laser beam in the range 500-250 nm resulted in the formation of a vivid band in the solution. This band consisted of complexes of compounds of bivalent iron and potassium ferricyanide (Turnbull blue) and moved downflow. We determined its velocity by recording the position of the marking at equal time intervals and by measuring the distance traveled by the band during the recorded period. The concentration of potassium ferrioxalate is chosen on the basis of the problem being solved in the experiment: the concentration is made small if it is necessary to obtain a long colored marking. The concentration is increased if it is necessary to obtain a very dense contrasting marking of short length (such as in boundary-layer studies). Since the products of photolysis weakly absorb the stimulating radiation, the length of the marking depends almost linearly on the energy of the laser pulse (Fig. 1).

Figure 2 shows the dependence of the length of the marking on the concentration of potassium ferrioxalate. It should be noted that the marking is almost invisible at concentrations less than 0.1 g/liter. According to the experiments, a vivid wake is formed at a potassium ferrioxalate concentration greater than 0.2 g/liter. On the other hand, an increase in the concentration of potassium ferrioxalate leads to a reduction in the length of the colored marking. The optimum concentration is probably 0.3 g/liter, when the length of the marking is about 3 cm at an energy of 75 mJ. The coloring reaction is irreversible, and the movement of the marking can be followed for a sufficiently long time. One shortcoming of potassium ferrioxalate as a photochromic liquid is the slow coloring compared to spiropyrans, since the reaction occurs in several stages.

To study the temperature field, we chose the method of holographic interferometry for the following reasons: of the optical methods which give quantitative information on the refractive index, it is possible to use either classical interferometry or the chosen method of holographic interferometry. However, when this method is used in combination with the method of a photochromic liquid, it is desirable to observe the motion of the colored marking against a background of diffuse lighting rather than a luminous spot. It is also desirable to simultaneously use this diffuse light to study the temperature profile. This can be done only by using holograms.

Figure 3 shows the optical system of the unit used for full-scale studies. The beam from the LG-38 helium-neon laser 1 is rotated by the mirror 2 and strikes the beam splitter 3, which separates it into two beams: a working beam and a reference beam. The working beam is rotated by an opaque mirror, broadened by the lens 4, and directed to the diffuser 5 installed in front of a hydrodynamic channel or a tray with the liquid 6. After passing the object, the working beam strikes photographic plate 7. The reference beam is reflected by the mirror, broadened by the negative lens 4, and passes over a plane-parallel plate 8 used for studies by the finite-band method. After passing over the plate, the beam also strikes the photographic plate. After exposure (recording of the holographic image of the object before disturbances), the photographic plate is developed in situ and interference bands are observed through the resulting hologram. These bands are created by changes in temperature in the test liquid. The pattern obtained is reflected in the mirror 9 and strikes the photographic recording equipment: an LV-04 high-speed slow-motion camera 10 and a photographic camera 11. After the test flow is heated by a pulse from ruby laser 12, a radiation pulse is emitted and passes through the reverse telescope 13 (to create a narrow beam). The
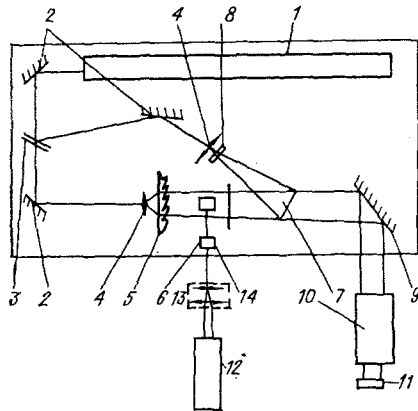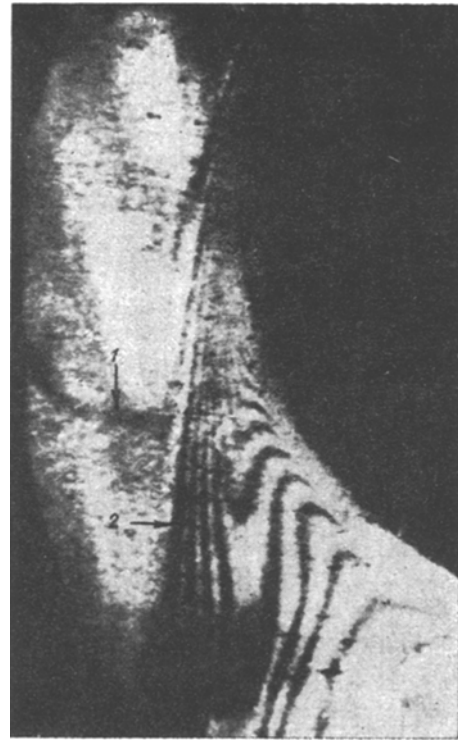
Fig. 3

Fig. 4

radiation pulse then strikes the KDR crystal 14, which converts the wavelength of the laser radiation into light with a wavelength that causes a photochemical reaction in the photochromic liquid. Colored markings are created in the liquid and are transported downflow. These markings are projected onto the photographic recording equipment against the background of the diffuser beam illuminated by the working light. Here, the colored markings are recorded together with the interference pattern. To increase the contrast of the interference bands, a polarizing sheet 15 is placed after the object. The sheet does not transmit light with polarization differing from the polarization of the reference wave. In certain experiments, a film camera is used as the recording apparatus.

Simultaneous recording of the temperature and velocity fields makes it possible to solve certain problems which could not be solved if temperature and velocity were studied separately.

Let the flow in a certain volume be described by the equations

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\nabla\mathbf{v}\right) = -\nabla p + \rho g\beta\nabla T + \mu_{(T)}\nabla^2\mathbf{v}, \quad \frac{\partial T}{\partial t} + \mathbf{v}\nabla T = k\nabla^2 T, \tag{1}$$

where ρ and p are density and pressure; $\mathbf{v}$ is velocity; μ is absolute viscosity, which is a function of temperature; g is the gravitational constant; β is the coefficient of cubical expansion; T is temperature; k is thermal conductivity; ∇ is the del operator.

We use the resulting values of temperature and velocity (the temperature obtained from the change in the interference bands, the velocity obtained from the motion of the colored marking) to find the gradients and second derivatives of temperature and velocity in space. We then use measured values of temperature and velocity at different moments of time to find $\partial T/\partial t$ and $\partial \mathbf{v}/\partial t$. The dependence of density and absolute viscosity on temperature is given in the tables in [3].

Inserting the values found for the temperature and velocity gradients into Eq. (1), we find the pressure gradient. Assuming the pressure on the surface of the photochromic liquid to be equal to the atmospheric pressure, we find the pressure distribution in the test volume at different moments of time. Thus, simultaneous measurement of temperature and velocity makes it possible to obtain the pressure distribution over the entire volume for convective flows. This could not be done by any other method (without introducing perturbations into the flow).

Figure 4 shows one of the frames of the film record which depicts flow about a cylinder in a channel. The interference bands were obtained by the real-time method in accordance with the optical scheme in Fig. 3. Interference lines 2 and the position of the colored marking 1 are visible on the photograph. It can be seen that the marking and the interference lines are poorly defined. This is related to the fact that the interference lines are localized in the region between the object and the hologram. Thus, the objective lens of the film camera must be directed between the sharp image of the colored marking and the lines of the interferogram.

For simultaneous sharp recording of the colored marking and interference bands, it is necessary to significantly stop down the objective lens. This cannot always be done, since it entails the use of highly sensitive film with a large grain size and, thus, low resolution with regard to the information obtained. These problems can be circumvented either by using a light-amplifying apparatus such as the high-speed camera in Fig. 3 or by recording the interferograms together with the image of the colored marking through the use of two exposures with holograms from the focused image.

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INFLUENCE OF GAS FLOW ON THE DISTRIBUTION FUNCTION

OF DISSOCIATING MOLECULES IN VIBRATIONAL LEVELS

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1. The influence of gas motion on the reaction kinetics of strongly excited molecules was examined in [1-4] — where it was established that significant nonequilibrium corrections, in magnitude, that are proportional to the spatial derivative of the macroscopic quantities, their powers, and derivatives, occur in the expressions for the macroscopic reaction rate. It is shown in [5-8] that upon taking more complete account of the properties of the kinetic equation solutions for high molecule energies they depend in a nonlinear manner on the spatial derivatives. In particular, the rate of diatomic molecule dissociation — truncated harmonic oscillators — depends exponentially on ∇u, where u is the flow velocity [8] in a nonisothermal convective flow.

Nonequilibrium correction to the reaction rate is a result of perturbations of the molecule distribution in the vibrational levels. The solution obtained in [8] for the distribution function possesses the property of locality, which is not fully in agreement with the explanation presented in [8], whence there results that the population of the upper energetic levels do not succeed in following the change in the translational temperature. Another interpretation of the results obtained is given below.

2. As is known [9], the law of conservation of the distribution functions holds in the model of a harmonic oscillator with an infinite number of levels if the initial distribution is a Boltzmann one. The population of the i-th vibrational level x_i at each instant is here determined by the formula

$$x_i = (1 - q)q^i, \qquad (2.1)$$