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PHOTOCHROMIC METHOD OF VISUALIZING HYDRODYNAMIC FLOWS

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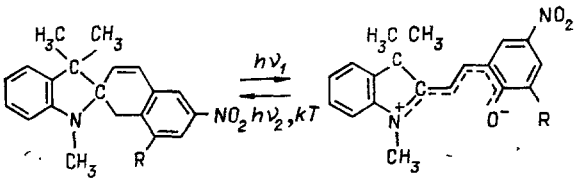
The traditional methods of visualizing flow in a liquid involve introducing tracers, colored liquid, solid particles, or bubbles [1, 2].

The photochromic method involves the use of colored markers initiated by UV irradiation in the initially colorless liquid, in which the photochromic substance is dissolved [3]. As the photo-induced color persists for a certain time, it is possible to record the color label visually or by means of a camera [4].

The photochromic method is a noncontacting one, and it introduces virtually no perturbations into the flow, and thus can provide repeated fast production of colored lines, intersecting lines, and planes at a given point within the flow by the use of collimated UV radiation.

The photochromic method was proposed in 1967 and was developed in [5-11]. The method has been used to examine turbulence in circular tubes, to determine the velocity pattern in flow around a sphere, and to examine the flow at the wall in a rough tube [7-11]. The photochromic compounds are mainly derivatives of dinitrobenzylpyridine, which are dissolved in alcohol or kerosene, and the lengths of the colored labels do not exceed 2.5 cm, which substantially restricted the utility of the method. We have used compounds from the class of nitro derivatives of indoline spiropyrans SPP, which produce labels of various colors in accordance with the nature of the SPP and the solvent [3]. The SPP powder was dissolved in distilled water, alcohol, or silicone oil. The photochromic reaction produced by UV radiation involves a reversible transition from the colorless state to the colored one as follows:



One can adjust the color and the lifetime of the colored form by introducing substituents with various donor-acceptor features in position R.

The experiments were performed with the apparatus shown schematically in Fig. 1, where 1 is an FS-7 filter, 2 are lenses, 3 is a ZhZS-9 filter, 4 is the hydraulic channel, 5 a matt screen, and 6 a KV-1000 cine light. The colored mark was produced by the radiation at the second harmonic of a ruby laser, λ_1 = 347 nm. The Q-switched single-pulse ruby laser type OGM-20 was used as the master oscillator, with subsequent amplification in a single-phase amplifying stage type GUS-1 [12]. To transform the basic ruby radiation λ_0 = 649 nm into the second harmonic with λ_1 = 347 nm, we used a KDP nonlinear component [12]. The energy in the fundamental after amplification was 2-3 J. Also, 2-3% of the fundamental was converted to the second harmonic.

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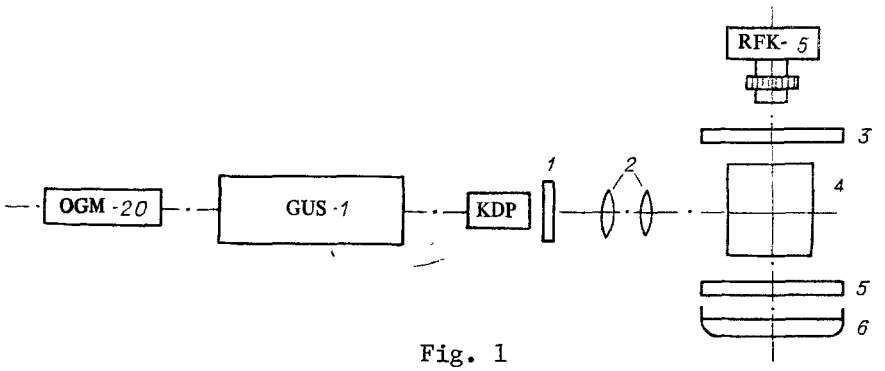

Fig. 1

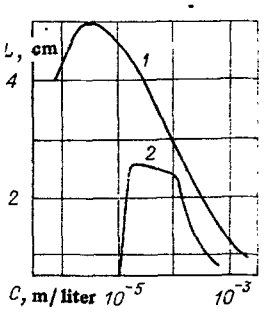

Fig. 2

The colored traces were recorded with an RFK-5 camera working at a high speed. We used high-contrast Mikrat-200 film, which was processed in fine-grained KTs-1 developer [13].

The time required to convert the solution from the initial form to the photo-induced one (response time) was determined mainly by the activating intensity. The amount of energy required to produce the necessary optical-density difference was determined by the light sensitivity.

The radiation at λ = 347 nm acted on the SPP solution to produce an optical density difference $\Delta D = 0.9$ with an exposure H_e = 9 kJ/m^2 in a pulse time τ of 10^{-8} sec [14]. This SPP response time is a consequence of the virtually inertia-free character of the coloring and bleaching. In principle, the response time of a photochromic compound is restricted by the natural time scales of the photochemical or photophysical transformations, which have $\tau = 10^{-13}$-10^{-7} sec for most photochromic compounds.

The length and diameter of the colored trace are dependent on the energy of the activating radiation and the concentration of the photochromic compound. The laser system enabled us to produce traces of various lengths and diameters at a given SPP concentration by varying the pumping energy in the GUS-1 amplifying system. We examined the effects of SPP concentration on the lifetime, and we found that the lifetime varied only slightly with the concentration, being dependent on the solvent and the form of the substance, the usual range being from 5 sec to 5 min. Figure 2 shows how the length of the SPP trace in aqueous solution is dependent on the concentration at a given activating energy (curve 1) as well as the dependence of the trace length on the DNBP concentration in alcohol (curve 2) recorded in [7].

Figure 3 shows photographs of a liquid with a free surface moving in a planar trough of width 4 cm under a pressure difference between header and receiving tanks; we show the colored label in the flow initiated by the laser at various instants: a) T = 0, b) T = 0.1 sec, and c) T = 0.4 sec. The UV beam was perpendicular to the flow. As the colored tracer is produced in 10^{-8} sec, the line is produced effectively instantaneously. These colored lines may be produced any number of times, and the corresponding films enable one to determine the flow conditions and instantaneous velocity profiles. Figure 3 shows the velocity profile in the flow produced by a pressure gradient in the horizontal plane.

Disadvantages of the method include the restricted length of the colored trace, which is not more than 10 cm, and the need to use channels with transparent walls, as well as

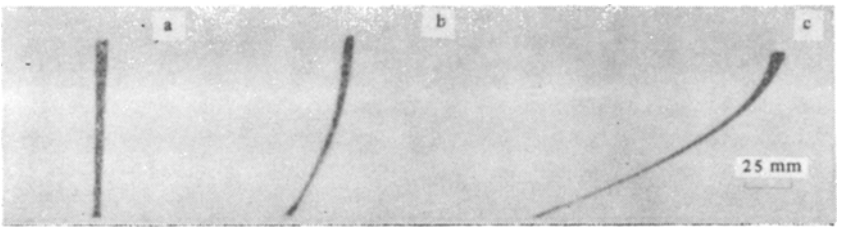

Fig. 3.

special working liquids: photochromic solutions.

The photochromic method is of value primarily in rapid and efficient quantitative analysis of hydrodynamic flow structures, localizing vortex and stagnant zones, identifying points of detachment in circulation currents, and generally in systems with complicated geometry (mixers, diffusors, curved channels, channels of variable cross section, flow around obstacles, etc.).

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