ON THE USE OF SALT TRACERS FOR MEASURING THE DYNAMICS OF A LIQUID BY OPTICAL METHODS

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UDC 532.577

During the sedimentation of small salt crystals in a stationary liquid, long cylindrical salt tracers are formed; it is proposed to use these in studying free flows during the pulsed turbulization of the liquid.

Present visualization methods [1] vary in relation to the form of the tracer constituents and in the means of creating these.

Tracers should satisfy the following requirements: a) they should have zero buoyancy; b) they should have a fairly long life; c) they should be photogenic (light-emitting).

In quantitative velocity measurements, further requirements are also imposed upon the shape and geometrical size of the tracers determining the spatial resolution of the visualization field, and also on the time required for the formation of the tracers in the liquid, which determines the type of hydrodynamic problems in which these may be used.

The foregoing requirements are satisfied by tracers of the thermal type, created in the liquid by pulsed laser radiation and recorded by means of shadow devices [2]. Being formed almost instantaneously in the flow by virtue of changes taking place in the physical properties of the liquid, thermal tracers rise to the surface very slowly and enable both laminar and turbulent flows to be visualized [2]. This property makes these tracers a reliable means of studying both slow and rapid processes taking place in the liquid [3].

In experiments relating to explosions and shock processes in liquids [4], and to the development of regions of turbulent mixing, intermittent phenomena, ejection processes, etc. in free flows during the pulsed turbulization of the liquid by vibrating [3] or moving [5] sources of perturbation, as well as in other experiments involving the spatial tracing of the zone under consideration by a dense series of long (several tens of centimeters) cylindrical tracers, the use of the methods discussed in [2] is vitiated by the complexity of the equipment required. One characteristic of this type of experiment lies in the fact that, before the beginning of the experiment, the liquid in the basin (cuvette) is stationary, so that the possibility arises of using tracers with a finite time of formation, obtained by easier means than laser technology. As a simple method of studying the phenomena accompanying the pulsed excitation of a stationary liquid [3-5], spatial delineation of the region under consideration may be effected by using salt tracers, obtained by dissolving small (up to 0.1 mm^3) common salt crystals in the stationary liquid. The salt tracers may be visualized by means of shadow devices.

The salt trace in the stationary liquid takes the form of a thin cylinder, with a diameter to a certain extent independent of the crystal dimensions; this form is uniquely determined by the physical nature of the solvent. (For crystal volumes greater than 0.1-0.5 mm^3, a Karman track develops behind the moving particle.) In distilled water at room temperature the transverse dimensions of the cylindrical tracers observed by means of a shadow device amount to 1.5 ± 0.1 mm for cubic common salt crystals 0.001-0.1 mm^3 in volume. The length of the tracers is uniquely specified for every solvent by the dimensions of the crys-

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Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 70-74, September-October, 1973. Original article submitted April 16, 1973.

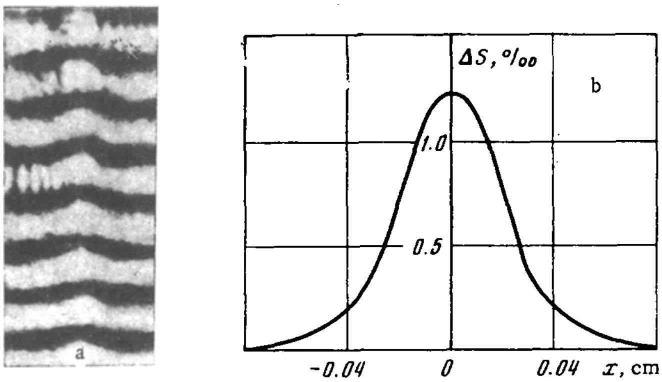

Fig. 1

tals, and in distilled water it exceeds 60 cm. The mean rate of formation of the tracers (mean rate of sedimentation of a crystal ~0.1 mm^3 in volume) is 10 cm/sec.

The life time of a salt trace in stationary water (t_S) is determined by the diffusion coefficient of the salt ($D \approx 10^{-5}$ cm$^2 \cdot$ sec^{-1} [6]) and amounts to over two minutes on recording the tracer with a shadow device having a vertical orientation of the Schlieren knife-edge. The value of t_s is one or two orders of magnitude greater than the time required for the formation of the salt traces. This enables us to use these for the spatial demarcation of hydrodynamic fields. The smallness of the diffusion coefficient D relative to the thermal diffusivity of water $\alpha \approx 10^{-3}$ cm^2/sec [6] explains why the lifetime of the salt tracer is so much longer than that of a thermal tracer [2].

On studying the capacity of salt tracers to follow flows by means of an interference instrument (interference pattern in Fig. 1a), we obtained the density and salt content of the liquid in the tracer in comparison with the background by using the well-known relationships [7, 8]

$$\Delta n \approx 0.23\,\Delta\rho \approx 3.33\cdot 10^{-4}\,\Delta S$$

Here $\Delta\rho$, ΔS, Δn are the differences in density (g/cm^3), salinity ($^0/_{00}$), and optical refractive index between the tracer and the background (distilled water). The interference pattern in Fig. 1a was obtained some time after the formation of the mark. The distribution of salinity with respect to the radius of the cross section deduced from this pattern (Fig. 1b) has a symmetrical shape, with a maximum of 1.23 $^0/_{00}$. A change of one per mill ($^0/_{00}$) in the salinity S has the same effect on n as a change of 3.3° in temperature T (for water $\Delta n \approx 10^{-4}\,\Delta T$ [9]).

From the resultant parameters of the salt traces, we may estimate the accuracy and spatial resolution obtained on measuring the liquid-flow velocity fields by the method proposed.

The density of the liquid in the trace differs from the density in the surrounding water ($\Delta\rho \approx 10^{-3}$ g$\cdot$cm^{-3}), so that the tracer will not follow the flow precisely; it will fall under the influence of gravitational forces. The mean rate of sedimentation of various parts of the salt traces measured in these experiments amounted to several tenths of a mm/sec. This agrees with the rate of sedimentation calculated by the Stokes formula [10] for a sphere falling in a viscous liquid. Remembering that the cross section of the trace determining the spatial resolution cannot be regulated, we see that it is most effective to use salt traces for visualizing large-scale processes with liquid velocities exceeding 3-5 cm/sec. In these cases the systematic error in measuring the velocity, determined by the sedimentation of the tracer, is ~1%. During the sedimentation of the crystal the boundary layers of the liquid are set in motion. This may also constitute a source of error when measuring flow velocity fields. Measurements with laser tracers showed that these motions ceased several seconds after the formation of the salt tracer.

In order to verify the potentialities of the method proposed experiments analogous to those of [3, 5] were carried out in a plane glass cell, but with the space under examination delineated by means of a series of vertical (z axis) salt tracers, which were created in the uniform liquid before the beginning of the experiment by means of a simple dosing device. The distance between the tracers was chosen so as to ensure the necessary spatial resolution, without impeding the interpretation of the results as a result of the superposition of neighboring tracers during the turbulent motion of the liquid. In the case of three-dimensional

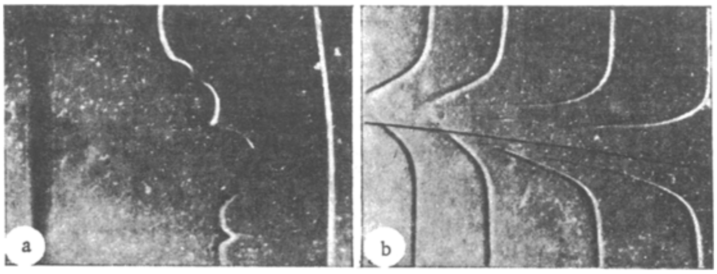

Fig. 2

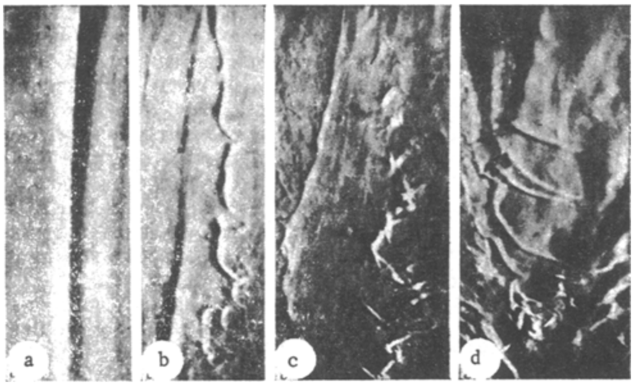

Fig. 3

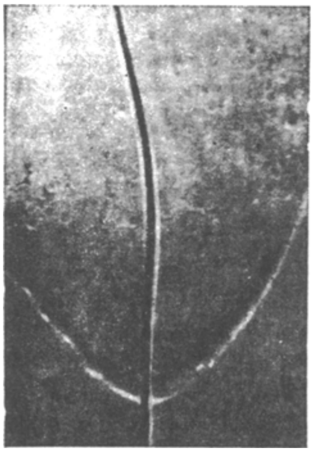

Fig. 4

flows in rectangular cuvettes, the demarcation of the space under consideration may be carried out by means of parallel series of salt tracers disposed in the vertical yz and xz planes, while the processes taking place may be recorded in two directions (x and y) at the same time.

During the experiments a pulse turbulizer placed in the middle of the cuvette was used to create a region of turbulent mixing, propagating from the center to the periphery, which was recorded by means of a shadow device and motion-picture camera. From the resultant negatives, the time development of the mixing region was analyzed, together with the initiation of motion in the stationary liquid; the rate of momentum transfer was also deduced. Figure 2a presents an example of the visualization of the mixing region by means of a salt tracer. The photograph clearly shows the boundaries of the turbulent zone and the spatial dimensions of the eddies, while the setting in motion of the initially stationary liquid may also clearly be recognized. Using salt tracers we may at the same time study the dynamics of the liquid inside and outside the region of turbulent mixing and on the boundary.

In another experiment we visualized a laminar submerged flow arising from the motion of a small solid (several mm^3 in size) in a uniform liquid (Fig. 2b). Using the tracers and the motion-picture negatives, we determined the mode of flow, the velocity profile, and the flow boundaries.

One disadvantage of the proposed method of visualization is the impossibility of using it to study the dynamics of a liquid existing in a state of motion. Salt tracers may only be used to study the initial stages of processes associated with the pulsed excitation of a stationary liquid. A second disadvantage is the impossibility of creating long cylindrical tracers with an arbitrary initial orientation (differing from the direction of the z axis). Using vertical tracers we may measure two components of the three-dimensional velocity vector $-V_x$ and V_y by recording the flux in two directions, $-x$ and y, but we cannot obtain any information regarding the motion of the liquid along the z axis. The velocity vector is determined by using tracers situated orthogonally with respect to each other (in the case of salt tracers, vertical and horizontal).

Short horizontal tracers (up to 10 cm long) may be created in a stationary dielectric liquid by means of an electric field. For this purpose we let down two plane electrodes into the specified region, place a jet or drop of salt solution between them, and apply a steady voltage of a few hundred volts. The drop of salt solution is obtained by the sedimentation of salt crystals having a volume of the order of 10^{-5} mm^3 as these are being completely dissolved in the crystal. Under the influence of the electric field there is a gradual spreading of the salt jet along the electric lines of force. Figure 3a, b, c, d illustrates successive stages in this process (the direction of the electric current is perpendicular to the jet). The horizontal salt tracers so obtained at various levels (Fig. 3d) may be used for visualizing the flows (after stopping the jet and disconnecting the electric field), but the general nonuniform background will interfere with our interpretation of the results of the measurements.

A sharp horizontal tracer may be obtained from a drop of salt solution placed directly in an electric field in the specified region of the stationary liquid. Like the jet, the drop will spread along the line of the electric field at a rate determined by the current density, but the surrounding background will now be uniform.

If salt drops are created between the electrodes at various levels in the liquid, on connecting the electric field we may obtain a series of parallel horizontal tracers with a prespecified distance between them. By supplementing these tracers with vertical ones (the field being disconnected) we may visualize three-dimensional flows. Figure 4 gives an example of the visualization of a submerged three-dimensional flow by salt tracers.

Mutually orthogonal tracers were created in a rectangular cuvette containing stationary water; horizontal ones (x axis) by the action of an electric field on a drop of salt solution, and vertical ones (z axis) by the sedimentation of a salt crystal in the absence of the field. Visualization of the flow was achieved by means of a shadow system arranged along the y axis with a horizontal orientation of the Schlieren knife-edge. No simultaneous recording of the flow along the x or z axes was attempted. The submerged flow arose in the liquid as a result of the motion of a sphere ~ 1 cm^3 in volume in an arbitrary direction.

An experimental verification of the accuracy of the proposed method was carried out in a horizontal rectangular hydraulic channel containing a transparent section, using laser tracers of the same diameter, which followed the flow of the liquid very accurately [2, 3]. The vertical cylindrical salt and thermal tracers were created very close to one another, with the outlet tap of the hydraulic channel closed. On opening the tap, transient flow began, and this was visualized by the tracers. The tracers of both types invariably followed each other (without lag or lead) over the whole transparent section of the hydraulic channel (~ 15 cm) for flow rates exceeding 3 cm/sec. The diameter of the thermal tracer increased with time much more rapidly than that of the salt tracer. This effect was associated with the difference between the heat- and salt-diffusion coefficients in water.

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