# DEVELOPMENT OF TURBULENT MIXING IN A FLUID

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The development of turbulent mixing produced by a linear source in a flat cell is studied with dyes and a laser thermal marker. The velocity field outside the mixing region is determined. The agreement of region size determined by dye diffusion and thermal marker deformation is shown.

A large number of observations, measurements, and theoretical papers [1, 2] have been devoted to the study of the characteristics of turbulent transport and fluid motion within and on the boundaries of free turbulent flows. Such studies are necessary both for the understanding of the mechanisms for creation and decay of turbulence and of the dynamics involved in setting fluids into turbulent motions and for various practical applications. The study of turbulence and the dynamics involved in interpenetration of fluids and of the shape and typical motion of the boundary defining the region of turbulent motion in a fluid is usually made with a thermoanemometer or with tracer particles which are transported only by the turbulent fluid [1].

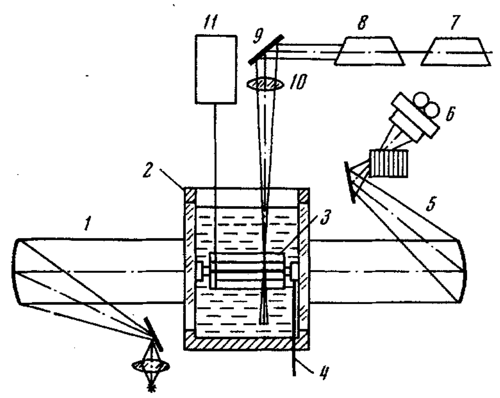


Fig. 1

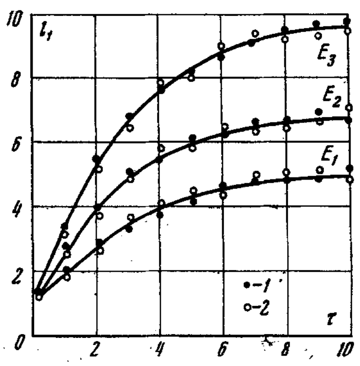


Fig. 2

The intermittance factor is easily determined by the first method, but it is necessary to combine the results of several experiments for the determination of the dynamics of boundary motion because the measurement is made at a single point in the flow. In addition, the introduction of a probe into the region under study leads to perturbation of the flow. A deficiency of the second method is the impossibility of studying the flow structure outside the region of turbulent mixing.

In this work, the size of the mixing region created by a linear source, the characteristics of the turbulence, and the parameters of fluid motion outside the mixing region were studied by means of dye diffusion and deformation of a laser thermal marker [1, 3, 4]. A diagram of the apparatus is shown in Fig. 1.

In the flat laboratory tank 2 of length 600 mm, width 50 mm, and height 250 mm, the lateral walls of which are made of optical glass, there is the six-bladed turbulizer 3, 15 or 20 mm in diameter. The drive mechanism 11 sets the turbulizer into oscillatory motion without rotation through an angle of 120°. Thus a region of turbulent mixing is created in the fluid which diffuses freely after the excitation ceases. The energy imparted to the fluid is changed by changing the frequency of oscillation and the duration of turbulizer operation. Before the beginning of an experiment, the spaces be-

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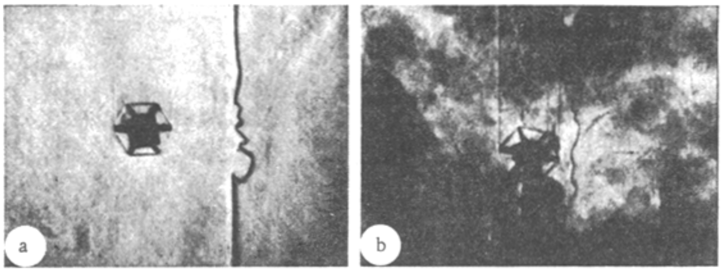


Fig. 3

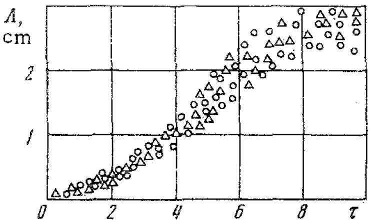


Fig. 4

tween the blades of the tubulizer are filled with a dye (violet ink) fed through an opening in the body of the turbulizer, a hollow axle, and the feed pipe 4 in order to visualize the region of turbulent mixing. Infrared radiation from the pulsed neodymium laser 8, which is directed to a given location in the tank by means of the rotating prism 9 and focussing lens 10, creates a thermal marker in the fluid. Adjustment of the optical system for creation of the marker is carried out with the OKG-13 He–Ne laser 7. The dye and thermal marker positions are recorded by means of the IAB-451 shadowgraph device 1, 5 and the "Konvas-avtomat" movie camera 6 operating at speeds of 24 and 32 frames per second.

The neodymium laser (radiation wavelength 1.06 $\mu$m) operated in the free-running mode at a pulse repetition rate of 2 Hz and a radiation energy of ~1 J/pulse. Because of absorption of laser radiation over the entire depth of the tank, a vertical thermal marker 0.5-1 mm in diameter was created with a lifetime of several seconds.

The size of the mixing region and the characteristics of the turbulence were determined by measurements of the deformation and displacement of the thermal marker and of the transport of the dye on the same negative, which was analyzed on a IFO-451 microphotometer. Since the thermal marker was formed over a large distance, it was possible to study the dynamics of fluid motion simultaneously within, on the boundary of, and outside the region of turbulent mixing. The time of marker formation was fixed by pulse duration and could be $10^{-8}$ sec, which made it possible to determine both small-scale and large-scale velocity pulsations by choosing the appropriate recording speed. The long lifetime permitted the study of slow fluid motions (to $10^{-1}$ cm/sec) outside the region of turbulent mixing and of the nature of boundary motion.

Velocity pulsations with a scale $\lambda$ greater than the diameter d of the thermal marker lead to deformation and displacement of the marker, but small-scale pulsations ($\lambda < d$) give rise to a broadening of the thermal marker that is considerably more rapid (at high levels of turbulence) than the broadening because of molecular diffusion determined by the marker lifetime in the quiescent fluid. By studying the behavior of thermal markers of different diameters (marker diameter depends on the focal distance of the converging lens, the angular divergence of the laser radiation, the distance from laser to lens, and the aberrations of the focussing system), the microscale $\lambda_0$ of the turbulence and other characteristics of turbulent motion can be determined.

An analysis of the films showed that during and after turbulizer operation the mixing region expanded identically in all directions because of the symmetrical conditions of excitation. Measurements of the size of the mixing region as a function of time for various energies (E) of the initial perturbation are given in Fig. 2. Along the ordinate is plotted the ratio of the diameter of the region of turbulent mixing to the turbulizer diameter ($l_1$), and along the abscissa, the ratio of the time from the start of the experiment to the time of turbulizer operation ($\tau$). The energy of the initial perturbation was determined in relative units from the duration of turbulizer operation for a given oscillation frequency. The experimental values (1) correspond to measurements of region size derived from marker deformation, and the values (2) to those derived from dye diffusion ($E_3 > E_2 > E_1$). The region boundary determined by the two methods is in agreement.

Since marker deformation is associated with diffusion of momentum and transport of the dye is determined by diffusion of mass, one can assume because of the agreement of region size that the values of the coefficients for turbulent diffusion of mass and of momentum are the same in this case.

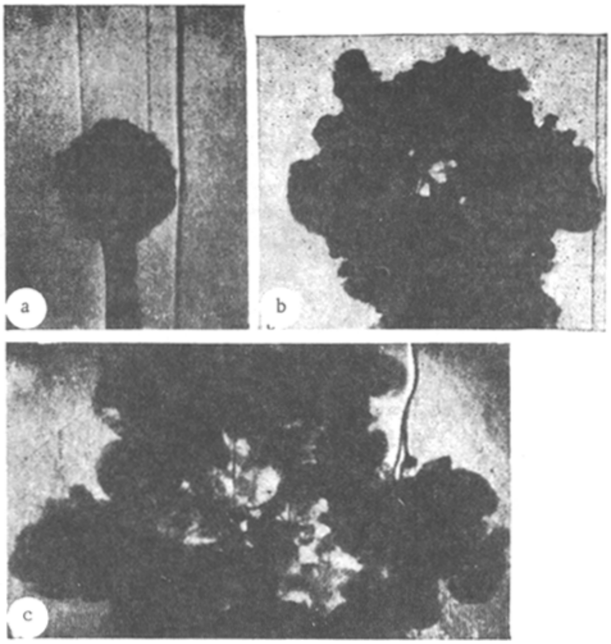

Fig. 5

In the early stage of development, the size of the region grows in direct proportion to time, and subsequently the rate of growth decreases; in the region $2 < \tau < 8$, $l_1 = K\tau^{1/2}$ (K is a factor which depends on the energy of the initial excitation).

Velocity pulsations of various scales are observed within the region of turbulent mixing. The smallest recorded scale of velocity variation is $\lambda_0 = (5 \cdot 10^{-2} \pm 6 \cdot 10^{-3})$ cm. Vortices of such a size are observed on the boundary of the region of turbulent motion as defined by dye diffusion.

From the measured values of $\lambda_0$, one can estimate the magnitude of energy dissipation [5], $\varepsilon = \nu^3/\lambda_0^4$ $\sim 0.1 \mathrm{cm}^2/\mathrm{sec}^3$ for $2 < \tau < 8$ ($\nu = 1.03 \cdot 10^{-2}$ cm²/sec is the kinematic viscosity of water at 18°C), which corresponds to a velocity variation $U\lambda_0 \approx \nu/\lambda_0 = 0.2$ cm/sec over a distance of the order of $\lambda_0$.

The experimentally measured value of velocity with a characteristic variation dimension of the order of $\lambda_0$ agrees with this.

Velocity pulsations of different scales noticeably deform the thermal marker at various time intervals after its formation depending on the magnitude of the velocity, which makes it possible to determine the scale and magnitude of velocity variations. In the first frames after the formation of a thermal marker, pulsations with maximum velocity values appear. In subsequent frames, the shape of the marker becomes more complex and reflects an entire spectrum of velocity pulsations.

As is clear from the negatives obtained, pulsations with scales from $\lambda_0$ to the macroscale turbulence $\Lambda$ (scale of maximum velocity variation) participate in the dynamics of turbulent motion. This can be observed in Toeppler pictures of marker deformation without dye (Fig. 3a) and with dye (Fig. 3b). Figure 4 shows the time dependence of macroscale turbulence obtained from a statistical analysis of ~1500 frames. At the initial time ($\tau \simeq 1$), $\Lambda \simeq 0.3$ cm and subsequently grows to 3 cm. For $2 < \tau < 8$, the value of the coefficient of turbulent diffusion remains constant and is $D = \Lambda U_\Lambda \simeq 20$ cm²/sec for an initial excitation $E = E_3$ ($U_\Lambda$ is the magnitude of velocity variation over distances of the order of $\Lambda$). The size $l$ of the region of turbulent mixing calculated from this value of D, $l \simeq (Dt)^{1/2}$, agrees with observed values (t it time).

The intensity of turbulence in the mixing region falls as a consequence of energy transfer to the quiescent fluid during boundary motion and because of viscous dissipation and friction at the lateral walls. Degeneration of small-scale turbulence begins near the turbulizer and propagates from the center to the periphery, which can be explained by energy loss because of friction with the turbulizer.

The boundary of the region of turbulent mixing, which is clearly visible in the photographs shown (Fig. 5), advances into the surrounding fluid because of the diffusion of vorticity and is of varying form depending on time. For $\tau \lesssim 1$, when the intensity of turbulence is high, a cross section of the boundary is a circle with nonuniformities of the order of $\lambda_0$ as determined both from the size of the vortices in the surrounding fluid (Fig. 5a) and from deformation of the marker. With subsequent increase in the size of the mixing region and decrease in intensity of turbulence, the shape of the boundary becomes more complex with nonuniformities having scales from $\lambda_0$ to $\lambda$ being observed (Fig. 5b), and in the final stages of development nonuniformities on the scale of $\Lambda$ are observed (Fig. 5c).

Motion of the fluid outside the region of turbulent mixing creates displacement of the fluid boundary with only the largest-scale pulsations playing a noticeable role.

Displacement of the boundary occurs at convection velocity. The concept of convection velocity is used for a description of the ratio between spatial displacement and time displacement at maximum space-time correlation. For a fixed pattern, the convection velocity is the velocity of the pattern [1] and can be markedly different from the velocity of the fluid. As is clear from Figs. 5a, 5b, and 5c, the velocity of the fluid outside the region of turbulent mixing is close in value to the convection velocity (velocity of the boundary).

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