THE ROLE OF TURBULENCE IN RIVER HYDRAULICS

by

A. A. Kalinske
University of Iowa
Iowa City, Iowa

Turbulence plays a most important role in regard to the influences that rivers have on their channels and beds. Certain general items regarding river hydraulics might be mentioned to indicate the effect that turbulence has on various river flow phenomena. Unquestionably the most important phenomenon which is controlled to a large extent by turbulence is that of sediment transportation. Both the movement of bed load and the carrying of material in suspension are more or less the result of the action of turbulent eddies in the flowing water. Even the rhythmic ripples and sand waves seem to be by-products of the turbulence mechanism. Offhand this is difficult to visualize, since turbulence is such a haphazard phenomenon. However, it should be remembered that at the bed, where the eddies originate, the vortex formations probably have considerable regularity—just as we find behind cylinders and other bodies. The vertical distribution of the temporal mean velocity is, of course, the result of the momentum-transferring characteristics of the eddies, and it is their particular behavior which gives us the various mean-velocity curves that have been found. This particular item will receive more detailed attention further on in the paper.

However, it is not the principal purpose of this paper to discuss the effects of turbulence, but rather to analyze the turbulence itself and present data regarding its characteristics. It is important that engineers first understand the physical aspects of turbulence, and be able to talk about it quantitatively, before they take the further step of studying its results. The prime purpose of this paper is therefore to present basic information and data relating to turbulence characteristics in rivers and open channels.

ORIGIN AND DIFFUSION OF TURBULENCE

The basic picture illustrating the origin of turbulence starts with a region or layer having high shearing stress, which can be compared to what is known in hydrodynamics as a "surface of discontinuity." This surface may become wavy, and momentarily a fairly stable wave pattern may develop. Color injections into a water stream at or near the critical Reynolds number exhibit this clearly. An increase in shear stress will cause these waves to grow and finally develop "breakers," which cause vortex formations. As the vortices develop, they are carried on into the fluid stream, and eventually their form becomes so complex that a mass of liquid filled with them is called turbulent, since no regularity is apparent or present.

In channel or pipe flow the regions of high shear where such vortices develop are, for a fluid of constant density, near solid boundaries, since physically that is where the shear is the greatest. Thus, so far as rivers are concerned, the eddies which make up the turbulence have their beginning at the river bottom or at the banks. At smooth boundaries the vortices form due to the "wrinkling up" of the layer next to the boundary, which is under high stress; however, a thin film clings to the boundary and moves in a laminar state. Near rough boundaries, in addition to the vortex formation due to excessive shear, roughness projections such as sand ripples, sand waves, and even individual sand grains cause localized regions of high shear and produce eddies in their wake.

Once these vortices form, they begin to move transversely to the stream flow. Such transverse movement is quite characteristic of eddies and is the cause of the intense mixing encountered in turbulent flow. The vortices when first formed may be more or less cylindrical or probably ring-shaped; however, because of the complex forces acting on such a vortex due to the mutual interaction of neighboring vortices, it is quickly deformed into an extremely complex shape, so that its individuality is practically lost. As individual vortices move about, they may combine with others or break down into smaller ones. When they encounter a solid surface or the free water surface, their form is undoubtedly greatly changed. Of course, the energy of the vortex is constantly being dissipated due to the action of viscosity—in fact, when normal, uniform flow is established, the rate of transfer of energy into vortices is exactly equal to the total rate at which the energy of the eddies is dissipated by viscosity.

Thus the energy of the eddy motion, though supplied principally at the bottom, is diffused throughout the whole stream due to the motion of the eddies. Not only is the eddy energy transferred, but also other liquid properties and materials suspended in the liquid. It is the diffusing characteristic of eddies and not the action of viscosity which controls the shape of the mean-velocity curve. In fact, any peculiarities of the shape of the mean-velocity curve will be related to the behavior of the eddies in the turbulent flow, and therefore any attempted explanations must be based on our knowledge of the turbulence mechanism.

INTENSITY OF TURBULENCE

One of the best physical pictures of turbulence is obtained by recording the velocity fluctuations at various points in the section of the stream. In the laboratory this can be done in flowing water by use of colored jets and suspended immiscible particles using various photographic techniques. For field use instruments do not as yet exist which will follow the velocity variations accurately enough to give a true picture of the velocity fluctuations. However, for large rivers a fairly good idea of the turbulence present can be obtained by using an ordinary current meter and recording continuously the time required to make each revolution or part of a revolution. Of course, a current meter will not respond to the most rapid velocity fluctuations; however, very good comparative data can be obtained which will tend to indicate the magnitude of the velocity fluctuations.

With the cooperation of the Rock Island (Illinois) Office of the U. S. Army Engineers some data have been obtained on velocity fluctuations in the Mississippi River. The velocity-measuring instrument used was an ordinary Price current meter so arranged that the time required for making a single revolution of the cup-wheel was recorded. This was accomplished by having a mark made for each revolution of the wheel by an electrically-actuated pencil on a paper strip moved at constant speed. By measuring the time for each revolution it was possible to obtain values of the water velocity for small increments of time—say of the order of one second, depending on the speed of the wheel. Of course, a current meter will not respond to the smallest velocity fluctuations. Also, a Price meter does not give a true indication of velocity fluctuations in just one direction; that is, it is not uni-directional in its response. However, it does give a measure of turbulence which is useful for comparative studies.

In Fig. 1 are shown velocity-fluctuation data taken at three depths in the Mississippi River where the total depth was 19.0 feet. Note the apparent increase in magnitude of the fluctuations from the surface down, and also the increase in scale, since the fluctuations near the bottom are of lower frequency. A statistical analysis of the frequency of occurrence of various magnitudes of the velocity over about a ten-minute period was made in order to see what law the fluctuations followed. From this a block diagram

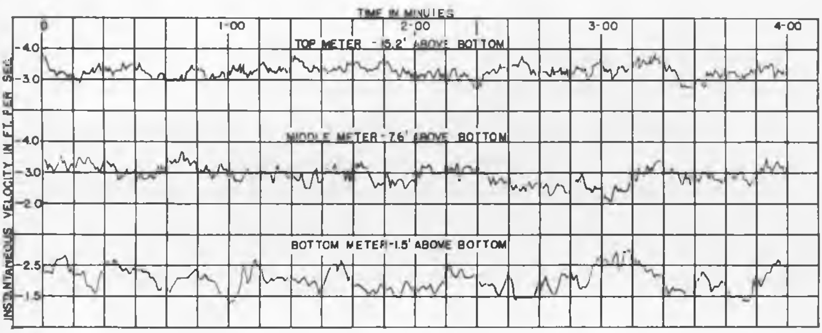

FIG. 1.—VELOCITY FLUCTUATIONS IN MISSISSIPPI RIVER AS OBTAINED WITH PRICE CURRENT METER. TOTAL DEPTH 19.0 FT.

was made and a smooth curve drawn through the centers of the tops of the blocks. The smooth curve fitted the equation of the normal error law, which is as follows:

$$f\,(U - \bar{U}) = \frac{1}{\sqrt{2\pi}\sigma}\, e^{-\frac{(U-\bar{U})^2}{2\sigma^2}} \tag{1}$$

in which

U = velocity at any instant

$\bar{U}$ = temporal mean velocity

$\sigma = \sqrt{\overline{(U - \bar{U})^2}}$

The function of $f\ (U - \bar{U})$ indicates the frequency of occurrence of values of the velocity between $(U-\bar{U})$ and $(U-\bar{U}) + d(U-\bar{U})$. The term σ is the root-mean-square value of the velocity fluctuation, or the so-called standard deviation; it has been adopted as a measure of the intensity of the turbulence.

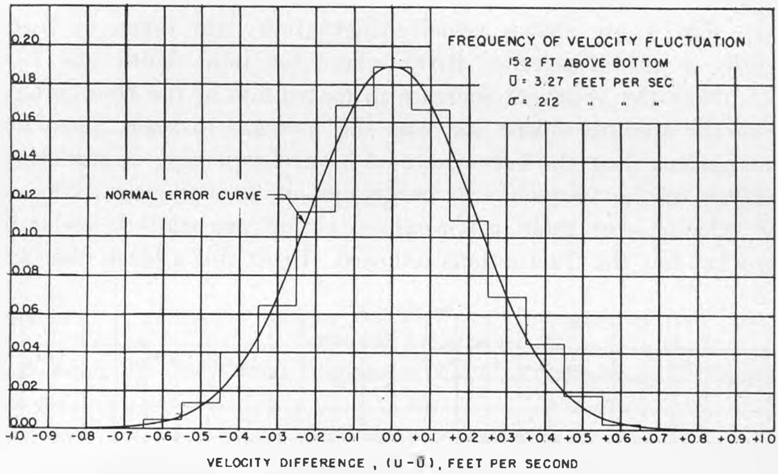

FIG. 2.—FREQUENCY OF VELOCITY FLUCTUATION 15.2 FEET ABOVE BOTTOM.

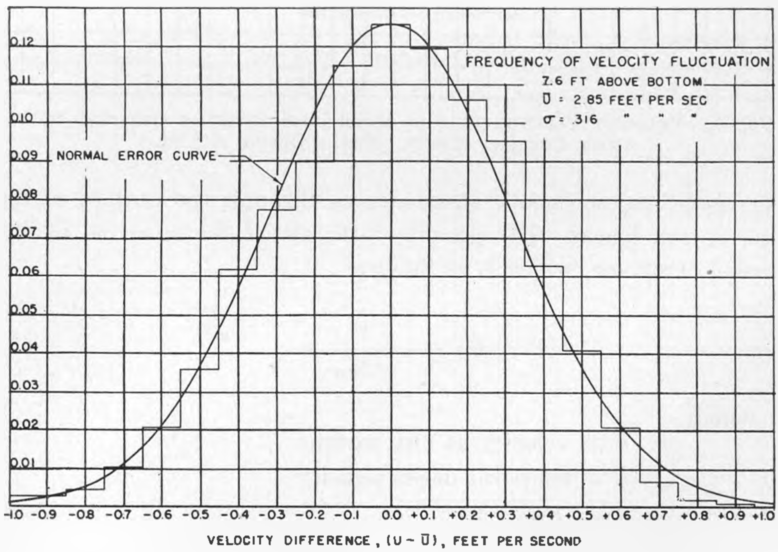

FIG. 3.—FREQUENCY OF VELOCITY FLUCTUATION 7.6 FEET ABOVE BOTTOM.

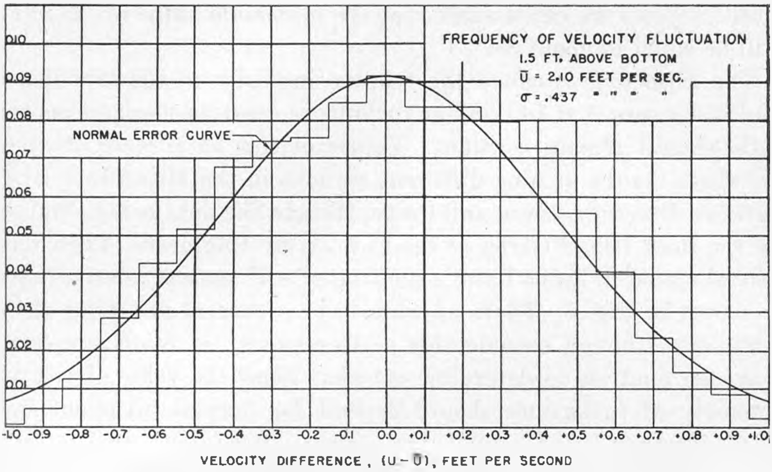

FIG. 4.—FREQUENCY OF VELOCITY FLUCTUATION 1.5 FEET ABOVE BOTTOM.

In Figs. 2, 3, and 4 are shown the frequency curves for the data in Fig. 1. Note how well the normal error law is followed. The fact that the velocity fluctuations follow the normal error law permits making certain conclusions: First, fully developed turbulence appears to be a haphazard velocity fluctuation. Second, the normal error law shows that values of $(U - \bar{U})$ equal to 3σ or greater will occur only about 0.30 percent of the time. Therefore, for prac-

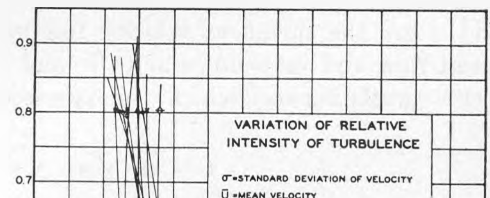

FIG. 5.—VARIATION OF RELATIVE INTENSITY OF TURBULENCE WITH RELATIVE DEPTH IN MISSISSIPPI RIVER.

tical purposes we can assume that the maximum value of $(U - \bar{U})$ will be equal to about 3σ.

The ratio $\sigma/\bar{U}$ is called the relative intensity of the turbulence, and it appears that for similar turbulence-creating mechanisms this ratio should remain constant. Values of this ratio were obtained for three depths at nine different sections in the Mississippi River between Dubuque, Iowa, and Cairo, Illinois, the data being obtained by the Rock Island Office of the U. S. Army Engineers. These data are tabulated in Table I and a plotting of $\sigma/\bar{U}$ against relative depth is shown in Fig. 5. There appears to be a general grouping of the data, even though considerable scatter exists. It is of interest to make an analysis to determine on what items the value of relative intensity of turbulence should depend for normal turbulent flow in a wide river.

In fully-developed turbulent flow Reynolds has shown that the unit shear τ must equal $\rho\,\overline{uv}$, wherein ρ is the unit fluid density, u and v are the turbulent velocity fluctuations in the direction of mean flow and perpendicular to it, and the bar indicates a mean. Let a correlation coefficient r be expressed thus:

$$r = \overline{uv} / \sqrt{\overline{u^2}}\ \sqrt{\overline{v^2}} \tag{2}$$

Therefore,

$$\tau = r\rho\ \sqrt{\overline{u^2}}\ \sqrt{\overline{v^2}} \tag{3}$$

At any distance from the boundary the longitudinal and transverse velocities should be proportional, therefore $\sqrt{\overline{v^2}} = m\sqrt{\overline{u^2}}$. For similar turbulent flows m should vary only with relative distance from the boundary. We then have:

$$\tau = \rho r m\ \overline{u^2} \tag{4}$$

Note that $\sqrt{\overline{u^2}}$ is really σ, if we assume that $(U - \bar{U})$ for the river measurements represents the true value of u. Let $rm = K$, which constant should depend only on relative location with respect to the boundary. For a wide river the shear is equal to

$$\tau = \gamma\,(d - y)\,S \tag{5}$$

in which γ is the unit weight of water, y the distance above the bottom, d the total depth, and S the surface slope. If the bottom

TABLE I

MEAN-VELOCITY AND VELOCITY-FLUCTUATION DATA FOR MISSISSIPPI RIVER

Section	Total Depth, Ft.	Dist. Above Bottom, y, Ft.	Mean Velocity $\bar{U}$, Ft. per Sec.	σ Ft. per Sec.	$\sigma/\bar{U}$
1	19.0	1.5	2.10	.44	.209
		7.6	2.85	.32	.111
		15.0	3.27	.21	.065
2	17.0	1.5	2.43	.41	.166
		6.8	3.02	.34	.114
		13.6	3.46	.27	.079
3	21.4	1.5	2.28	.42	.184
		8.6	2.91	.31	.107
		17.1	3.30	.21	.064
4	23.7	1.5	2.59	.57	.220
		9.5	3.67	.39	.106
		19.0	4.15	.34	.082
5	21.6	1.5	1.25	.18	.144
		8.6	2.04	.22	.108
		17.3	2.47	.15	.061
6	21.7	1.5	1.87	.44	.236
		8.7	2.95	.31	.105
		17.4	3.43	.26	.074
7	16.2	1.5	2.25	.34	.150
		6.5	2.80	.23	.082
		13.0	3.07	.18	.059
8	14.7	1.0	2.10	.35	.167
		5.7	2.63	.22	.084
		11.7	2.84	.19	.067
9	17.7	1.5	2.84	.36	.127
		7.1	3.26	.33	.101
		14.2	3.58	.32	.089

shear is τ_0, then $\tau = \tau_0 \, (1 - y/d)$. Therefore,

$$\sigma = \sqrt{\frac{\tau_0 \, (1 - y/d)}{\rho K}} \tag{6}$$

Using the Chezy equation for the mean velocity of flow, $\bar{U}_m$, we obtain,

$$\tau_0 = \gamma \bar{U}_m^2 / C^2 \tag{7}$$

Therefore,

$$\frac{\sigma}{\bar{U}_m} = \frac{1}{C}\sqrt{\frac{g(1-y/d)}{K}} \tag{8}$$

The logarithmic velocity-distribution equation for a wide channel is:

$$\bar{U}/\bar{U}_m = 1 + \frac{\sqrt{g}}{.4C}\,(1 + \log_e y/d) \tag{9}$$

From Eqs. (8) and (9) it is apparent that at any particular distance from the bottom the ratio $\sigma/\bar{U}$ is dependent on the Chezy C, which in turn depends on the relative roughness of the bottom and the Reynolds number of the flow. For a large river as the Mississippi, C probably is fairly independent of the Reynolds number, and thus it can be stated that the relative intensity of the turbulence depends on the relative roughness of the bottom.

The current meters were not, of course, able to record the peaks of the velocity fluctuations; therefore, it should be remembered that the indicated values of $\sigma/\bar{U}$ are undoubtedly low. Other measurements on turbulence indicate that for normal turbulent flow in channels or pipes $\sigma/\bar{U}$ can easily be equal to ⅓ near boundaries. If, then, as stated before, $(U_{max} - \bar{U}) = 3\sigma$, it is seen that the value of U_{max} can be $2\bar{U}$. In other words fluctuations equal to twice the mean velocity at a point in the turbulent zone near a boundary can readily be expected.

SCALE OF TURBULENCE

Another important characteristic of turbulence is its scale, which depends on the size of the eddies present. In Fig. 1, showing the velocity fluctuations, variations in scale are apparent. Probably the simplest quantitative measure of the scale would be obtained by measuring from the velocity-fluctuation curves the time intervals between crossings of the mean-velocity line and thus get an average value for this time. Multiplying this time by the mean velocity would give a length factor which should be a measure of the eddy size.

G. I. Taylor [1][1] has made a mathematical analysis which ties the concept of scale to the statistical idea of correlation between the ve-

[1] References appear at the end of the article.

locities at two different points—such as, for instance, two points a distance x apart in the direction of flow. He defines a correlation coefficient R_x thus:

$$R_x = \overline{u\,u_x}/\overline{u^2} \tag{10}$$

Now if the distance x is very small, R_x approaches unity; as x increases, R_x becomes zero. The value of R_x ought to be high if the distance x is less than an eddy diameter. A length factor is then defined,

$$L = \int_0^\infty R_x \, dx \tag{11}$$

By evaluating R_x for various values of x so that a curve can be plotted, the value of L can be obtained. It can be shown that if the velocity fluctuations are haphazard, having no periodicity, the value of R_x starts at 1.0 and approaches zero. For the case of uniform velocity, $dx = \bar{U}\, dt$ and Eq. (11) can be written

$$L = \bar{U} \int_0^\infty R_t \, dt \tag{12}$$

From the velocity data such as shown in Fig. 1, the values of R_t can be calculated for various increments of time t. The work is time-consuming, since a great many values of u and u_t must be read

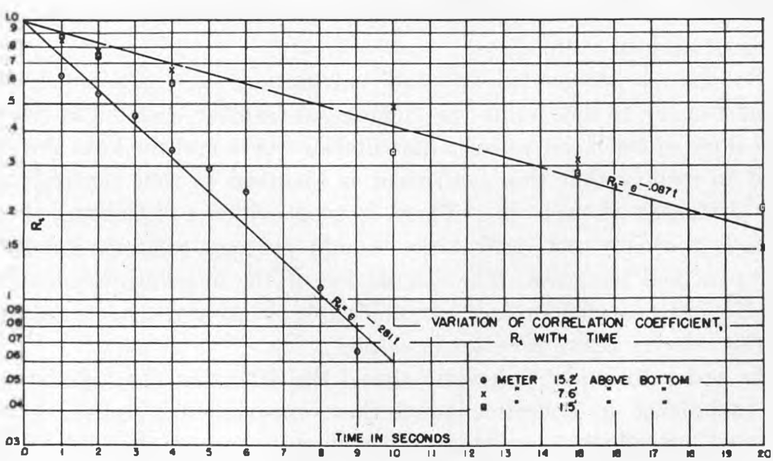

FIG. 6.—VARIATION OF CORRELATION COEFFICIENT.

before a proper average value of $\overline{u\ u_t}$ can be obtained. This work was done for the data shown in Fig. 1, and the values of R_t that were obtained are shown in Fig. 6. Note that the form of the curves is:

$$R_t = e^{-kt} \tag{13}$$

This is quite interesting, since certain theoretical considerations indicate that this correlation coefficient should vary exponentially with time. The value of k is dependent on the slope of the curve and, theoretically, the determining of one value of R_t therefore permits the evaluation of k, since $R_t = 1$ when $t = 0$. The integration of Eq. (12) using Eq. (13) for R_t is very simple:

$$L = \bar{U}/k \tag{14}$$

Thus the term k characterizes the scale of the turbulence.

MIXING CHARACTERISTICS OF TURBULENCE

Another turbulence characteristic which is of considerable significance to the engineer is the mixing coefficient. This is a parameter which evaluates the ability of turbulence to transfer momentum, heat, sediment, etc., from one region of the fluid to another. This coefficient depends on how fast eddies move transversely to the stream and the mean distance of their travel. The speed of their movement is undoubtedly dependent on the turbulence intensity, since if the eddies rotate rapidly they will also move about rapidly. The distance of their travel depends on how many are present and on their size.

So far as suspended-sediment calculations are concerned, it is customary to determine the momentum-transfer coefficient from the slope of the mean velocity-distribution curve and the local shear, and to assume that this coefficient is identical to that controlling the diffusion of mass [2]. There is good evidence indicating that this is probably not quite true, though perhaps accurate enough for practical purposes. The calculation of the momentum-transfer coefficient near the surface is not feasible or accurate, particularly if the velocity curve reverses in slope.

In order to study in greater detail the diffusion characteristics of turbulence in normal channel flow, experimental studies were carried on which permitted a direct measure of the diffusion coefficient for mass mixing. Briefly, this was accomplished by injecting into the flowing water immiscible droplets, or in some instances chemicals, and determining the spread of this foreign matter at several distances downstream from the injection point. A detailed discussion of the technique and the results obtained was published by Kalinske and Robertson [3]. In general, though the directly-measured diffusion coefficient compared quite well with that determined from the mean-velocity curve and shear, significant differences were noted.

An elaborate and detailed study relating to the direct measure of the diffusion coefficient and suspended-material movement in open channels was carried out by C. L. Pien, as a doctoral thesis under the writer's direction and the results will be published elsewhere. The directly-measured diffusion coefficient was used to calculate suspended-sediment distribution in an open channel and a very good check was obtained with actual sediment measurements. The diffusion coefficient was measured by injecting a mixture of hydrochloric acid and alcohol (having the same specific gravity as water) and determining the average concentrations of the diffused mixture at various points downstream by taking water samples and analyzing for chloride concentration. This proved to be a speedy method and could be used in dirty water quite readily.

Effect of the Free Surface

One of the significant peculiarities of liquid flow in open channels is the presence of the free surface, which has a profound effect on the mean velocity distribution in the cross section. The behavior of vortices, which originate at the bottom or sides of a channel, as they approach a surface of discontinuity such as a free water surface is a phenomenon about which little definite information exists. The free surface does not create any turbulence, since no appreciable shear exists there—unless, of course, there is a strong wind, and waves and breakers develop.

There is no question but that the reverse curvature of the velocity-distribution curve at the surface is tied up with the turbulence action. Evidence exists which shows that this reverse curvature occurs in very wide rivers where the side effects are negligible. However, there is also evidence which indicates that no reverse curvature of the velocity occurs in certain other wide channels. For instance, velocity measurements made by Van Veen [4] in the Straits of

Dover definitely show that the maximum velocity occurred at the surface. The depth was about 130 feet and the mean velocity 3 feet per second. It is entirely possible that normal turbulent flow may not have been established in the case of flow in the Dover Straits, and therefore the turbulence originating at the bottom would not have reached the surface.

The dynamics of vortex movement shows that it is entirely possible for a vortex—such as, for instance, a ring vortex—to pass through fluid having a considerably different forward velocity, and to acquire or give off momentum only very slowly. In addition, the forces developed on a ring vortex as it nears a free surface tend to pull it up into the surface. All this tends to lend plausibility to the idea that the slowing down of the surface water can be caused by the accumulation at the surface of water which is part of slower-moving eddies which originated at the boundaries of the channel. Of course, this may not be the complete explanation of the phenomenon of the reverse curvature of the velocity curve. The existence of secondary currents causing the mean flow at certain points to be inclined to the channel walls may be in some fashion related to the existence of an apparent shear at the surface.

This particular problem has been the subject of such prolonged controversy and disagreement that it is hoped that reliable, controlled experiments will soon be made to shed more definite light on this most interesting feature of turbulent flow in open channels.

Concluding Remarks

In conclusion, the writer wishes to summarize a few of the engineering problems in which a more complete knowledge regarding the various turbulence characteristics mentioned would provide significant information for their proper solution.

First, regarding the intensity of turbulence: The relative intensity of turbulence has been shown to be an important item in measuring drag on bodies. It is an important variable that must be controlled and its action understood if model studies relating to drag are to be analyzed properly. Another field of work in which knowledge of the intensity of turbulence is vital is that of sediment transportation. It is gradually becoming realized that, for instance, in the bed-load problem measurement of average velocity and average shear are of little significance when values twice the mean can occur momentarily. The measurement of mean velocities and mean sediment concentrations is influenced by the intensity of turbulence, since true time averages cannot be obtained unless the time interval is large enough for the fluctuations to be averaged properly.

In regard to the scale of turbulence, probably the most practical application that should be pointed out is that relating to the dissipation of the turbulence energy. Large eddies are destructive, and they should be broken up or prevented from forming. The smaller the eddies, the quicker will the turbulence energy be dissipated.

The engineering importance of the mixing coefficient is too obvious to require any elaboration. Sediment transportation, heat transfer, and river pollution are but a few of the large general-engineering problems which require knowledge of turbulent mixing.

REFERENCES

[1] Taylor, G. I., "Statistical Theory of Turbulence," *Proc. of Royal Society of London,* Vol. 151A, 1935, p. 424.

[2] Lane, E. W., and Kalinske, A. A., "Engineering Calculations of Suspended Sediment," *Trans., Amer. Geophysical Union,* 1941, p. 603.

[3] Kalinske, A. A., and Robertson, J. M., "Turbulence in Open Channel Flow," *Eng. News-Record,* April 10, 1941, p. 53.

[4] Van Veen, J., "Water Movements in Straits of Dover," *Journal du Conseil International pour l'Exploration de la Mer,* Vol. 13, No. 1, 1938.