An Experimental Study of Liquid-Phase Turbulent Diffusion:

Part I. Fluid Mechanical Data

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Results from an investigation of the fully developed turbulent wake of a circular cylinder are presented. The study was conducted in the liquid phase, in the controlled flow field of a water tunnel. A technique was developed for measuring the intensity of turbulence in water. The decay of turbulence intensity downstream from a series of fine-mesh wire screens was measured and compared with aerodynamic decay laws. Profiles of the turbulence intensity in the cylinder wake were also obtained. This paper is Part I of a study of liquid phase turbulent mass transfer in the wake of a cylinder. The mass transfer results are reported in Part II .

This paper is Part I of a report from an investigation of liquid phase mass transfer in the turbulent wake of a cylinder. This portion of the report is concerned with the fluid mechanical data required, in addition to local concentration information, to compute local mass transfer coefficients. Velocity profiles, turbulence intensities, and the effect of various operational parameters on such variables of importance are discussed in some detail.

The system chosen for study was the fully developed turbulent wake of a circular cylinder. In the center of such a wake there is a strong variation of turbulence intensity in the downstream direction, and this variation occurs within a convenient distance from the cylinder. A hollow cylinder with a porous wall was used in order that a wake of electrolyte could be established downstream by forcing a solution of electrolyte through the porous wall. Concentration profiles were obtained at various stations in the wake, and turbulent mass transfer coefficients were then calculated from these profiles. The latter are reported in Part II of this effort.

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Heretofore one of the major experimental difficulties encountered in studies involving the liquid phase has been the inability to measure readily either the scale of turbulence or the intensity. There is at present no instrument for liquid-phase research comparable to the hot-wire anemometer. Part of this investigation concerned the development of a technique for measuring the turbulence intensity in water. Although the scale of turbulence cannot be measured directly in water, the variation of transfer coefficient with scale may be studied in some measure by comparing transfer coefficients in the wakes of cylinders of different size. The assumption is thus made that the scale of turbulence characteristic of diffusion varies as the gross dimensions of the system, for example wake width, or pipe diameter for turbulent flow in pipes. Such a variation of length scales with the width of the shear region is not unknown. Townsend (*35, 37, 38*) has shown that the longitudinal scale, a characteristic microscale, and a length parameter characteristic of the dissipation in a wake are proportional to the wake width.

In constructing apparatus for experimentation in the liquid phase, it would be useful to know to what extent aerodynamic correlations may justifiably be used for design purposes. During the course of the investigation data were taken in an attempt to verify the similarity in air and water of the effect of screens on spatial variations in mean velocity, the decay of turbulence intensity downstream from grids, and the turbulence intensity in the fully developed turbulent wake of a circular cylinder.

The relative rates of transfer of mass and momentum are also of interest. From the data taken a comparison is made (Part II) in terms of the turbulent Schmidt number, the ratio of the transfer coefficient of momentum to that of mass.

Previous investigations of turbulent mass transfer in water include those of Kalinske and his co-workers (*17, 18, 19*), van Driest (*5*), and the recent work of Flint, Kada, and Hanratty (*8*) involving the equations of Taylor (*32*) and Wilson (*41*) using point or line sources. For such experiments the source and its support must be of such a size that the fluid field is not disturbed. Roshko (*24*) and Corrsin and Uberoi (*4*) have established the conditions wherein the source may be considered as a point or line. The work of Hegge Zijnen (*12*) serves as an interesting reference to the kinds of difficulties inherent in any attempt to obtain a mass source which does not disturb the flow. When a source does disturb the flow, it is evident that the diffusing material may spread faster parallel to the tube than transverse to it [see, for example, Towle and Sherwood (*34*)]. Other studies include the work of Sherwood and Woertz (*29*), Schwarz and Hoelscher (*28*), and many others (*16, 21, 22, 26, 39*). The results of Schwarz and Hoelscher are of the same general shape as those predicted by Dryden (*6*).

The turbulent Schmidt number is of interest, but the only measurement of this ratio in liquids is that of Forstall and Gaylord (9). Their results indicate that mass spreads considerably faster than momentum in water. From both theory and experimentation the turbulent transfer coefficients should be functions of velocity, turbulence intensity, a scale of motion, and possibly the physical properties of the flowing medium.

EXPERIMENTAL EQUIPMENT AND MEASURING TECHNIQUES

The Water Tunnel

The investigation was carried out in the 8-in.-square, closed-return water tunnel described elsewhere (*20, 30*). The important features will be summarized briefly.

The tunnel provides a working section in which the fluid mechanical variables of the flowing stream are known and controllable. The 1,000 gal./min., 580 rev./min. pump is driven by a 7.5-hp. DC motor, the speed of which may be regulated by a resistor bank and rheostat in the field circuit. The pump impeller is brass. The cast iron body of the pump is coated with brine resistant paint.

The upper sections of the tunnel are constructed of plexiglas, and the lower and side sections are of brass. All sections are of 8-in. square cross section except the sections adjacent to the pump, which are square-to-round sections. All joints between sections are gasketed with rubber O-rings in flanges held together by C-clamps.

Temperature in the tunnel was controlled by a cooling coil and two 1,000-watt immersion heaters mounted downstream from the working section. Since the mechanical action of the pump gradually heated the water, and because the thermal capacity of the 60 gal. of water was high, temperature regulation within a few hundredths of a degree Centigrade could be obtained

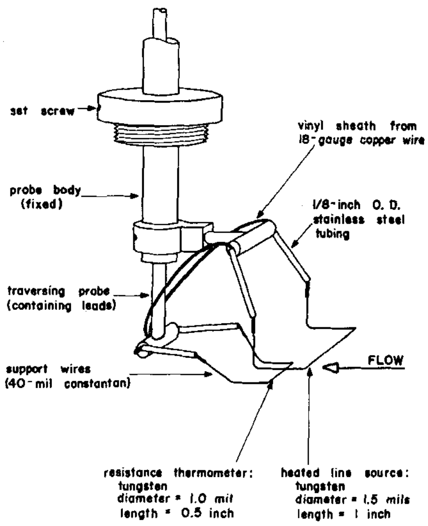

Fig. 1. Probe for measurement of turbulence intensity.

by manual manipulation of the needle valve controlling the flow of cooling water. To accomplish the rapid initial heating of cold tunnel water to operating temperature a bank of eight high-temperature gas burners was directed against the sides of the lower brass sections.

The water level in the tunnel was controlled by a siphon mounted in the riser section extending above the tunnel proper. Oscillation of the free surface in the riser was prevented by suspending a square of perforated plexiglas at the bottom of the riser, parallel to the top of the tunnel.

Spatial variations of mean velocity within the tunnel were reduced by inserting square-mesh screens, woven from stainless steel wire. These screens also permitted some control over the turbulence intensity and scale in the working section.

The velocity in the tunnel, for a typical set of damping screens, could be varied from about 1 to 6 ft./sec. in fifteen increments. For a cylinder of 1-in. diameter, at 20°C., this corresponds to a range of Reynolds numbers from 7,700 to 46,000.

At the present time there is no instrument commercially available for the reliable measurement of instantaneous point velocities in water. Several instruments are in the process of being developed. Attempts have been made to use standard hot-wire and hot-film anemometry (*13*), electrolytic methods (*23*), unplatinized conductivity probes (*7*), and electromagnetic induction techniques (*11*). An attempt has also been made to use stroboscopic photographic techniques involving colored droplets (*40*) with some success.

The method suggested by Schubauer (*27*) for measuring turbulence intensity involves measurement of temperature profiles downstream from a heated line source. The thermal wake of the heated wire spreads through the action of molecular diffusion and the effect of the free stream turbulence transverse to the axis of the wire. The method is well-known and will not be reviewed here. Suffice it to say that the angle subtended by the width of the wake, arbitrarily defined, is measured, and the angle characteristic of molecular diffusion solely is subtracted from it. The remaining angle is then assumed to characterize the effect of turbulence on the spread of the thermal wake. This angle is correlated with turbulence intensity measurements obtained with the hot-wire anemometer.

Since publication of this method, several investigators have shown the reliability of the method by checking it against measurements by hot wires (*1, 39*). Of more importance to the present investigation, where turbulence intensities were measured in the wake of a cylinder, is the further work of Corrsin and Uberoi (*4*) employing Schubauer's method to measure the intensity in the anisotropic turbulence of a jet. Intensities by this method were found to agree satisfactorily with hot-wire measurements of the transverse turbulence component up to an intensity of 20%.

Hegge Zijnen (*12*) measured turbulence intensities across a turbulent air jet using both hot-wire anemometers and heat diffusion and calculated longitudinal and transverse turbulent intensities using the equations of Hinze (*14, 15*). The method of Schubauer checks well with the calculated values of Hegge Zijnen, up to intensities of about 25%.

Hence it can with some justification be assumed that the application of Schubauer's method, even to the skew temperature profiles obtained in shear flow, yields values for the transverse turbulence intensity in fair agreement with hot-wire data for intensities up to about 25%.

One other source of error which should be examined is that pointed out by Townsend (*37*) and by Batchelor and Townsend (*2*). The effect of the turbulent motion on the thermal wake behind a line source is to stretch and rotate fluid elements, causing large local temperature gradients to be produced. This has the effect of accelerating the spread due to molecular diffusion, causing it to be larger than when the fluid is not turbulent. The equation of Batchelor and Townsend which takes this effect into consideration is

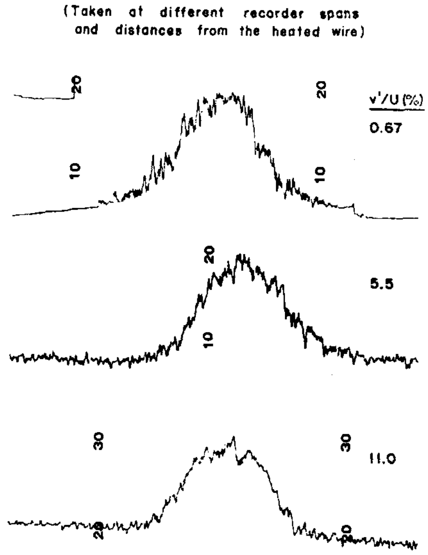

Fig. 2. Temperature profiles behind a line source.

$$\overline{Y_o^2} = \overline{Y^2} + 2K_T(t - t_o) + \frac{28}{45} K_T \frac{\epsilon}{\nu} (t - t_o)^3 \qquad (1)$$

The second term in the equation represents the direct contribution of molecular diffusion to the spread, which is considered in Schubauer's treatment. The third term represents the contribution to the spread from accelerated molecular diffusion, neglected in Schubauer's treatment. The third term may be calculated by using, as a rough approximation of the dissipation, the equation of Townsend (35):

$$\epsilon = \frac{3}{2} \frac{(\overline{u^2})^{3/2}}{L_\epsilon} \qquad (2)$$

where the dissipation scale is approximately equal to 1/5 the width of the mean flow variation. Such a calculation shows that the wake spread due to accelerated molecular diffusion in this study is less than ½% of the spread characteristic of the transverse intensity, both downstream from the screens and in the cylinder wake. The reasons causing the accelerated diffusion effects to be so small in the present cases are that the thermal diffusivity of water is very small, more than two orders of magnitude smaller than that for air; and that the time interval involved is small when measurements are made within 1 in. of the source at these water velocities.

The equation of Townsend (37) was derived to describe the interaction of molecular diffusion and turbulent motion which becomes appreciable at times such that

$$K_T(t - t_o) << 2\nu^{3/2}\epsilon^{-1/2}$$

is not satisfied. Although the equation of Saffman (25), which gives a different (negative) expression for the interaction, is an approximation to the same order of time as that of Townsend, Saffman states that his equation is "clearly of limited value since it becomes negative at $t - t_o$ increases. In fact (it) is unlikely to hold far outside its theoretical range of validity as given by" (the above equation).

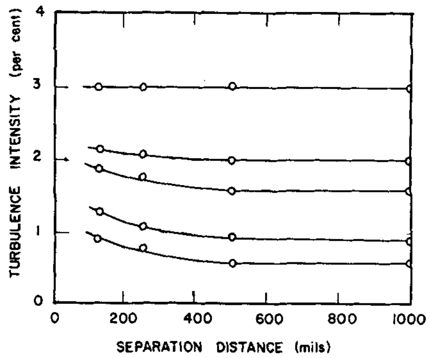

Fig. 3. Effect of distance between line source and resistance thermometer on calculated turbulence intensity.

For the purpose of the equation in this paper, that is to show that the magnitude of the interaction term is small, either interaction expression would suffice, since the interaction as given by Saffman is even smaller than that given by Townsend.

Use of Schubauer's Method in Water

The difficulty in the measurement of turbulence intensities in water with Schubauer's technique is occasioned by the magnitude of the temperature differences which must be measured. The following observations emphasize this difficulty. Working in a turbulent air jet Corrsin and Uberoi (4) report that the thermal wake behind a line source heated to 300° to 700°C. is barely detectable 1 in. downstream. For work in water the maximum wire temperature is, of course, 100°C. If equal volumes of air and water were to absorb the same quantity of heat from a source, the ratio of the temperature rise of the water to that of the air would be only 0.0004.

In the present investigation a heated wire of 0.0015-in. diameter, approximately 1 in. long, was used to approximate a line source. It was found that the temperature profiles downstream could be measured adequately with a resistance thermometer placed parallel to the source. For this purpose a tungsten wire of 0.001-in. diameter, approximately ½ in. long, was used. The probe used for the measurements is shown in Figure 1. The resistance thermometer was connected as one leg of a sensitive recording bridge, which could be read to six significant figures. The sensitivity limit corresponded to approximately 0.002°C.

The recording bridge constructed for this study is described in detail elsewhere (30, 31). Simple adjustments allow its use with alternating current as an impedance or conductivity bridge. The recorder slidewire is shunted with a three-dial decade box, allowing adjustment of the span in discrete steps. A recorder was employed, containing a sensitive 12X amplifier. The current to heat the line source was supplied by a 0.01% AC regulator, and was controlled with a variable autotransformer and a 44-ohm rheostat. The regulator was isolated from the control circuit by a 100-watt isolation transformer.

To facilitate the measurement of the temperature profiles the transversing probe was mounted on a micrometer screw and driven through the thermal wake at constant speed by a synchronous motor and a suitable gear train. The gear train allowed the probe to be driven through the wake at speeds from 0.0075 to 0.75 in./min. Thus a temperature profile behind the source could be recorded directly in a few minutes. Sample temperature profiles are shown in Figure 2 taken at different recorder spans and source-to-resistance-thermometer distances.

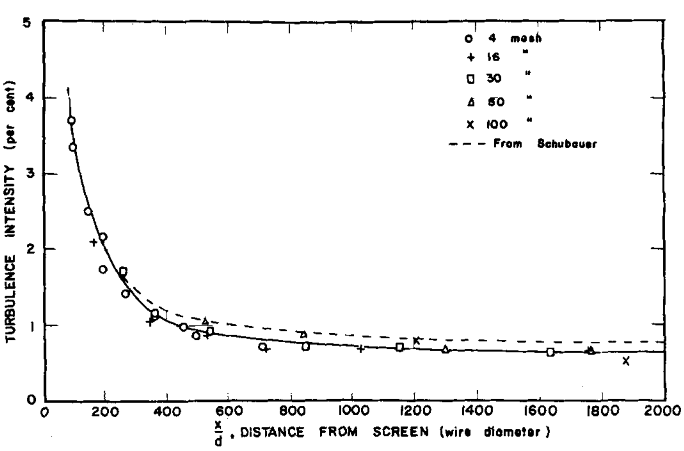

Fig. 4. Decay of turbulence downstream from wire screens.

For wires of the small diameters and large L/D used tungsten was the only material tried which would withstand the impact of the water very long. Platinum and nickel wires lasted less than 30 min. and stainless steel wires only a few hours. Tungsten wires had to be replaced every 10 to 15 operating hours, during which time their resistance gradually increased by about 5%. This was possibly caused by slow oxidation of the wires. During runs the effect on the background recorder trace of this slow change in resistance was cancelled by gradually cooling the water in the tunnel.

The tungsten wires were soft-soldered to the constantan support wires. Although a good soldered joint is not formed with the tungsten, the mechanical joint formed was stable enough that no difference could be detected between the signals and wake widths measured with the tungsten wires and those measured with platinum and nickel, both of which solder readily. Most intensities were calculated from the average value of the thermal width determined from six separate temperature profiles. Standard deviations for representative sets of six profiles varied from approximately 2% for intensities near 1% to about 5% for intensities near 11%. Reproducibility was approximately ± 5%.

In the present investigation measurements of turbulence intensity were made with the distance between source and resistance thermometer varied from 1/16 to 1-⅛ in. The effect of this distance on the calculated turbulence intensity is shown in Figure 3. For intensities above approximately 3% no appreciable effect of separation was noted. This is in agreement with the result of Schubauer. Separations as small as 1 mm. were used by Hegge Zijnen for intensities of approximately 15%. All present measurements of intensities below

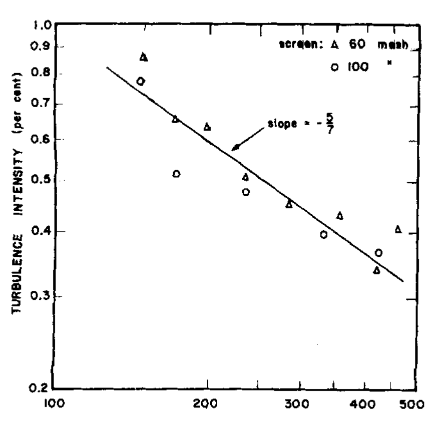

Fig. 5. Background turbulence from turning vanes.

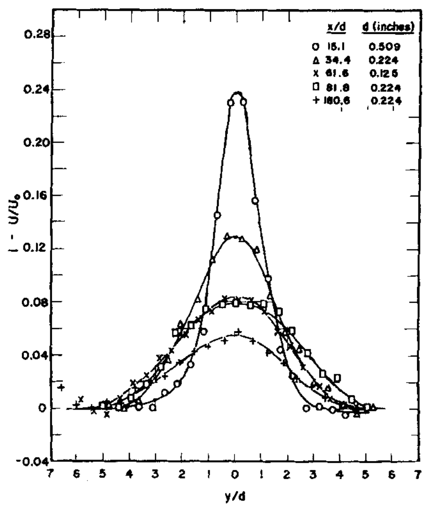

Fig. 6. Velocity profiles.

2.5% were made with a separation of approximately 1 in. Velocities were measured with total head tubes of 1/16- and 1/8-in. O.D. and an inclined water manometer and were found reproducible to ± 1%. The readings were not corrected for effects of turbulence or mean velocity gradients.

DECAY OF TURBULENCE DOWNSTREAM FROM SCREENS

As a check on the performance of the intensity measurement apparatus in the system, and also to determine if the decay of intensity of turbulence behind screens in water resembles that in air, decay curves were measured in the water tunnel downstream from screens of 4, 16, 30, 60 and 100 mesh, having wire diameters of 0.063, 0.016, 0.01, 0.0065, and 0.0045 in., respectively. The results are shown in Figure 4, where the dotted line represents the data obtained by Schubauer in a wind tunnel at the National Bureau of Standards. Attempts were made to measure the decay behind a 250-mesh screen, but it was impossible to keep bubbles from collecting on the upstream side of the screen and disturbing the turbulence field downstream.

The only decay data in the literature taken in water are those of Vanoni and Brooks (*40*) for the initial period of decay, or approximately 100-mesh lengths. These data agree well with the present data.

Baines and Peterson (*1*) made many measurements in air of decay behind grids of many different types and sizes, using both the hot-wire anemometer and the diffusion of heat and mass from sources. Their data obeyed the decay law of Frenkiel (*10*); that is

$$\frac{u'}{U} = A\left(\frac{x}{d}\right)^{-5/7} \qquad (4)$$

This decay law was followed well by the data obtained in this study up to distances of about 500 wire diameters downstream, after which the decay was too slow. Taylor (*33*) was led to infer that the slowness of decay in Schubauer's data for similar distances downstream was caused by the slow decay of background turbulence of large scale. Since data of the present study exhibit the same trends as do Schubauer's data, an attempt was made to substantiate Taylor's reasoning from the data of this study.

One obvious source of background turbulence in the water tunnel was the row of turning vanes upstream from the screen section. Figure 5 shows the slow-decay data plotted as a function of the downstream distance from these turning vanes in vane diameters. It is evident that the turbulence far downstream of the screen is decaying at a rate which is characteristic of the turbulence from these vanes.

It should be noted that the present decay data also follow the prediction of Batchelor and Townsend (*3*)

$$\left(\frac{\overline{U}}{u'}\right)^2 \alpha \frac{x}{M} \qquad (5)$$

out to about 100-mesh lengths about as well as the prediction of Frenkiel. Unfortunately, for decay in the intensity range from 0.9% to 3%, very accurate data are required to differentiate between the two decay predictions. For higher intensities the data of Baines and Peterson tend to favor Frenkiel's decay law.

VELOCITY AND TURBULENCE INTENSITY PROFILES

Cylinders

The hollow, porous wall cylinders used in the investigation were specially fabricated from alundum. This material has a porosity of approximately 30% and a particle retention

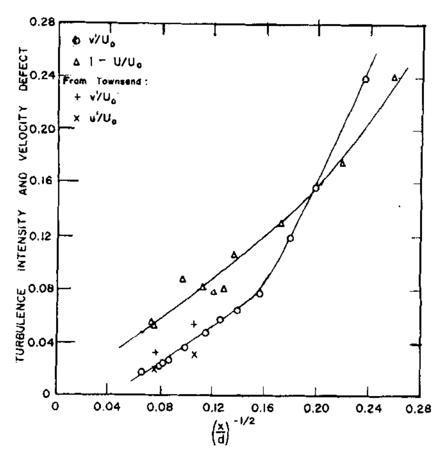

Fig. 7. Peaks of turbulence intensity profiles and velocity defect profiles vs. distance from cylinder.

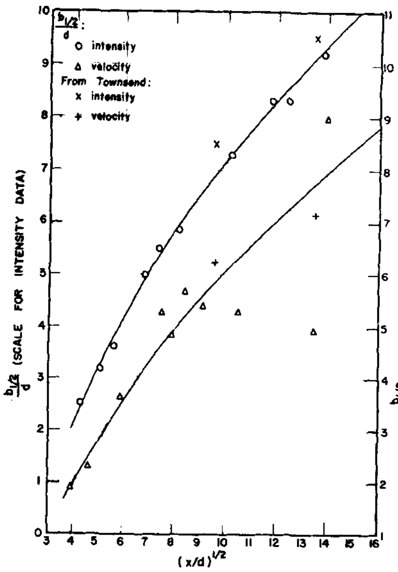

Fig. 8. Half widths of turbulence intensity profiles and velocity profiles vs. distance from cylinder.

size of 20 μ. The cylinders were 8 in. long and of three diameters: 0.145-, 0.224-, and 0.509-in. O.D. Short lengths of ⅛-in. stainless steel tubing were cemented to the end of the tubes, with a polymerizable acrylic plastic powder which is mixed with a liquid monomer prior to use. The steel tubes were inserted through packing glands to hold the cylinders in place in the tunnel. (The cylinder porosity characteristics were of importance in Part II of this paper.)

Velocity Profiles

Velocity profiles were measured in the wakes of the two larger cylinders and ⅛-in. O.D. stainless steel tubing. Sample profiles, normalized to the dimension of the 0.224-in. cylinder, are shown in Figure 6. Plots of peak velocity defects and profile half widths as functions of downstream distance are shown in Figures 7 and 8.

Turbulence Intensity Profiles

Turbulence intensity profiles were measured in the wakes of the three alundum cylinders and in the wake of a ¼-in. diameter smooth brass cylinder. Sample profiles are shown in Figures 9 and 10 normalized in terms of the 0.224-in. cylinder. The high intensities were obtained with small distances separating the heated wire and the resistance thermometer. This served to make the temperatures large enough to sense with reasonable accuracy and to reduce the variation of velocity and intensity over the measured width of these wide-angle wakes. Above about 12% turbulence intensity the accuracy of the method became poor, and the measurements were used only to indicate the trend of the data.

The half widths of the profiles and the intensities at wake center are also shown as functions of the downstream distance in Figures 7 and 8. The intensities at wake center are seen to compare reasonably with those of Townsend.

It is of interest to note that a double peak in the intensity profiles begins to appear at about 55 to 60 cylinder diameters downstream. Townsend (*36*) made careful intensity measurements with the hot-wire anemometer in the wake of a cylinder and also reported such double peaks. However Townsend notes the phenomenon for the u and w components of velocity, whereas the present method supposedly measures only the v component. The two measuring methods are, of course, fundamentally different, the hot-wire measurements being essentially point values, while the diffusion method depends on wake spread over a finite distance. Hinze and Hegge Zijnen (*12, 14, 15*) indicate that the wake spread is related to both the lateral and longitudinal intensities, but the data of the present investigation are not of sufficient accuracy to permit application of their equations. It appears from Figure 7 that the peak transverse intensities 100 to 200 diam. downstream as measured by the diffusion method fall between the u and v component intensities measured by Townsend. A more detailed experimental and theoretical investigation of the phenomenon is required to provide a satisfactory explanation.

CONCLUSIONS

Velocity profiles in the wake of a cylinder oriented perpendicular to the main flow stream in the working section of a water tunnel were measured. Reynolds numbers for the flow based on cylinder diameter and mesh size of

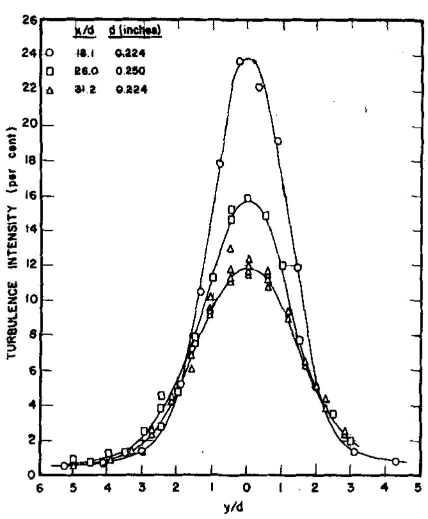

Fig. 9. Turbulence intensity profiles.

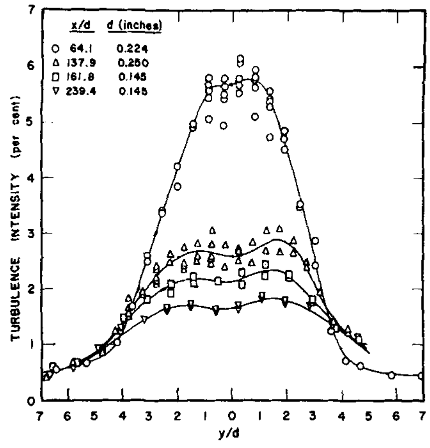

Fig. 10. Turbulence intensity profiles.

the screens in the flow straightening sections clearly indicate that the cylinder was primarily responsible for the turbulence generated.

An instrument for measuring turbulence intensity in water has been developed, based on the method of Schubauer, and used to measure turbulence intensity profiles in the wake. These are likewise reported.

These data will be used in Part II of this report along with concentration data to calculate local values of the turbulent mass transfer coefficient in the wake of the cylinder.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance of Mr. J. Fred Maienshein of the Minneapolis-Honeywell Regulator Company. We are also appreciative of the efforts of Mr. Bernard Baker, who competently performed the many machining operations required in the construction of the equipment.

The authors are indebted to the Wilbur B. Driver Company, of Newark, New Jersey, and the Thermionic Products Company, of Plainfield, New Jersey, for the donation of generous samples of wire for the project.

The funds necessary for the support of the project were supplied by the National Science Foundation in the form of a grant.

During his terminal year one of the authors held the American Cyanamid Fellowship, and he wishes to express his appreciation for this assistance.

NOTATION

- A = constant
- $b_{1/2}$ = wake width at one half the peak value
- d = diameter of cylinder or screen wire
- K_T = thermal diffusivity
- L_ϵ = dissipation length scale
- M = mesh length
- t = time
- t_o = time at beginning of diffusion
- U = velocity in x-direction

U_o = mean velocity external to the wake

u, v, w = fluctuating components of velocity

u', v' = root-mean-square fluctuating velocities

x = distance from cylinder (or screen) in the direction of bulk flow

$\overline{Y^2}$ = mean - square displacement from wake center

$\overline{Y_\theta^2}$ = mean square displacement in thermal wake, measured

ν = kinematic viscosity

ϵ = dissipation of turbulence per unit mass

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Part II.

Calculation of Local Turbulent Mass Transfer Coefficients in the Turbulent Wake of a Cylinder

Turbulent mass-transfer coefficients were calculated from concentration profiles obtained in the wake of a hollow cylinder having a porous wall through which a solution of electrolyte was flowing. These coefficients are presented as functions of the turbulence intensity and the width of the transport region. This paper is a continuation of the previous report on this subject and utilizes the results presented earlier.

Interest in liquid phase catalytic reactions and heat transfer has served to focus attention on those physical properties of flowing liquids which determine their ability to transfer heat and mass. Since one of the characteristics of turbulence is its ability to disperse local concentrations of heat and mass very rapidly, interest in turbulent dispersion has developed rapidly.

At present turbulent transport phenomena are usually treated from mixing-length theories and by analogy with molecular diffusion. A complete understanding of the observable phenomena must await a satisfactory elucidation of turbulent shear flow. However correlations which will allow estimation of turbulent transport coefficients remain necessary for engineering purposes. Such correlations are conspicuously lacking for the liquid phase.

This paper is Part II of a report from a study of turbulent diffusion in the liquid phase. Part I was concerned with the fluid mechanical details in the wake of a cylinder oriented perpendicularly to the mean flow in the working section of a water tunnel. In the center of such a wake there is a strong variation of turbulence intensity in the downstream direction, and this variation occurs within a convenient distance from the cylinder. A hollow cylinder with a porous wall was used in order that a wake of electrolyte could be established downstream by forcing a solution of electrolyte through the porous wall. Concentration profiles were obtained at various stations in the wake, and the turbulent mass transfer coefficients were calculated from these profiles.

EXPERIMENTAL PROCEDURES AND MEASUREMENT TECHNIQUES

The Water Tunnel

The study was conducted in the controlled and reproducible flow field of a water tunnel. This tunnel has been described elsewhere, and the details of its construction and operation will not be reproduced here.

Measurement of the Turbulence Variables

A knowledge of the velocity profiles and turbulence intensities at various points