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

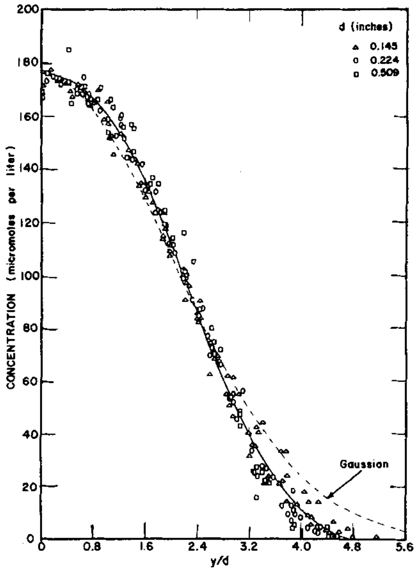

Fig. 1. Composite concentration profile for all data scaled to arbitrary half width and peak concentration.

throughout the wake of the cylinder was necessary in order to compute and correlate the mass transfer coefficients. The details of these measurements and the results are presented in Part I of this paper.

Measurement of Concentration

Filtered solutions of reagent grade potassium nitrate were used as the electrolyte. This was pumped through the wall of the cylinder from a reservoir feed control metering system at such a flow rate that the dilution ratio of the main stream was of the order of 1,000/1. Hence it is inconceivable that this stream flowing through the wall of the cylinder could have had a measurable effect on the flow field. Furthermore since measurements were made in a wake, since primary interest of this work was on diffusion in a wake, and since measurements were made far downstream from the wake source, the question of the effect of electrolyte flow through the cylinder is rather irrelevant. This point was not investigated further. Temperature control in the injection system was to within ± 0.1°C. The system allowed the flow rate to be held constant to within 0.5% of the mean value over a range of 30 to 180 cc./min.

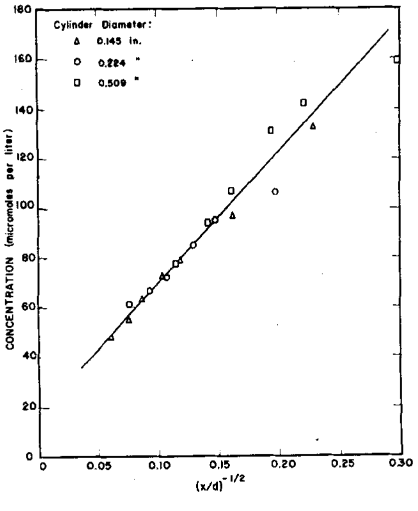

Fig. 2. Variation of peak concentration with distance from cylinder.

Sensing Instrument

The sensing instrument employed for concentration measurement was an electrical conductivity probe. The construction and operation of this device and its associated equipment are discussed elsewhere (8, 9) and will be only briefly summarized here.

Concentration fluctuations in the electrolyte wake were too large and rapid to allow average concentration measurements to be made with standard conductivity equipment or with other AC bridges with standard null detectors. Furthermore since some of the large scale fluctuations appeared to be in the frequency range less than 1 cycle/sec., a device was required which would average over long time periods to allow mean values of concentration to be determined with fair precision.

A suitable averaging device was constructed employing the thermal lag of a mass of material to damp the fluctuations. The construction, operation, and characteristics of this device are described in detail elsewhere (8, 9).

For purposes of discussion a time constant is defined as the period of time required for the bridge recorder trace (proportional to concentration at the probe location) to move from one equilibrium position to another (within the limits of stability and readability of the recorder) after a step change in the resistance of the conductivity probe. The time constants of the thermal averaging devices varied according to their construction from 15 sec. to about 6 min. Modifications of this device will allow time constants of about 20 min. to be attained. For the concentration measurements made in this investigation thermal averaging devices having time constants of approximately 1¼ min. were used. It has subsequently been noted that a similar device, apparently having a small time constant, was employed by Kestin and Maeder (5).

The system could be made very sensitive to changes in average voltage or current. Variations in average voltage of ± 0.005% have been detected.

Since the water tunnel is closed-return and hence continuously circulates the same water, the background conductivity rises as a run is made with electrolyte flowing through the wall of the cylinder. This effect was cancelled by placing a compensating circuit, similar to the measuring circuit, in an arm of the bridge adjacent to the measuring arm. The compensating probe was placed outside the electrolyte wake, where it sensed only the background concentration. Cross talk, or mutual interference between the two cells, was eliminated by powering each cell circuit from a separate isolation transformer. Calibration procedure, a schematic diagram of the circuit, and operating procedure are also detailed elsewhere (8, 9).

Run Procedure

With no electrolyte flowing and the measuring probe at a fixed position in the wake the recorder pen was allowed to come to the equilibrium position characteristic of background tap water at 25.1°C. The electrolyte flow was started and slowly increased to the predetermined value for the series of runs. The pen moved to a position characteristic of the concentration above the background at that point. After 1½ to 2 min. the probe was moved to another position. The latter portion of the trace during this interval was interpreted from the calibration plot.

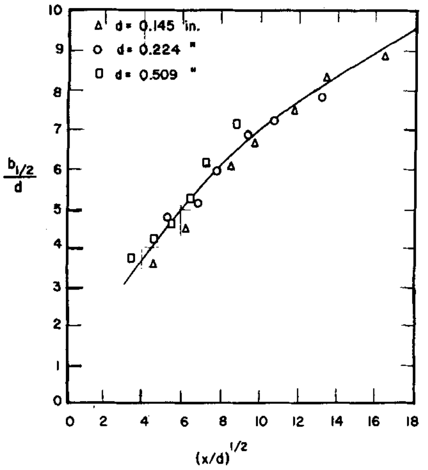

Fig. 3. Half widths of concentration profiles vs. distance from cylinder.

RESULTS

Concentration Profiles

Concentration profiles in the wakes of all cylinders used were found to be similar when normalized in terms of an arbitrary peak concentration and half width. The normalized profiles from all three cylinders are shown in Figure 1. To permit use of this similarity plot for smoothing purposes smoothed curves of peak concentration and wake half width as functions of downstream distance were constructed. The peak concentration was plotted vs. $\left(\frac{x}{d}\right)^{-1/2}$, which is pre-

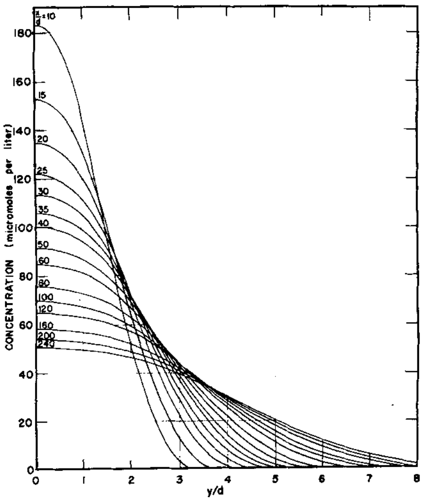

Fig. 4. Smoothed concentration profiles.

Table 1. Comparison of Heat and Mass Transfer Coefficients from Equation (9) With Previous Investigation

Reference	U, (ft./sec.)	$\frac{u'}{U}$, (%)	b, (in.)	Transfer coefficient, (sq. ft./hr.)	
				Measured	From Equation (9)
Isakoff and Drew, "Proc. Gen. Disc. on Heat Transfer," Inst. of Mech. Eng. and ASME, London (1951), heat transfer in mercury, fully-developed turbulent flow in pipes	0.98	3	1.5	0.818	1.08
Page, Schlinger, Breaux, and Sage, *Ind. Eng. Chem.*, **44**, 424 (1952), heat transfer in air, two-dimensional channel flow	60.	3	0.7	32.4	31.0
McCarter, Stutzman, and Koch, *Ind. Eng. Chem.*, **41**, 1290 (1949), heat transfer in air, turbulent flow in a round tube	7.16	3	8.0	60.	42.3
Sherwood and Woertz, *Ind. Eng. Chem.*, **31**, 1034 (1939), diffusion of water vapor in air, helium and carbon dioxide, two-dimensional channel flow	32.8	4	2.0	71.6	64.6
Dhanak, *A.I.Ch.E. Journal*, **4**, 190 (1958), diffusion of water vapor in air, two-dimensional channel flow	49.8	3	1.925	64.8	70.7
Towle and Sherwood, *Ind. Eng. Chem.*, **31**, 457 (1939), diffusion of carbon dioxide and hydrogen in air, point source in fully developed turbulent duct flow	32.	3	6.0	93.	142
Schwarz and Hoelscher, *A.I.Ch.E. Journal*, **2**, 101 (1956), diffusion of water in air, fully developed turbulent pipe flow†	14.5	3	3.33	20	35.6
Mickelsen, *NACA Tech. Note No. 3570* (1955), diffusion of helium in air, point source in fully developed turbulent pipe flow**	50	3.4	8	138	334
	75	3.3	8	199	387
	122	3.15	8	774	756
	160	3.0	8	884	945
Schlinger and Sage, *Ind. Eng. Chem.*, **45**, 2636 (1953), diffusion of natural gas in air, large source in a round tube	50	3	2.5	37.8	92.3
Kalinske and Pien, *Ind. Eng. Chem.*, **36**, 220 (1944), diffusion of a mixture of HCl and ethanol in water, flow in an open water channel††	1.8	4.2	7.4	4.7	13.8
Flint, Kada, and Hanratty, *A.I.Ch.E. Journal*, **6**, 325 (1960), diffusion of KCl in water, point source in turbulent pipe flow***	0.435	5	3.0	0.547	1.6
	2.16	4.5	3.0	2.74	7.2
	3.8	4	3.0	2.74	11.2

* Measured diffusivities taken from the farthest downstream position, so the turbulence could be considered characteristic of the duct.

† Measured diffusivities vary from 0 to 30 sq. ft./hr. as a smooth function of radius; 20 sq. ft./hr. is a rough average figure.

** Measured values obtained from integration of reported spreading coefficients, taken far downstream, of the duct.

†† All values are average of reported data.

*** From data at Reynolds Numbers of 10,000, 50,000, and 88,000.

dicted by Batchelor (*1*) to be linear far downstream from the source. As shown in Figure 2 the linear relationship was found to describe the results quite satisfactorily and was used as an approximation close to the cylinder, where the data scatter somewhat. A plot of the wake half width vs. $\left(\frac{x}{d}\right)^{1/2}$, which Batchelor also predicts to be linear far downstream, is shown in Figure 3. From these smoothed curves concentration profiles were calculated and are shown in Figure 4. These profiles were used for the graphical calculation of mass transfer coefficients.

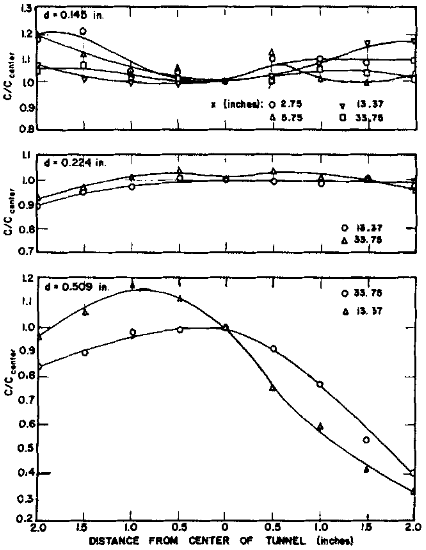

Fig. 5. Concentration profiles parallel to cylinders.

Concentration profiles were also taken parallel to the cylinder, near the wake center, to determine how far the wakes departed from being two dimensional. These profiles are shown in Figure 5, where it is seen that the profiles for the 0.509-in. cylinder depart rather strongly. However, excepting the profile nearest the 0.509-in. cylinder, the gradients parallel to the axis of the cylinder are much smaller than the transverse gradients. Thus it would be expected that the profiles parallel to the cylinder would not appreciably change shape with increasing downstream direction. Such is seen to be the case.

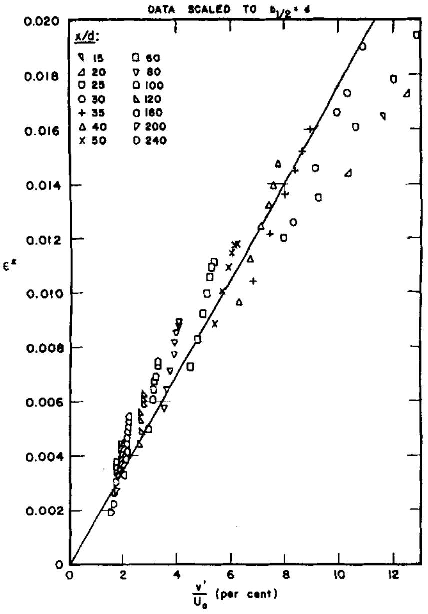

Fig. 6. Variation of dimensionless transfer coefficient with turbulence intensity.

Table 2. Comparison of Turbulent Schmidt and Prandtl Numbers

Reference	Fluid	N_{Sc_T}	N_{Pr_T}
Present work	Water	0.46-0.93	
Forstall and Gaylord (*9*)	Water	0.75-0.965	
Sherwood and Woertz (*7*)	Air, CO_2, He,	0.63	
Hinze (*4*)	Air	0.77	
Schwarz and Hoelscher (*6*)	Air	1-2	
Corrsin and Uberoi (*2*)	Air		0.70
Townsend, (*10, 12*)	Air		0.60

TURBULENT MASS TRANSFER COEFFICIENTS IN THE WAKE OF A CYLINDER

The application of Reynolds' restrictions to the two-dimensional diffusion equation for the flowing system gives

$$\overline{U}\frac{\partial \overline{C}}{\partial x}+\overline{V}\frac{\partial \overline{C}}{\partial y}=D\left[\frac{\partial^2 \overline{C}}{\partial x^2}+\frac{\partial^2 \overline{C}}{\partial y^2}\right]-\frac{\partial}{\partial x}(\overline{u\,c})-\frac{\partial}{\partial y}(\overline{v\,c}) \qquad (1)$$

where the overbars represent time averages, and u, v, and c are the fluctuating components of velocity and concentration. Applying a boundary-layer type of approximation one gets

$$\frac{\partial^2 \overline{C}}{\partial x^2} << \frac{\partial^2 \overline{C}}{\partial y^2} \qquad (2)$$

and

$$\frac{\partial}{\partial x}(\overline{u\,c}) << \overline{U}\frac{\partial \overline{C}}{\partial x} \qquad (3)$$

Particularly for liquids, where D is small, molecular diffusion as characterized by $D\dfrac{\partial^2 \overline{C}}{\partial y^2}$ is very small compared with turbulent transport. Since $\overline{V} = 0$ in a two-dimensional wake, the equation is

$$\overline{U}\frac{\partial \overline{C}}{\partial x} = -\frac{\partial}{\partial y}(\overline{v\,c}) \qquad (4)$$

Integrating with respect to y one obtains

$$(\overline{v\,c}) = -\int_0^y \overline{U}\left(\frac{\partial \overline{C}}{\partial x}\right)dy \qquad (5)$$

This equation allows calculation of the turbulent flux of contaminant $(\overline{v\,c})$ from velocity and concentration profiles. A turbulent transfer coefficient may be defined in the standard form as the ratio of the flux to the negative gradient:

$$\epsilon = -\frac{(\overline{v\,c})}{\partial \overline{C}/\partial y} \qquad (6)$$

In dimensionless form

$$\epsilon^* = \frac{U_o d \displaystyle\int_0^{y^*} U^*\left(\frac{\partial C}{\partial x^*}\right)dy^*}{\partial \overline{C}/\partial y^*} \qquad (7)$$

Mass transfer coefficients of this form were calculated from the smoothed concentration profiles. The integration and both differentiations were performed graphically.

Two further considerations are necessary before the mass transfer coefficients can be properly interpreted. The description of mass transfer by a differential equation presupposes a continuous flow pattern. Measurements by Townsend (*11*) of the intermittency factor in a turbulent wake show that a continuous flow pattern exists only in the central portion of the wake. The intermittency factor may be roughly defined as the fraction of time that fully turbulent fluid is present at the measuring point. It will be assumed that the mass transfer coefficients calculated in this study are valid only in this central region. From the data of Townsend the intermittency is above 0.9 from the center of the wake out to about 0.88 times the half width of the momentum wake. This corresponds to approximately 0.6 times the half width of the concentration wake. This will arbitrarily be considered the region in which the present analysis retains validity.

The calculated transfer coefficients were found to vary approximately as the half width of the wake and the intensity. To obtain a plot of the transfer coefficient as a function only of the root-mean-square fluctuating velocity all transfer coefficients were scaled to the same arbitrary half width of one cylinder diameter and plotted vs. the turbulence intensity in Figure 6. The line may be represented by the equation

$$\epsilon^* = 0.176\left(\frac{b_{1/2}}{d}\right)\left(\frac{v'}{U_o}\right) \qquad (8)$$

Since the width of the transport region was about 2.15 times the half width, the transfer coefficient may be written as

$$\epsilon = 0.082\, U_o\, b\left(\frac{v'}{U_o}\right) \qquad (9)$$

A detailed analysis of errors of this result could not be justified at this time. Considering the graphical operations which were required and the contribution of the error generated by this calculational procedure, and considering uncertainties in the data and error generated from the necessary smoothing technique, one can estimate the uncertainty of the correlation presented by Equation (8) to be approximately 40%. It was concluded that the graphical differentiation of the smooth concentration profiles contributed less uncertainty to the result than did the smoothing operation from the raw data.

Complete graphical calculations were also carried out for each set of concentration profiles separately. These results are shown in Figure 7, where the lines represent the correlation obtained from the smoother calculations. The major portion of the scatter is seen to be within the estimated accuracy of the correlation.

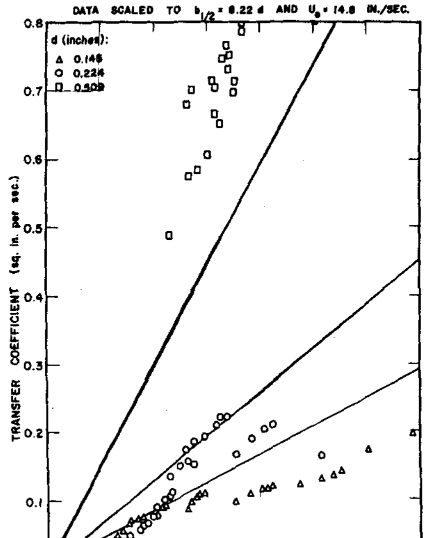

Fig. 7. Transfer coefficients from concentration profiles for each cylinder compared with lines from correlation equation.

Comparison with Previous Work

From Equation (9) predictions accurate to within about 40% may be made for those previous investigations for which the turbulence conditions can be estimated. Since the equation contains only fluid mechanical variables, it may be useful in describing heat transfer as well as diffusion. Table 1 presents turbulent diffusivities of both heat and mass obtained by other investigators, estimates of the width of the transport region and turbulence intensity in which they worked, and the diffusivities which would be predicted by the correlation from the present study. For those cases in which the width of the transport region is well-defined, such as for pipe flow and two-dimensional channels, agreement is seen to be within the accuracy of the correlation. For the cases of diffusion from point sources it was impossible to know whether the turbulent scale was characteristic of the varying transport region or of the width of the flow system. For these cases only the roughest of estimations were made for conditions far downstream from the source in order that the characteristic width related to the scale of turbulence could be considered the duct width. For these cases the predicted coefficients are seen to be in only order-of-magnitude agreement.

If the transfer coefficient is considered to be the product of the root-mean-square fluctuating velocity and a characteristic diffusion scale or mixing length, this scale is found to be 0.176 times the half width.

As discussed in Part I of this work the proposed correlation of Sherwood and Woertz (Table 1) giving the product of diffusivity and gas density as a function of Reynolds number predicts diffusivities much lower than those obtained by Kalinske and Pien (Table 1). Their correlation also yields diffusivities much lower than those found in the present work. Since density is not a variable in their correlation, and since their work was carried out in a single geometry with a percentage variation in viscosity no larger than the scatter of the data, what is shown is the relation of the diffusivity and velocity. A plot of their diffusivity values vs. velocity gives a linear correlation of their data, and values from this correlation agree well with transfer coefficients from the present work. It appears then that the turbulent transfer coefficients are independent of the physical properties of both the flowing medium and the diffusing substance.

Turbulent Schmidt Number

The velocity data in the cylinder wake were not of sufficient accuracy to justify detailed point calculations of the eddy viscosity. However a rough estimate of the over-all turbulent Schmidt number can be obtained by the simplified procedure of Forstall and Gaylord (3). From the assumption of gradient diffusion

$$(\overline{u\,v}) = -\nu_T \left(\frac{\partial U}{\partial y}\right)$$

$$(\overline{v\,c}) = -\epsilon \left(\frac{\partial C}{\partial y}\right) \qquad (10)$$

For the rough approximation that the velocity and concentration profiles are similar

$$\frac{\nu_T}{\epsilon}\,\frac{d\left(\frac{U}{U_{\max}}\right)}{U/U_{\max}} = \frac{d\left(\frac{C}{C_{\max}}\right)}{\frac{C}{C_{\max}}} \qquad (11)$$

If N_{Sc_T} is assumed constant

$$\frac{C}{C_{\max}} = \left(\frac{U}{U_{\max}}\right)^{N_{Sc_T}} \qquad (12)$$

Now the admittedly rough approximation is made that the concentration and velocity profiles are Gaussian. Thus

$$\frac{U}{U_{\max}} = \exp\left[-0.694\left(\frac{y}{y_{1/2}}\right)_u^2\right]$$

$$\frac{C}{C_{\max}} = \exp\left[-0.694\left(\frac{y}{y_{1/2}}\right)_c^2\right] \qquad (13)$$

whence

$$N_{Sc_T} = \left[\frac{(y_{1/2})_u}{(y_{1/2})_c}\right]^2 \qquad (14)$$

Values of the turbulent Schmidt number calculated from the data of the present investigation vary from 0.46 at 30 diam. downstream to 0.93 at 230 diam. A weighted average for the entire flow field would be 0.73 Comparison of these values with the literature is shown in Table 2.

CONCLUSIONS

Local turbulent mass transfer coefficients have been reported for liquid phase turbulent diffusion in the wake of a cylinder.

The turbulent mass transfer coefficient has been shown to be an approximately linear function of velocity, turbulence intensity, and the width of the transport region.

When proper adjustments are made for the above variables, the correlation presented has been shown to allow estimation of transfer coefficients for heat and mass transport in both liquids and gases.

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NOTATION

b = width of transport region
$b_{1/2}$ = wake width at one half the peak value
C = concentration
c = fluctuating component of concentration
D = molecular diffusivity
d = diameter of cylinder or screen wire
U = velocity in x direction
U_o = mean velocity external to the wake
U^* = U/U_o
V = velocity in y direction
u, v = fluctuating components of velocity
u', v' = root-mean-square fluctuating velocities
x = distance from cylinder (or screen) in the direction of bulk flow
x^* = x/d
y = distance from the center of the wake, perpendicular to the plane of the wake
$y_{1/2}$ = y at the point where concentration or velocity defect is half the value at wake center
y^* = y/d
ϵ = turbulent transfer coefficient
ϵ^* = dimensionless transfer coefficient
ν_T = turbulent kinematic viscosity
N_{Pr_T} = turbulent Prandtl number
N_{Sc_T} = turbulent Schmidt number

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