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THE FLOW AND DIFFUSION STRUCTURE IN THE WAKES OF CYLINDRICAL OBSTACLES

by

Kiran M. Kothari*, Robert N. Meroney, and Jon A. Peterka

1.0 INTRODUCTION

The paper presents wind-tunnel study of momentum and vortex wakes of cylindrical obstacles deeply submerged in a neutral turbulent boundary layer. The aims of the research were to determine flow and diffusion characteristics in the wake of cylindrical obstacles. The tests were performed in the low speed Industrial Wind Tunnel located in the Fluid Dynamics and Diffusion Laboratory at Colorado State University.

A surface obstacle in the planetary boundary layer creates a wake behind the obstacle. The wake is generally characterized by increased turbulence intensity and decreased mean longitudinal velocity and an obstacle wake of this type is known as a Momentum Wake. Passage of a shear flow around a surface obstacle also creates a system of longitudinal vortices in the wake and obstacle wake of this type is classified as a Vortex Wake. The vortex brings higher momentum, less turbulent fluid from higher elevations of the turbulent boundary layer to increase the mean velocity and decrease the turbulence intensity near the wake centerline. Hansen et al. (1975) and Woo et al. (1976) have observed these vortices in the obstacle wake. Kothari et al. (1980) have evaluated the effects of momentum and vortex wake on mean velocity and temperature in the wake of obstacle placed in a stably stratified turbulent boundary layer. Yang and Meroney (1970) have performed the gaseous dispersion into stratified building wakes. Huber and Snyder (1976) have developed a prediction technique for pollutant concentration in building wakes utilizing the decay rate of excess turbulent intensity from Peterka and Cermak (1975). No systematic experiments are known to the authors for diffusion in the wakes of cylindrical obstacles.

2.0 EXPERIMENTAL METHODS

All experimental measurements were performed in the Industrial Aerodynamics Wind Tunnel. Simulation of the atmospheric boundary layer criteria has been discussed by Cermak (1975), and Cermak and Arya (1970).

The experimental measurements of wake and concentration were performed behind the following three cylinders: 1) height to diameter ratio of one with smooth cylindrical surface (cylinder 1), 2) height to diameter ratio of one with rough cylindrical surface (cylinder 2), 3) height to diameter ratio of two with rough cylindrical surface (cylinder 3).

Measurements of mean velocity and turbulence intensity were accomplished with a single hot-wire anemometer. A series of wake

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Fluid Mechanics and Wind Engineering Program, Colorado State University, Fort Collins, Colorado 80523 measurements were made at x/D values of 3, 5, 7.5 and 10 at various vertical locations along the centerline with and without the obstacle. All velocity defect values were calculated by finding the difference between velocity at a point in the wake and velocity at the same point in the absence of obstacle.

The experimental measurements of turbulent diffusion in the wakes of the same cylinders were performed for three sources located along the centerline of the obstacle: at half diameter upstream at the ground (release location B), at half diameter downstream at the ground (release location A), and at the roof top cylinder center (release location C). Hydrocarbon tracer gases mixed with N_2 and CO_2 were utilized to obtain neutrally buoyant tracer gases. The gases were released at such rates to have no appreciable plume rise. The gas samples were collected downwind of the obstacles at x/D equal to 1, 3, 5, 10, 15 and 20. The collected samples were then analyzed through gas chromograph.

The concentration data was reduced to a nondimensional concentration coefficient, K. The coefficient K is determined from

$$K = \frac{\chi U A}{Q},$$

where

χ = the local concentration (ppm),
U = the velocity at the cylinder height (m/sec),
A = projected area of the cylinder to the approaching wind (m^2),
$Q = \chi_s \forall_s$,
χ_s = source strength (ppm),
$\forall_s$ = source volume flow rate (m^3/sec).

3.0 THEORETICAL METHODS

A theoretical foundation for building wake flow structure has been developed by Hunt and Smith (1969). Momentum wake theory is based on the assumption that only small perturbations of velocity and turbulence intensity are caused by the obstacle, that the eddy viscosity is constant, and that the approach flow mean velocity profile power-law exponent n << 1. For a three-dimensional building and small n, Hunt's theory predicts that the mean velocity defect decays as $x^{-1.5}$. A similar prediction of the turbulence intensity excess variance decay rate of x^{-2} was proposed by Hunt (1971).

Peterka and Cermak (1975) observed horseshoe vortices downwind of the idealized building structure. Noting these results, Hunt (1975) developed a vortex wake theory to account for the effects of these horseshoe vortices. The longitudinal velocity excess due to a vortex in inviscid zone was determined by Hunt (1975). The excess velocity perturbation predicted by Hunt (1975) was doubled to account for two horseshoe vortices, one on each side of the cylinder, observed in the wake of the cylinder. Both these momentum and vortex wake theories will be evaluated and compared with the present velocity measurements.

4.0 RESULTS

The mean velocity, turbulence intensity and turbulent diffusion measurements in the wakes of cylindrical obstacles are discussed in this section. The mean velocity defect, Delta U, and turbulence intensity excess variance, Delta U VAR, are defined as follows:

$$\text{Delta U} = \left(\frac{U(z)}{U_\infty}\right)_{\text{without cylinder}} - \left(\frac{U(z)}{U_\infty}\right)_{\text{with cylinder}} ,$$

$$\text{Delta U VAR} = \left(\frac{u_{rms}(z)}{U(z)}\right)^2_{\text{with cylinder}} - \left(\frac{u_{rms}(z)}{U(z)}\right)^2_{\text{without cylinder}}{}'$$

where $u_{rms}(z)$ is the root mean square (rms) of velocity at height z.

At the entrance of the test section spires and trip were utilized. The wind-tunnel floor was covered with 1.27 cm high roughness element to generate the fully developed turbulent boundary layer, shown in Figure 1, approaching the obstacles. The velocity profile power-law exponent, n, characteristic roughness, z_o, and friction velocity, u_*, were 0.21, 0.23 cm, and 15 cm/sec, respectively.

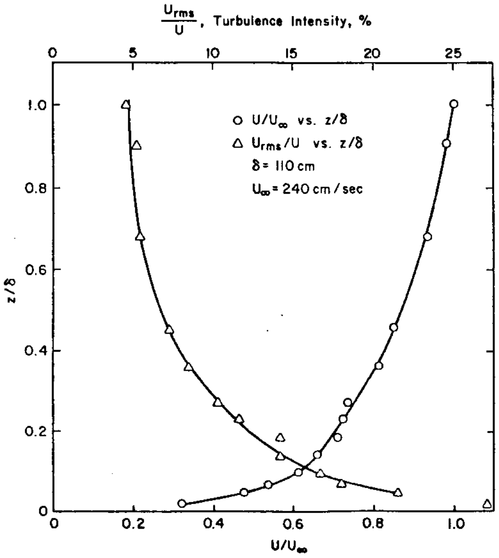


Figure 1. Approach flow characteristics.

4.1 Experimental Measurements of Mean Velocity in the Wakes of Cylinders

The vertical profiles of mean velocity defect, Delta U, are displayed in Figures 2 and 3. The maximum vertical extent of the velocity defect is 1 to 2H and is of the same order of magnitude as reported by Woo et al. (1976) and Kothari et al. (1980). The velocity defects in the wake of cylinders 1 and 2 are about the same, indicating that the effect of cylinder roughness on wake velocities were negligible. It should be noted that measurements at x/D equal to 3 should be utilized as qualitative informations as the hot-wire measurements are not accurate in the recirculation zone behind the cylinders. The interesting feature of the wakes is that they extend to about 10D downstream, much shorter than those reported by Hansen et al. (1975), Woo et al. (1976), and Kothari et al. (1980). This is the result of

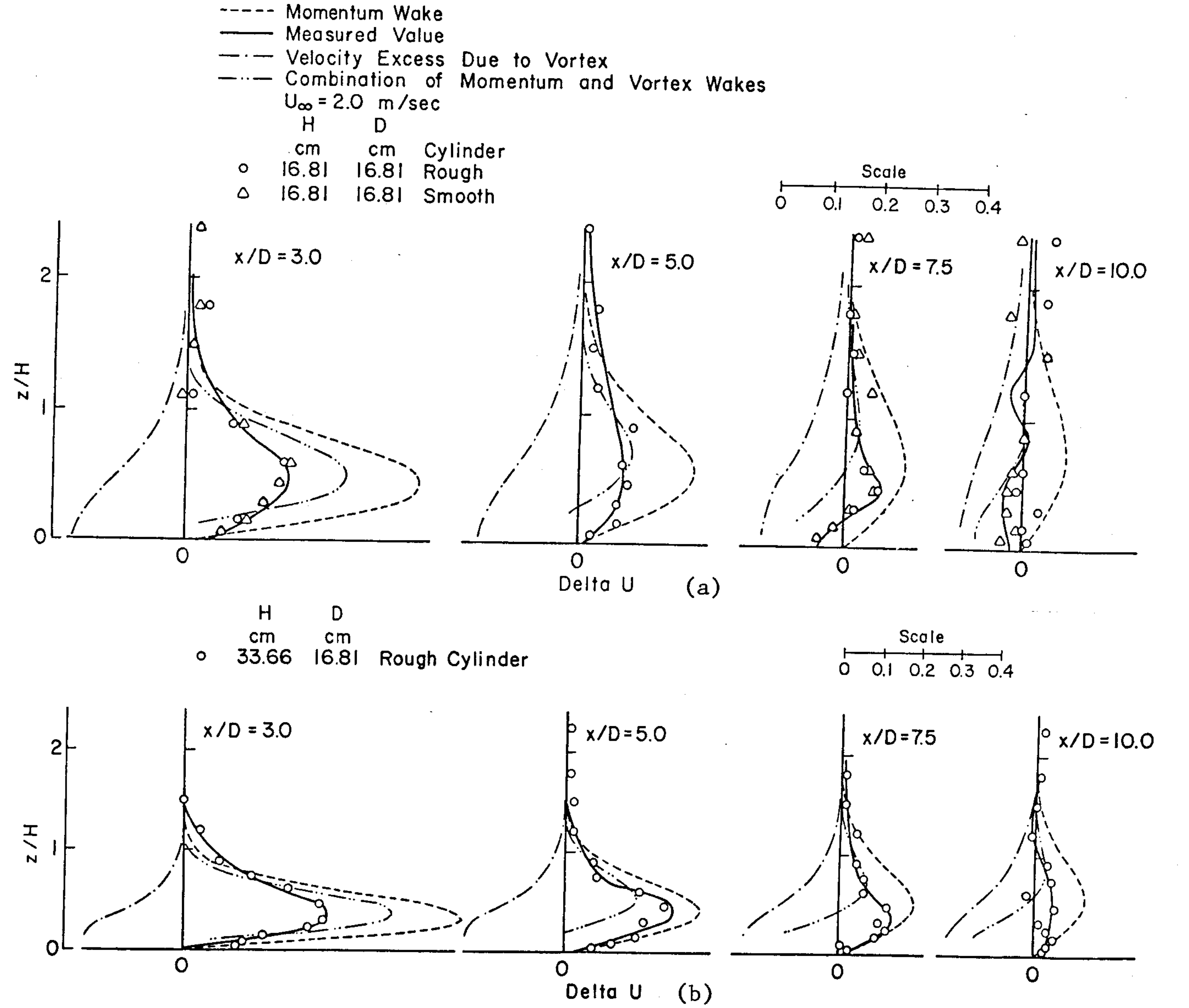


Figure 2. Comparison of the measured vertical profiles of velocity defect on the centerline of cylinders with the momentum and vortex wake theory.

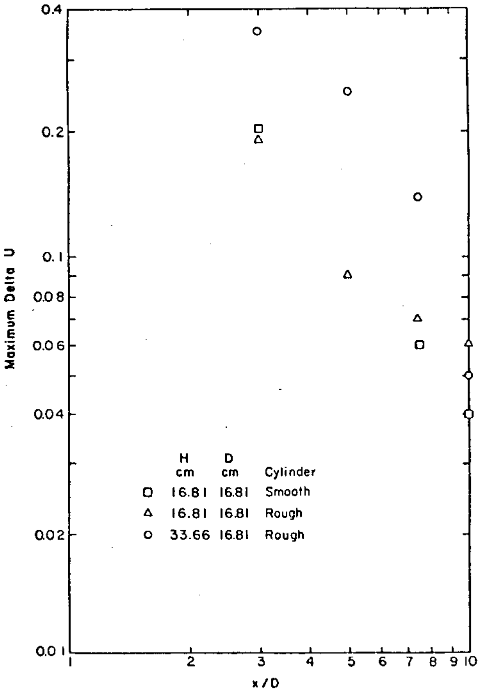


Figure 3. Decay rates of mean velocity defect in the wakes of cylinders.

action of horseshoe vortices bringing excess velocity from the top of the turbulent boundary layer towards ground along the centerline of cylinder and reducing velocity defect. The maximum velocity defect occuring at each x/D for all three cylinders are shown in Figure 3. It can be seen that the velocity defect in the wake of cylinder 3 is higher than in the wakes of cylinder 1 and 2, as expected due to its height.

4.2 Comparison of the Experimental Measurements of Mean Velocity with the Wake Theories

The theories of Hunt contain the basic physical models for momentum and vortex wake representations, and should present a reasonable prediction of wake velocity.

The force coefficient, C_{Fx}, and constants γ, λ and a in the momentum wake theory were assumed equal to 1.3, 1.0, 1.0 and 0.0, respectively. The theoretical predictions for mean velocity defect suggested by the momentum wake theory were then calculated. The vertical profiles of the mean velocity defect, Delta U, for various x/D locations for cylinders 1, 2 and 3 are shown in Figures 2(a), 2(a) and 2(b), respectively. It should be noted that any mean velocity excess observed in the wake will never be predicted by the momentum wake theory.

The vortex wake theory requires the position of the vortex in the wake and circulation at $x = 0$. In the present calculations the lateral center of vortex were obtained from the measurements of Hansen et al. (1976), the vertical center of vortex was assumed constant and equal to 0.3 H, and circulation at $x = 0$ was calculated using the method of Kothari et al. (1980). The results of the calculations of the vortex wake along the centerline of the cylinders for various x/D are also shown in Figure 2.

The sum of the momentum wake velocity defect and the vortex wake velocity excess are also shown in Figure 2, along with the experimental measurements. The comparison between the measurements and combined predictions are very good for heights greater than z/H equal to 0.5 for all x/D distances. Near the ground, the effect of predicted vortex wake excess velocity is higher. This implies that the vortex wake solution for inviscid region cannot be extrapolated into higher shear region near the ground.

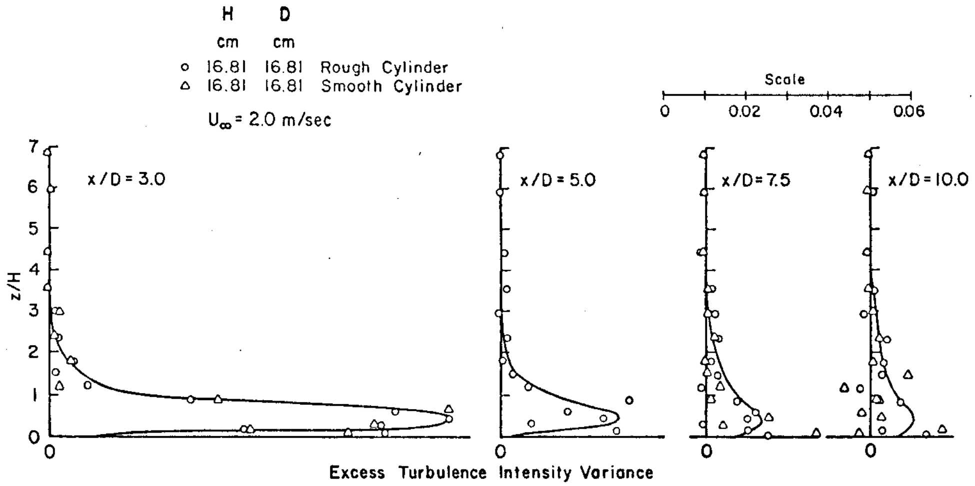
4.3 Turbulence Measurements

The vertical profiles of excess turbulence intensity variance, Delta U VAR, are displayed in Figures 4(a), 4(a) and 4(b) for cylinders 1, 2 and 3, respectively. Again, the Delta U VAR in the wake of cylinders 1 and 2 are about the same, implying that the effects of cylinder roughness of wake turbulence was negligible. It should be noted that these Delta U VAR also returns to the undisturbed state within approximately 10D downstream. The Delta U VAR approaches to zero within z/H equal to 2.0 for all three cylinders similar to the observations of Kothari et al. (1980). The maximum Delta U VAR occuring at each x/D is plotted in Figure 5 for all obstacles with the theoretical predicted slope of -2. The experimental measurements show slightly higher decay rate. The slightly higher decay rate seems to originate from the action of the two horseshoe vortices bringing less turbulent fluid down toward the surface on the centerline.

4.4 Experimental Measurements of Turbulent Diffusion in the Wakes of Cylinders

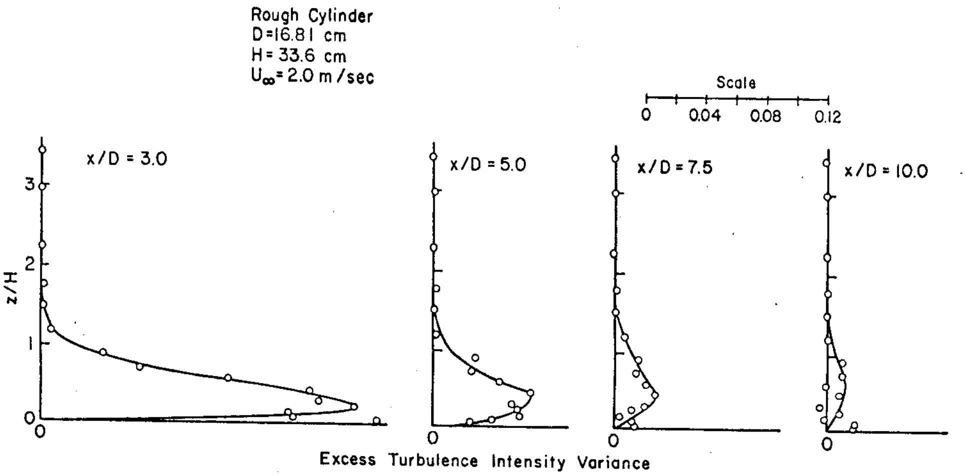
The vertical and horizontal profiles of concentration were performed in the wake of the same three cylindrical obstacles for three release locations. Only the ground-level concentrations are reported in this paper.

Figures 6(a), 6(b) and 6(c) show the maximum nondimensional concentration, K, for all release locations plotted against x/D for



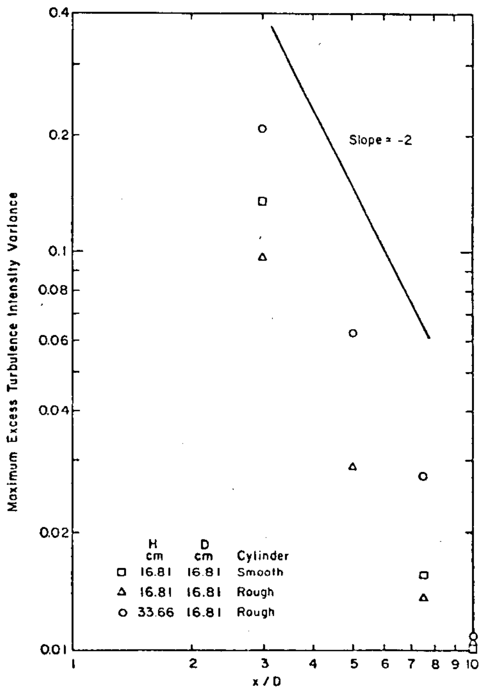
(a)

Figure 4. Vertical proviles of excess turbulence intensity variance on the centerline of cylinders.



(b)

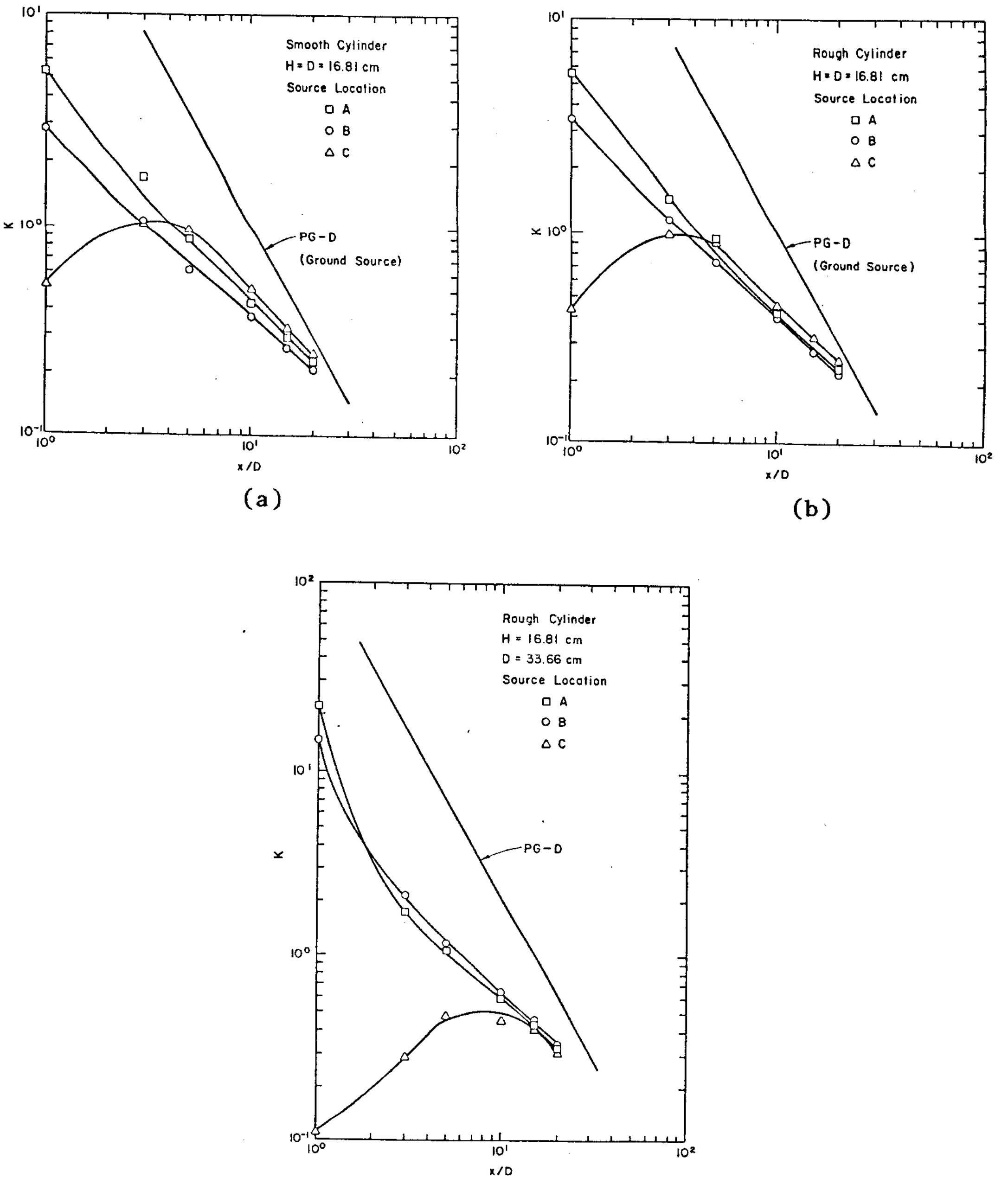
Figure 4. Continued.



	H cm	D cm	Cylinder
□	16.81	16.81	Smooth
△	16.81	16.81	Rough
○	33.66	16.81	Rough

Figure 5. Decay rates of excess turbulence intensity variance in the wakes of cylinders.

cylinders 1, 2 and 3, respectively. The Pasquill-Gifford (P-G) prediction for ground level releases are also shown in Figure 6. In the vicinity of the obstacle, the major fraction of the dispersion is the result of the obstacle generated mechanical turbulence in the cavity and wake region. The additional turbulence generated by the obstacles result into the lower ground level concentration, for both ground level releases, than that predicted by P-G curves. The more effluent entering the cavity, the greater the ground level concentration. Ground level release (A) has nearly 100 percent, ground level release (B) has slightly smaller percent, and roof top release (C) has



(a)

(b)

(c)

Figure 6. Ground level concentration vs. downwind distance on the centerline of cylinders.

much less percent of their effluent in the cavity. This resulted in the maximum concentration for release point A, minimum concentration for release point C, and in between concentration for release point B. The roof top release concentrations approaching that of the ground releases is an indication of where the elevated plume becomes entrained into the wake and is brought to ground level. This seems to occur about fifteen diameters downwind of the cylinders. The ground level concentrations in the wakes of cylinders 1 and 2 are about the same for each release position, again indicating the effects of cylinder roughness was negligible.

5.0 CONCLUSIONS

The experimental measurements of the flow and diffusion structure in the wakes of cylindrical obstacles were performed. The wake velocities, turbulence intensities and turbulent diffusions were approximately the same for identical cylindrical dimensions but having slightly different cylinder surface roughness. The maximum velocity defects in the wake are in fair agreement with that predicted by combined momentum and vortex wake theory. The maximum turbulence variance excess show a slightly higher decay rate than the predicted decay rate of -2.0. It is concluded that for determination of flow and diffusion in the wake of isolated cylindrical obstacles the effects of momentum and vortex wakes should be analyzed.

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