FLOW PAST CIRCULAR CYLINDER OF FINITE LENGTH PLACED NORMAL TO GROUND PLANE IN UNIFORM SHEAR FLOW*

BY SHIKI OKAMOTO** AND MIKI YAGITA***

This paper describes a flow past a circular cylinder whose one end is set on a flat plate and the other free end is immersed in a shear flow. The surface pressure distribution on the cylinder was measured and drag coefficients were determined by integration of the result. Experimental results for a shear flow were compared with those for a uniform stream. The main results are as follows: (1) The effect of the free end is limited to within $3d$ from the top of the cylinder. (2) The local drag coefficient divided by local dynamic pressure increases from the neighborhood of the top to the bottom of the cylinder as the length to diameter ratio and the velocity gradient increase. (3) In the wake of the cylinder, the velocity of the center portion of the wake, which is accelerated by the downwash, is larger than the local mean velocity.

KEY WORDS: Boundary Layer, Uniform Shear Flow, Circular Cylinder, Finite Length, Velocity Gradient, Surface Pressure, Drag, Wake

1. Introduction

Many investigations have been performed theoretically and experimentally on a flow past a two-dimensional circular cylinder, but a few studies have been carried out on a circular cylinder of finite length placed normally to the ground plane, such as a stack, a cylindrical building, and an oil tank. Okamoto-Yagita⁽¹⁾ have experimentally investigated a flow past a circular cylinder of finite length placed normally to the ground plane in a uniform stream in which the ratio of the thickness of boundary layer on the ground to the height of the cylinder is in the range of $0.15 \sim 0.01$.

However since a stack is embedded in an atmospheric boundary layer of several hundred meters thickness, it is necessary to study the flow past an obstacle immersed in a turbulent boundary layer on the ground plane. As far as the flow past a circular cylinder embedded in the boundary layer is concerned, Kiya⁽²⁾ has investigated the case in which the axis of cylinder is parallel to the y -axis. Taniguchi et al.⁽³⁾⁽⁴⁾ have studied the surface-pressure and the drag coefficient of a circular cylinder placed vertically to the ground plane, and Chen-Mangione⁽⁵⁾ have measured the frequency of vortices shedding behind a two-dimensional circular cylinder.

This paper presents an experimental investigation of a flow past a circular

cylinder of finite length placed normally to the ground plane in a uniform shear stream produced by Owen-Zienkiewicz's⁽⁶⁾ method.

Nomenclature

x, y, z : coordinates with origin at center of bottom of cylinder (see Fig.1)
 d : diameter of circular cylinder
 l : length of circular cylinder
 h : height of working section of wind tunnel
 U : local velocity of free stream
 U_c : velocity of free stream at $z=h/2$
 u : x -component of time-mean velocity in wake behind cylinder
 u' : x -component of velocity fluctuation in free stream
 ρ : density of air
 ν : kinematic viscosity of air
 P : static pressure on surface of circular cylinder
 $P_{s\infty}$: local static pressure of free stream
 C_p : surface-pressure coefficient of circular cylinder $= (P - P_{s\infty}) / (1/2)\rho U^2$
 θ : circular angle measured from forward stagnation point
 C_D : local pressure drag coefficient

$$= \int_0^\pi C_p(\theta, z/d) \cos\theta d\theta$$

 Re : Reynolds number $= dU_c/\nu$
 λ : velocity gradient
 $\lambda h/U_c$: nondimensional velocity gradient

2. Apparatus and Procedure of Measurement

The wind tunnel used in this experiment is the N.P.L. type wind tunnel having a 250mm square working section. A uniform shear

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** Associate Professor, Shibaura Institute of Technology, Shibaura, Minato-ku, Tokyo.

*** Research Associate, Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo.

stream was produced by setting a grid of rods at the exit of nozzle of wind tunnel using Owen-Zienkiewicz's method.

Since the accuracy of construction of the grid of rods influences significantly the velocity profile, the holes supporting the rods were bored through the frame with an accuracy of 1/100mm, and accuracy of construction of the grid was 3/100mm.

The velocity profile of a uniform shear stream can be expressed as $U = U_c + \lambda(z - h/2)$ or $U/U_c = 1 + (\lambda h/U_c)(z/h - 1/2)$. Two kinds of grids having $\lambda h/U_c = 0.4$ and 0.62 were used in this experiment. The measured velocity profile showed a slightly excess stream near the upper and lower walls in the working section as shown in Fig.1. The excess portion near the lower wall was cut away by setting the ground plate at 25mm above the lower wall, and by locating its leading edge at 300mm downstream of the grid. The resulting velocity profile was close to the expected profile of a uniform shear stream, as shown in Fig.2.

The circular cylinder model of 10mm diameter was located at 210mm downstream of the leading edge of the ground plate, because the disturbances produced by the grid decayed to a constant value at the position of the model, as shown in Fig.2. Pressure holes were bored along the generating line of the cylinder and then the pressure distributions on the surface were measured by rotating the cylinder about its axis.

The experiment was carried out at the wind velocity of $U_c = 19.2\text{m/s}$ which corresponds to $Re = 1.3 \times 10^4$. The surface-pressure distributions were measured for eight models of $\ell/d = 1, 3, 5, 7, 9, 12, 15$

Fig.1 Schema of apparatus and nomenclature

Fig.2 Velocity profile and turbulence intensity in uniform shear flow ($\lambda h/U_c = 0.4$)

and ∞ , while the velocities and static pressures in the wake were measured for two models of $\ell/d = 9$ and ∞ .

3. Results and Discussions

3.1. Surface-pressure distribution

Figure 3 shows the surface-pressure distributions along the circumference of the circular cylinder of $\ell/d = 9$ in a uniform shear stream of $\lambda h/U_c = 0.4$, and, for comparison, the pressure distribution for two-dimensional cylinder, namely, the distribution at the center of a cylinder spanned between the upper and lower walls of the test section is also written in this figure. Figures 4 ~ 6 show the iso-pressure lines obtained from the surface-pressure distributions respectively for $\ell/d = 5, 9$ and 12 in the case of $\lambda h/U_c = 0.4$. It has been found from the data on a uniform stream that the effect of the free end of the cylinder reaches its root portion for $\ell/d = 1 \sim 5$, while it is limited to the portion near the free end for $\ell/d \geq 7$, as shown in Fig.7. The iso-pressure lines for $\ell/d \leq 9$ in a uniform shear stream are similar to those in the uniform stream, and the region of low pressures at the rear side of the cylinder is limited to the portion within $3d$ from the top of the cylinder, as shown in Figs. 4 and 5. However, as the value of ℓ/d increases beyond 12, the region of low pressures at the rear side gradually extends toward the root of the cylinder as shown in Fig.6. The difference between the iso-pressure lines in a uniform stream and those in a uniform shear stream can be clearly seen in Figs.7 and 8. This difference can also be confirmed by visualization of the flow past the circular cylinder of $\ell/d = 10$ in a water channel. The ink issued from the rear bottom of the cylinder flows quickly upward by suction due to a low pressure at the rear side in the uniform shear stream, while such a secondary flow does not appear in the uniform stream, as shown in Fig.9.

Furthermore, the effect of velocity gradient on the iso-pressure lines can be given by comparison of Fig.5 with Fig.8. It is found that there is little difference between the iso-pressure lines for $\lambda h/U_c = 0.4$ and those for $\lambda h/U_c = 0.62$.

Fig.3 Surface-pressure distribution ($\lambda h/U_c = 0.4$, $\ell/d = 9$)

Fig. 4 Iso-pressure lines
($\lambda h/U_c = 0.4$, $\ell/d = 5$)

Fig. 5 Iso-pressure lines
($\lambda h/U_c = 0.4$, $\ell/d = 9$)

Fig. 6 Iso-pressure lines
($\lambda h/U_c = 0.4$, $\ell/d = 12$)

Fig. 7 Iso-pressure lines
(uniform flow $\ell/d = 9$)

Fig. 8 Iso-pressure lines
($\lambda h/U_c = 0.62$, $\ell/d = 9$)

Figure 10 shows the curves of C_p at $\theta = 0^\circ$ for various values of ℓ/d in the case of $\lambda h/U_c = 0.4$. The curves are similar in the portion near the free end and the effect of free end is limited to the region within $1.0d$ from the free end for cylinders of $\ell/d \geq 2$, in like manner as in a uniform stream.

The range of end effect expands downward as θ increases. Figure 11 shows the curves of C_p at $\theta = 180^\circ$ for various values of ℓ/d . The end effect reaches the root for cylinders of $\ell/d \leq 5$, but it is limited to the region within $3d$ from the free end for cylinders of $\ell/d \geq 7$, while the end effect is limited to the region within $4d$ from the top in a uniform stream.

The pressure in the portion beneath the range of end effect is almost constant for cylinders of $\ell/d = 7$ and 9 , and it decreases slowly toward the root for cylinders of $\ell/d = 12$ and 15 , in like manner as for a two-dimensional cylinder, in a uniform shear stream, while it is almost constant in a uniform stream.

(a) Uniform flow, $l/d=10$ (b) $\lambda h/U_c=1.11$, $l/d=10$ Fig.9 Flow visualization in water channel ($Re=520$)

3.2. Local drag coefficient

The total drag of a circular cylinder consists of a pressure drag and a frictional drag. Since the frictional drag is less than 2% of total drag for $Re \geq 10^4$ and hence negligibly small in this experiment, the pressure drag may be considered the total drag.

The local drag coefficient (C_D) in a uniform shear stream is shown in Fig.13, which may be compared with Fig.12 for a uniform stream. The local drag coefficient becomes maximum in the neighbourhood of free end as shown in Figs.12 and 13, and occurrence of the maximum value is considered to be due to a drop of pressure in the iso-pressure lines. A drop of pressure appears at $z/d = 4.3$ and $\theta = 70^\circ$ for a cylinder of $l/d = 5$ (see Fig.4) and at $z/d = 8.5$ and 11.5 and $\theta = 140^\circ$ for cylinders of $l/d = 9$ and 12 respectively (see Figs.5 and 6). Consequently, the distribution of C_D in the z -direction of cylinders of $l/d \leq 5$ differs from that of cylinders of $l/d \geq 7$.

The local drag coefficients of cylinders of $l/d \leq 5$ are smaller than those of a two-dimensional cylinder in both uniform shear stream and uniform stream, and the maximum local drag coefficient occurs near $0.8d$ apart from the free end in a uniform shear stream, while it occurs at $1.0d$ from the free end in a uniform stream. And the positions of maximum local drag coefficient of cylinders of $l/d \geq 7$ are near $0.35d$ from the free end in a uniform shear stream, while they are near $0.5d$ from the free end in a uniform stream. The end effect is limited to the neighbourhood of free end for cylinders of $l/d \geq 12$ in both uniform shear stream and uniform stream, and the local drag coefficient in the lower portion of cylinder has similar tendency to that in the two-dimensional cylinder. The values of C_D in the portion lower than $3d$ from the free end or the portion free from the end effect are smaller than that in the two-dimensional cylinder, and they approach the two-dimensional values as l/d increases.

Furthermore, comparison of the local drag coefficients of cylinder of $l/d = 5$ in uniform shear streams with various velocity gradients is made in Fig.14. The maximum value of C_D occurring near the free end decreases slightly as $\lambda h/U_c$ increases, and the values of C_D in the lower portion of

Fig.10 Pressure coefficient at $\theta=0^\circ$
($\lambda h/U_c=0.4$) Fig.11 Pressure coefficient at $\theta=180^\circ$
($\lambda h/U_c=0.4$)

cylinder free from the end effect increase as the root of cylinder is approached. It is expected from these results that the drag coefficient near the free end decreases and the downwash of free stream from the free end of cylinder weakens as the velocity gradient increases.

Fig.12 Local drag coefficient
(uniform flow)

Fig.13 Local drag coefficient
($\lambda h/U_c = 0.4$)

Fig.14 Local drag coefficient
($l/d = 9$)

3.3. Velocity distribution in wake behind circular cylinder

The wake behind a circular cylinder of finite length is important in relation to the problems of air pollution and the downwash from the top of stack is of interest because it influences the behavior of the plume.

Figure 15 shows a distribution of velocity defects $(U-u)/U$ in the y -direction of a circular cylinder of $l/d = 9$ at $z/d = 4.5$ and a two-dimensional cylinder at $z/d = 11.25$. A peak appears in the distribution of velocity defects at $x/d \leq 9$ and two peaks appear at $x/d \geq 17$ for circular cylinder of $l/d = 9$, while one peak appears at $y/d = 0$ for a two-dimensional cylinder. The peak velocity defect decreases as the downstream distance increases. Appearance of two peaks is due to the downwash from the free end of cylinder and this phenomenon is a feature of a circular cylinder of finite length. The velocity defect becomes negative at the center portion of wake at $x/d = 37$ and 67 in uniform shear stream, while there is no negative velocity defect in a uniform stream.

Figure 16 shows a distribution of velocity defects in the y -direction at various values of z/d in the uniform shear stream of $\lambda h/U_c = 0.4$. It is found from this figure that the downwash from the top of cylinder reaches $z/d = 4.5$ at $x/d = 17$ and $z/d = 2$ at $x/d = 67$. Considering the effect of velocity gradient on the velocity defect, the velocity defect in the center portion of wake at $x/d \leq 9$ increases as the velocity gradient increases, contrary to the case of a two-dimensional cylinder, and the velocity defect at $x/d \geq 37$ decreases with an increasing velocity gradient. If the velocity gradient

Fig.15 Profiles of velocity defect

Fig.16 Profiles of velocity defect
($\lambda h/U_c=0.4$, $l/d=9$)

increases still more, the secondary flow toward the top from the root of cylinder is intensified and the downwash from the top of cylinder is weakened. It is found from Figs.17 and 18 obtained in the water channel that the downwash in a uniform shear stream is weak compared with that in a uniform stream.

4. Conclusions

This paper presents an experimental study of a flow past a circular cylinder of finite length placed on the ground plane in a uniform shear flow. The results of the present study are summarized as follows:

- (1) The range of end effect is limited to the region within $3d$ from the top of cylinder in a uniform shear stream.
- (2) The pressure at the rear side of cylinder of $l/d \geq 12$ gradually decreases and the local drag coefficient increases as the root of cylinder in a uniform shear stream is approached, while the pressure at the rear side of cylinder of $l/d \geq 7$ is nearly constant in the lower portion free from the end effect in a uniform stream.
- (3) The pressure coefficient at the rear

Fig.17 Downwash from top of circular cylinder ($Re=520$, uniform flow $l/d=10$)

Fig.18 Downwash from top of circular cylinder ($Re=520$, $\lambda h/U_c=1.11$, $l/d=10$)

side of cylinder gradually decreases and the local drag coefficient increases as the velocity gradient increases.

- (4) The velocity defect becomes negative due to the downwash in the center region of the wake at $x/d \geq 37$, while there is no negative velocity defect in a uniform stream.
- (5) The secondary upward flow behind the circular cylinder is intensified and hence the downwash from the top of cylinder weakens as the velocity gradient increases.

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