Similarity in the Turbulent Near Wake of Bluff Bodies

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An experimental investigation has been carried out in the turbulent near wakes of several two-dimensional and axisymmetric bluff body models in the Reynolds number range of 1.13-5.0 × 10⁴. For a 2-D wedge, the effect of varying the blockage ratio up to 25% has also been studied. Based on the locations of minimum pressure and maximum reverse velocity on the wake axis, characteristic length and velocity scales are suggested for both 2-D and axisymmetric near wakes. Using these scales, similarities in the distributions of static pressure and velocity defect are shown to exist for various models, including those with high blockage ratios. The dependence of these scales on model bluffness and blockage ratio is discussed. The difference between the near wakes of 2-D and axisymmetric bluff models appears as the opposite variations of the characteristic length scale and the length of the recirculation region with the minimum pressure coefficient. In the 2-D case these lengths decrease with the minimum pressure coefficient, while in the axisymmetric case they increase with it. A shielded hot wire is used for finding the length of the recirculation region.

Nomenclature

BR	= blockage ratio based on area
C_D	= drag coefficient
c_p	$= p - p_\infty / \frac{1}{2}\rho u_\infty^2$
c_{p_b}	= base pressure coefficient
$c_{p\min}$	= minimum value of c_p on the wake axis
c_{pq}	= pressure coefficient at the reattachment point
d	= model base height or model diameter
n	= shedding frequency
p	= static pressure
p_∞	= freestream static pressure
S	= Strouhal number
u	= velocity
u_∞	= freestream velocity
u_{av}	$= u_\infty / (1 - \mathrm{BR})$
u_c	$= u_f - u_r$
$u_{c\max}$	= maximum value of u_c
u_f	= maximum forward velocity at any x
u_r	= velocity on the wake axis at any x
$\bar{u}$	= mean velocity
$\lvert\bar{u}\rvert$	= magnitude of mean velocity
x	= coordinate in flow direction
x_m	= characteristic length
x_r	= length of recirculation region
y	= normal coordinate
ρ	= density of air
ψ	= stream function

I. Introduction

IN studies on fluid flow in the turbulent near wake of bluff bodies, it is becoming increasingly apparent that the Strouhal number S characterizing the vortex shedding, the base pressure coefficient c_{p_b}, and the drag coefficient C_D are related phenomena. Attempts have been made by Roshko[1] and Bearman[2] to correlate these parameters and by Gerrard[3,4] to explain the mechanism of formation of vortices in the near wake. At the same time the similarity of fluid flow, which is fairly well established in the far wake, is being studied in the near wakes as well. The introduction of a wake Strouhal number by Roshko,[1] investigations of Roshko and Lau,[5] and Badrinarayanan,[6] and measurements by Carmody[7] on disks and by Calvert[8] on cones are attempts in such a direction.

Calvert[8] has reported measurements made in the near wake of cones of different vertex angles. He found that the static pressure distribution showed similarity in the near wake when suitable length and pressure coefficient scales were chosen for nondimensionalization.

The recirculation region of bluff bodies has beneficial effects for the flame stabilization in combustion chambers. The relatively low speeds and intense turbulent mixing due to unsteadiness of flow in the recirculation region help to sustain a flame at high speeds. In such cases the effect of blockage ratio also becomes important. A theory for fluid flow in a channel behind a bluff body has been developed by Abramovich[10] and several experimental investigations have been reported by Wright,[9] Davies and Beer,[11] Winterfeld,[12] and Goldshtik and Silantev.[13] An important conclusion of Wright's investigation has been that the problem of efficient flame stabilization in ducts by bluff bodies can be conveniently split up into two parts: chemistry of the combustion reaction, and the fluid dynamic aspect to estimate the residence time. And that the flow patterns about the bluff body flame stabilizers depend only on the fluid dynamic variables. Thus, it is of interest to know how the blockage ratio for 2-D bluff body near wakes affects the kind of similarity observed by Calvert[8] for axisymmetric bluff body near wakes.

The present experimental investigation was undertaken to study the similarities in the near wakes of 2-D bluff bodies along the lines of Calvert.[8] In addition, the effect of blockage ratio up to a value of 25% for 90° wedge models has also investigated. The 2-D models comprised of a circular cylinder, 90° wedges of four blockage ratios, a flat plate, and a rectangular cylinder of thickness to height ratio of 0.6. The last model has been known to have maximum C_D among rectangular cylinders.[14,15] It was our intention to find whether this unique feature could have its repercussions on the flow similarity as well. With an objective of essentially comparing the 2-D and the axisymmetric near wakes, a 90° cone and a disk were also included in the present investigation.

II. Experimental Setup and Procedure

A. Wind Tunnel and Test Section

Experiments were carried out in an open circuit, suction-type wind tunnel. It had a test section of 305 × 406 mm. Velocity in the test section was limited to about 12 m per sec. The turbulence level at the inlet of the test section at this velocity was about 0.5%.

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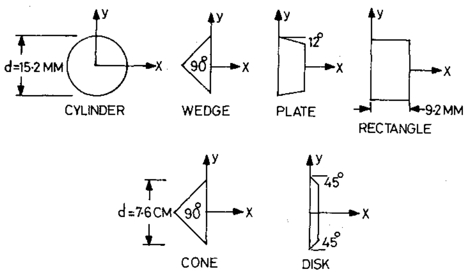

Fig. 1 Models and coordinates.

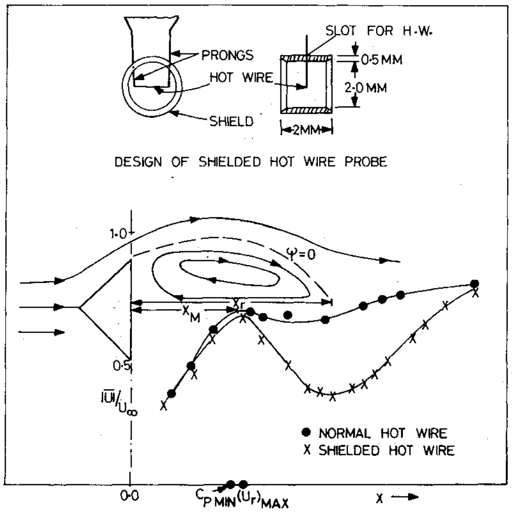

Fig. 2 Centerline mean velocity distribution, normal and shielded probes (wedge BR = 17.7%).

B. Models

Two dimensional models spanned the test section width of 406 mm and were placed at about 300 mm from the test section inlet. All four models of different configurations had a diameter or base height of 15.2 mm. This corresponded to a test section blockage ratio of 5% and allowed measurements up to 25d downstream. The blockage ratio effects were investigated for the 90° wedge using models of base heights 32 mm, 54 mm, and 76 mm corresponding to blockage ratios of 10.6%, 17.7%, and 25.0%, respectively.

Axisymmetric models of 76-mm diam, corresponding to BR of 3.6%, were placed at the same axial location as the two-dimensional models. They were held in position with the help of piano wires. No model vibrations were observed during the tests. The model geometries are sketched in Fig. 1.

The two-dimensional models of four different configurations were each studied at a Reynolds number of $1.15 \times 10.^4$ Larger models had Reynolds numbers of 2.9, 4.15, and $5.0 \times 10,^4$ corresponding to 10.6%, 17.7%, and 25% blockage ratios (BR), respectively. The Reynolds number for the axisymmetric models was $5.0 \times 10,^4$ same as in Calvert's[8] experiments.

C. Probes and Instrumentation

The base pressure measurements were made by means of tubes embedded in the base of the 2-D models. A pressure tap of 0.75-mm size was located at the center of the model. For pressure measurements along the wake center-line, brass disks of the design of Miller and Commings[16] were used. The disk diameters were 6.35 mm for small size bluff body models and 12.7 mm for larger ones. For measurements the disk was aligned with its plane parallel to the plane formed by the bluff body axis and the wake center line. It was found that the base pressure was not altered by the presence of the probe in this manner. However, if the plane of the disk was perpendicular to the plane formed by the bluff body axis and the wake center line the base pressure was significantly altered. The reference static pressure tap was located in the floor of the test section at 20-mm distance downstream from the test section inlet. A Flow Corporation MM-3 micromanometer with a least count of 0.0025 mm of alcohol was used for reading the pressure differences.

Constant-temperature hot-wire probes with the wire axis parallel to the model axis (for 2-D models) were used for most of the mean velocity measurements. The instruments used were a DISA 55 A01 anemometer, a DISA 55 D10 linearizer, and a Tektronix dual trace oscilloscope. Difficulties were encountered in ascertaining the values of mean velocities near the free reattachment region from the results of a normal hot-wire probe, since in this region it gave almost constant values at different locations. In view of this a shielded hot-wire probe (Fig. 2) was constructed and used for measurements of mean velocity along the axis. Such a probe has been successfully tried by Gunkel et al.[17] In the present case the shield was a Perspex ring of 3-mm diam and 2-mm thickness.

A comparison of typical sets of velocity distributions on the wake axis using bare and shielded hot-wire probes has been made in Fig. 2 for the 17.7% BR wedge model. A mean value of the fluctuating voltage reading was taken to represent the mean velocity. In the early part of the wake, both probes show an increasing magnitude of velocity ($|\bar{u}|$) with the distance measured from the base. However, after a maximum has been reached, the shielded hot wire shows a decreasing magnitude of velocity with x until it attains a minimum value. Thereafter the velocity magnitude increases. The velocity distribution obtained using shielded hot wire is more like the one expected in a recirculation region. It is also similar to the distribution obtained in the axisymmetric case with a bare-wire probe by Calvert[8] where the location of minimum velocity has been taken as the end of the recirculation region. Likewise, the location of velocity minimum on the wake centerline as obtained using the shielded hot-wire probe served as a useful criterion for the location of the free reattachment point for 2D models. For traverses in the y direction for the measurement of maximum forward velocity at various x locations, the bare-wire probe has been used. A single hot wire was used for finding shedding frequency, along with a General Radio Type 1900-A wave analyzer.

D. Sources of Errors and Assumptions

There are two major sources of error in the static pressure measurements on the wake centerline: 1) high turbulence intensity almost throughout the flowfield, and 2) the unsteady nature of the flow. Because of the second reason, the instantaneous-flow-velocity vector is likely to be inclined to the disk probe aligned with the wake centerline, thereby affecting the measured values of static pressure. The results are presented here without any corrections for these effects.

Since the vortices form alternately on either side of the wake centerline, the flow inclination with the plane of the disk is likely to be alternately positive and negative. Also, the mean velocities as measured with bare and shielded hot-wire probes differ at a maximum in the region of the free reattachment point. Therefore, the errors in the wake centerline pressure measurements are likely to be maximum near the free reattachment point. An attempt was made to estimate this error for the 17.7% BR wedge model. It was simply assumed that a flow inclination angle could be calculated by considering the mean velocity measured by the bare hot-wire probe as the total velocity in the x-y plane and that measured by the shielded-wire probe as its x component. It was further assumed that this flow inclination was alternately positive and negative with equal frequency with the plane of the disk, and the error in pressure reading would be an average of the errors found by static calibration for negative and positive values of this angle. The maximum error in c_p for the 17.7% BR model was found to be 7.5% of $c_{p\min}$. It is only an oversimplified estimate and has been obtained to show that measurement error is not likely to affect the similarity of pressure distribution, as shown later.

Table 1 Near wake parameters for 2-D models

Model	Blockage ratio(o/o)	$-c_{pmin} x \frac{u_\infty^2}{u_{cmax}^2}$	$\frac{c_{pa}}{c_{pmin}}$	$\frac{x_r}{d}$	$\frac{x_r - x_m}{x_m}$	$S = \frac{nd}{u_{av}}$
Rectangle	5	0.59	0.557	1.85	0.835	0.131
Plate	5	0.57	0.449	2.3	0.85	0.154
Cylinder	5	0.54	...	...	...	0.197
Wedge	5	0.554	0.485	2.3	0.76	0.18
Wedge	10.6	0.51	0.51	2.56	0.79	0.18
Wedge	17.7	0.54	0.515	1.88	0.88	0.184
Wedge	25.0	0.564	0.48	1.92	1.18	0.188

In the case of mean velocity measurements, the mean of extreme readings of a fluctuating voltage on the voltmeter does not represent the true average velocity. To estimate the error involved, three sets of 250 to 300 random readings were taken on a digital voltmeter by switching the voltmeter to "on" and "hold." The average values for each set so obtained were within 2-3% of each other. This average was compared with the previously recorded mean of extreme readings for the 17.7% BR wedge model. The three locations for such comparison were a point close to the model base, and the maximum velocity magnitude locations on the wake centerline.

The comparison showed that the mean recorded from extreme readings was higher by about 10% near the base and by only 5% at the other two locations, as compared to the average value of three sets obtained at the three respective locations. A better method would be to use an integrating-type digital voltmeter, which could give the average value of the signal over a known period of time. Such an equipment was not available for the present work.

In mean velocity measurements involving the shielded hot-wire probe, the velocity measured is not exactly the axial component of the velocity. Pitch and yaw calibration for the shielded hot-wire probe were carried out by inclining the probe to the freestream at angles ranging from 0° to 90° at 5° intervals. The data show that pitch curves were symmetric with respect to positive and negative inclinations, and that the probe was sensitive to flow inclination only above a pitch angle of 40°. Beyond and including angles of 60° it was found to deviate from the cosine curve by about 10%. It is believed that the mean velocity magnitudes measured with this probe are only representative of the x component of the velocity on the wake centerline. It is assumed that the location of the free reattachment point is coincident with the velocity minimum location of the shielded-wire traverse.

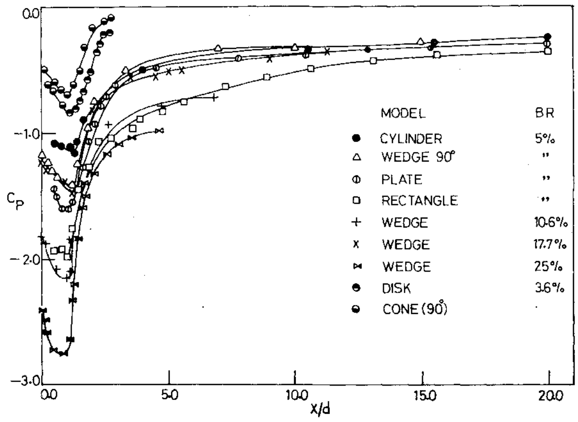

Fig. 3 Static pressure distribution.

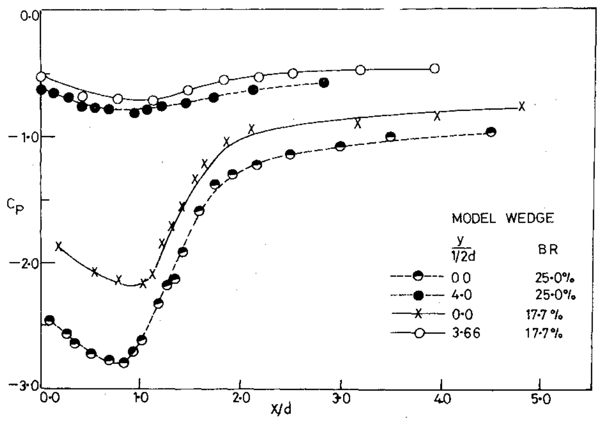

Fig. 4 Pressure coefficient variations with axial distance on the wake centerline and in the inviscid outerflow.

III. Experimental Results

The coordinate system is shown in Fig. 1. For all the models, the origin for measurements in the flow direction is taken to be the point of flow separation, except for the circular cylinder. For measurements normal to flow direction the origin is on the centerline of the wake. Bluffness of the model has been used throughout the text in the sense of Roshko,[1] a bluffer model being one with a lower value of base pressure coefficient.

Table 1 presents the dimensionless lengths of recirculation region x_r/d, and the Strouhal number based on u_{av} for 2-D models of varying bluffness and blockage ratio. For a 2-D flat plate model x_r/d is 2.3 for the present case of 5% BR. This compares well with a value of 2.3 as obtained by Arie and Rouse[18] for 8.3% BR, and 2.82 of Fail et al.[19] for a low BR similar model. The values of Strouhal number for different 2-D models are also in reasonable agreement with those of earlier investigations.[1,15,19]

A. Static Pressure Distribution

The distribution of static pressure coefficient c_p on the wake centerline is shown in Fig. 3 for different models. The first point on each curve for two-dimensional models is the base pressure coefficient. A pronounced low-pressure trough in the pressure distributions is a common feature for both two-dimensional and axisymmetric models in agreement with the earlier observations by Roshko,[1] Fail et al.,[19] and Gadd.[20] For two-dimensional models the location of the minimum pressure coefficient c_{pmin} shifts toward the model with decrease in the value of c_{pmin}, while it is just the opposite in the axisymmetric case. In the present case, the values of c_{pmin} are -1.16 and -1.72 for the cylinder and flat plate, respectively. The corresponding value obtained by Roshko for a cylinder is -1.33 and for the case of a flat plate Fail et al.[19] have obtained a value of -1.80.

With increase in blockage ratio, there is considerable decrease in the value of c_{pmin}. This is more than what can be accounted for in terms of increase in u_{av}. It is interesting to note that the 5% BR rectangle had as low a value of c_{pmin} as the 17.7% BR wedge. As is indicated in Fig. 2, the locations of minimum pressure coefficient c_{pmin} and the maximum reverse velocity were found to be close to each other for all the models. Of the two, the c_{pmin} location was closer to the model base.

A comparative study of pressure distributions in the outer flow and the wake centerline for the higher BR 2-D 90° wedge

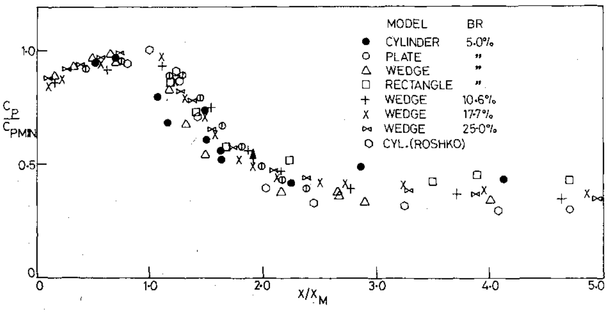

Fig. 5 Similarity of centerline pressure distribution ($x/x_m \leq 5$).

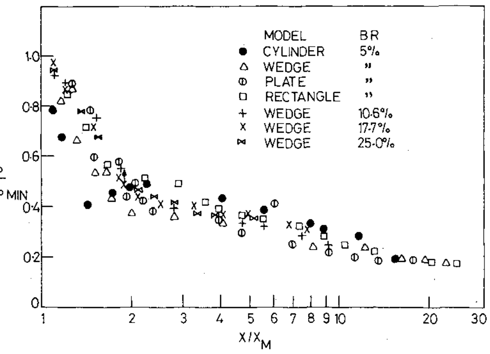

Fig. 6 Similarity of centerline pressure distribution ($5 \geq x/x_m \geq 25$).

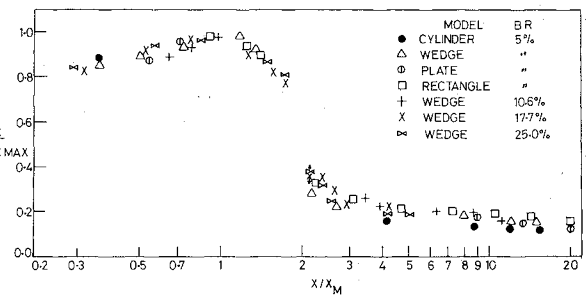

Fig. 7 Similarity of velocity defect.

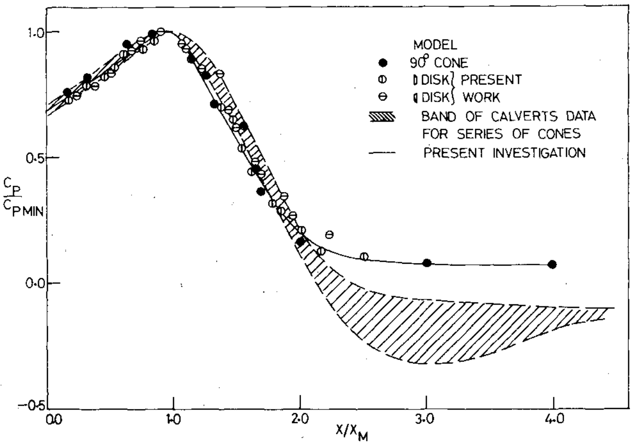

Fig. 8 Similarity of centerline pressure distribution (axisymmetric flow).

models is shown in Fig. 4. It is seen that the outer flow static pressure distribution is similar to that on the wake centerline. In particular, the x locations of the minimum pressure coefficient in the outer flow and the wake centerline are identical for higher BR 2-D models.

IV. Discussion

A. Length and Velocity Scales for Mean Flow

Roshko and Lau[5] have obtained a correlation in static pressure distribution in the reattachment region for a variety of geometrical configurations formed by various forebodies to downward facing steps. Also, Calvert[8] has shown similarity in the centerline static pressure distribution of near wakes of cones of varying vertex angles. Likewise, a similar attempt was made in the present case, using the axial distance of the minimum pressure point on the wake centerline from the separation point of the model as the appropriate length scale. This choice of length scale was based on several factors. First, the low pressure trough is a characteristic feature of pressure distribution for different models. In addition, it is the location of maximum wake width (the maximum separation between the two zero-streamlines), and the point of reverse velocity also occurs quite close to this point. For the last reason the distribution of velocity defect u_c (the difference between maximum velocity in the x direction and the velocity on the wake centerline at the same x location) shows a maximum at this location. It was also found that the quantity $c_{p\min} x (u_\infty / u_{c\max})^2$ was almost a constant for different models, as indicated in Table 1. It essentially means that if a pressure coefficient is obtained using $u_{c\max}$ as a velocity scale, then the minimum pressure coefficient is the same for different models.

Therefore, the distance of the minimum pressure point from the separation point and $u_{c\max}$ seem to be the appropriate length and velocity scales. Since $u_{c\max}$ is generally located a little downstream of $c_{p\min}$, a length scale x_m has been defined which is a mean of x values of $c_{p\min}$ and $u_{c\max}$ locations (Fig. 2). The typical distance between these two locations was $0.1d$.

B. Similarity of Mean Flow for 2D Models

With the previous choice of length scale, $c_p/c_{p\min}$ has been plotted as a function of x/x_m in Figs. 5 and 6. The first figure is on an enlarged scale for $0 \leq x/x_m \leq 5$, a region in which the change in magnitude of $c_p/c_{p\min}$ is large, and the second figure is a semi-log plot up to $x/x_m = 25$. Collapse of data is fair, considering the diversity of the models and the high blockage ratios. The pressure measurement errors are not likely to affect the location of $c_{p\min}$ since outer flow shows a pressure minimum at the same location as on the wake centerline (Fig. 4). Based on a simple estimate of the upper limit of correction on the c_p value, as discussed previously, estimated deviations for a model are shown by arrows in Figs. 5 and 6. The deviation from plotted results is likely to have same sign for different models.

For the circular cylinder, some points did not fit in the general trend. In the pressure recovery region, there was a slight decrease in pressure in the downstream direction, followed again by a pressure increase. Since this trend was not observed for other models, it was considered to be due to measurement errors in this region. Therefore, for the circular cylinder, results obtained by Roshko[1] are also presented. These do not show any peculiarities.

Normalized velocity defect $u_c/u_{c\max}$ is plotted against x/x_m in Fig. 7. The points close to free reattachment are not shown because of the uncertainty involved in the velocity magnitudes measured in this region. The effect of a $\pm 10\%$ measurement error in centerline velocity on correlation is shown for the 17.7% BR model near the free reattachment point by means of arrows. Again, collapse of data by using the length scale x_m and velocity scale $u_{c\max}$ for nondimensionalization is fair for models of varying bluffness and blockage ratio.

C. Similarity of Mean Flow for Axisymmetric Models

The same length and velocity scales have been employed for the axisymmetric flows as in the 2-D case. Figure 8 shows $c_p/c_{p\min}$ vs x/x_m curves for three models (the disk was tested both ways) along with the band of Calvert's[8] data for a series of cones. Fair agreement is obtained in the recirculation region, but outside this region ($x > x_r$), Calvert's data are scattered. This has been mentioned by Calvert and he explains

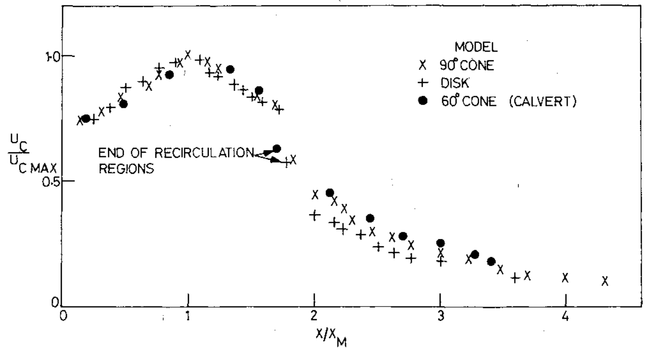

Fig. 9 Similarity of velocity defect in axisymmetric flow.

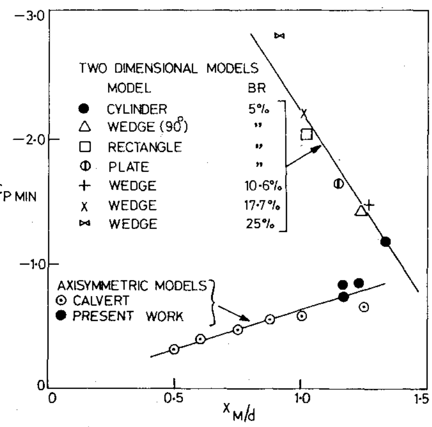

Fig. 10 Wake parameters.

this by replacing the coordinate $(1-c_p)/(c_{p\min})$ by $(1-c_p)/(c_{p\max}-c_{p\min})$. Here $c_{p\max}$ is maximum positive pressure coefficient on the wake centerline. Since no positive pressure coefficient was observed in the present experiments (the reason for this may be the higher BR in the present investigations) no such modification was needed and $c_p/c_{p\min}$ has been used as a coordinate.

Nondimensional velocity defect $(u_c/u_{c\max})$ is plotted against x/x_m in Fig. 9. Similarity can be observed both inside and outside the recirculation region. This confirms the appropriateness of the length and velocity scales used.

D. Near Wake Parameters

The variation of nondimensional characteristic length x_m/d is shown in Fig. 10. It is seen that x_m/d decreases with increasing bluffness for 2-D models. The data points for wedge models of different blockage ratios are also shown in Fig. 10. With increasing blockage ratio, x_m/d decreases. Since the effect of increase in blockage ratio is to decrease $c_{p\min}$, the blockage ratio increase has the same effect as increase in bluffness. However, for axisymmetric models, x_m/d increases with increase in bluffness. The opposite trend in the two cases appears to be due to the stronger periodicity in the two-dimensional near wakes.

The recirculation bubble can be divided into two regions: the first extending from model base to $x=x_m$ and the second from $x=x_m$ to $x=x_r$. While the extent of the first region decreases with bluffness and blockage ratio, the extent of second region in the nondimensional form $(x_r-x_m)/x_m$ increases with bluffness and blockage ratio, as shown in Table 1. However, the dimensionless length of the recirculation region (x_r/d) decreases with bluffness and blockage ratio for 2-D models and increases with bluffness for axisymmetric models.

V. Conclusions

Distribution of static pressure on the wake centerline indicates that a low-pressure trough is formed close to the base for both two-dimensional and axisymmetric models. Similarity in static pressure and the velocity defect distribution is found to exist for both 2-D and axisymmetric models in terms of suggested length and velocity scales.

The difference between the near wakes of 2-D and axisymmetric bluff models appears in the opposite variation of the characteristic length scale and length of recirculation region. In the 2-D case, these lengths decrease with the minimum pressure coefficient, while in the axisymmetric case they increase. A shielded hot wire is found useful in measurements of velocity on the wake centerline.

Effect of increasing blockage ratio for 2-D models is to decrease $c_{p\min}$ and x_m. As far as the distribution of mean-flow properties is concerned, the effect is similar to increase in bluffness. Dimensionless characteristic length x_m/d decreases with increase in blockage ratio. However, blockage effects are small for blockage ratios up to 10%.

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