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Subsonic Axisymmetric Base Flow Experiments with Base Modifications

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The mean flow in the near wake of a blunt base of a body of revolution is investigated in some detail. Further, a detailed study has been carried out to show how modifications to the base affect the near-wake flow and the base drag of the body. The results indicate that those base modifications which have been shown to yield significant drag reduction in two-dimensional low-speed flows will not necessarily do so in three-dimensional flows. This is because of the quite different nature of the flow in two- and three-dimensional wakes.

Nomenclature

C = center of base
C_D = total drag coefficient
C_{DB} = drag coefficient referred to base
C_p = pressure coefficient $= 2(p - p_\infty)/\rho U_\infty^2$
C_{pB} = base pressure coefficient
$\bar{C}_p$ = Calvert's parameter $= (C_p - C_{p\min})/(C_{p\max} - C_{p\min})$
D = diameter of the body
Δh = dynamic head
L = total length of the body
L' = length of the cylindrical portion
l = distance downstream from the transition ring
p = static pressure
r = radial distane from center of base
R = base radius
S = stagnation point
U = velocity outside the boundary layer
U_{CL} = velocity along the wake centerline
u = velocity in the boundary layer
x = axial distance from base (positive downstream, negative upstream)
X = axial location of the rear stagnation point
$\bar{x}$ = Calvert's parameter $= (x - x_m)/(X - x_m)$
y = radial or normal distance from the wake axis; also, normal distance from the surface of the model
θ = angular position of the pressure tappings on the base
δ = boundary-layer thickness
ρ = density

Subscripts

B = on the base
CL = along the wake centerline
m = minimum pressure location along the wake axis
∞ = freestream conditions

Introduction

PROVIDING a blunt base is almost always essential for bodies of revolution such as rockets, missiles, or even slender fuselages of aircraft, because it is in the aft region of these vehicles that propulsion units are normally installed. However, a blunt base will give rise to so-called base drag, which is an appreciable part of the total drag of the vehicle.

During the last few years, there have been several investigations[1-7] concerning the base pressure and base drag with respect to bodies of revolution in low-speed flow. A review of these studies shows that not all aspects of the base flow problem have been looked into, and that there still is a need for a thorough understanding of the flow in the wake region of a blunt based body of revolution.

For a body with a blunt base, the flow separates from the body in passing around the base. When the flow separates, a reduced pressure is produced on the base. This reduction in pressure is caused by the tendency of the two separated streams on either side of the base to entrain fluid from the base region and carry it away. Since no net mass can be removed, under steady flow conditions, a pressure gradient must be established to return the flow to this region, and counteract the scavenging tendency of mixing with external streams. A lower pressure in the base region is also compatible with the need to turn the external flow toward the axis of the body and thus cause the wake to close and terminate the separation region. A steady base flow with a recirculating fluid between the base and the rear stagnation point is thus obtained. The periodic vortex shedding, so pronounced in the case of two-dimensional base flows,[8] does not appear to be very prominent in an axisymmetric base flow.[2] The mean flow pattern dominates the wake.

In the present experiments, we have investigated, in some detail, the mean flow in the near wake of a blunt base of a body of revolution. Further, a detailed study has been carried out to find out how modifications to the blunt base geometry would affect this near-wake flow and what conseouences they would entail regarding the base drag of the body.

Experimental Setup and Technique

Figure 1a shows the basic model used for the tests. The forebody has an elliptical nose 165 mm long, while the central cylindrical portion is 177 mm long. The rear portion, which incorporates either the plain blunt base or its modifications, is interchangeable and 115 mm long. Thus, the model had a fineness ratio of 6.0.

Reference 5 points out that the location of the transition wire has a powerful influence on the base drag. It was also found that to obtain consistent data, the transition wire is best located well ahead of the base. In view of these considerations, a 1 mm diam transition ring was provided at the end of the forebody so that the boundary layer at the base was rendered turbulent.

The model was set along the axis of the tunnel at zero incidence to the freestream. It was supported by a strut from the

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Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Viscous Nonboundary-Layer Flows; Subsonic Flow.

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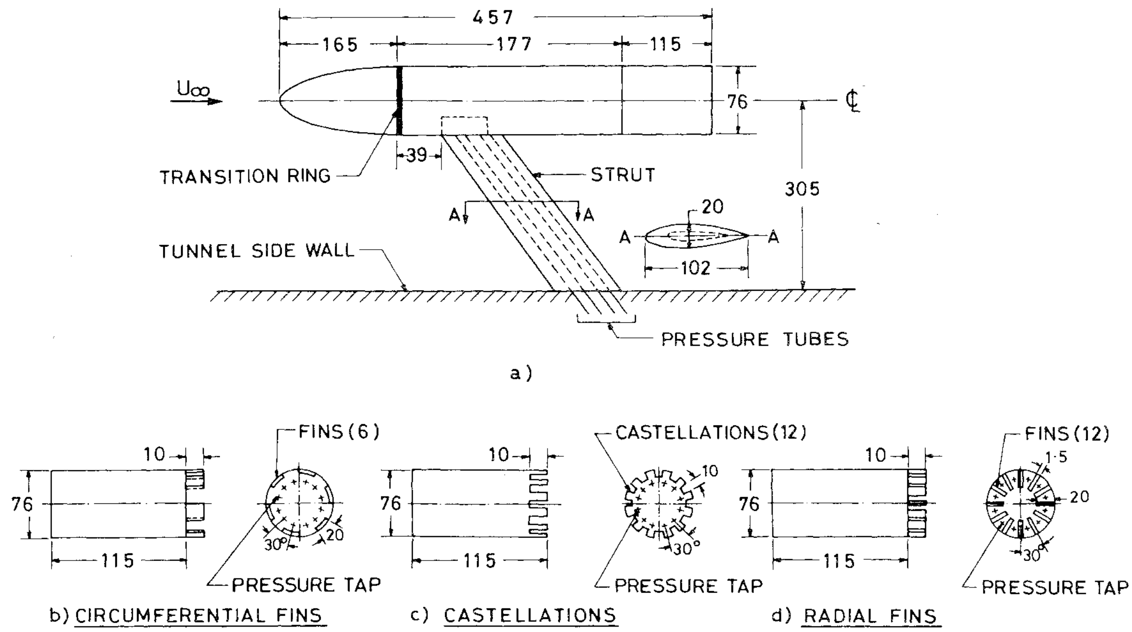

Fig. 1 Details of the basic model and base modifications (all dimensions in mm).

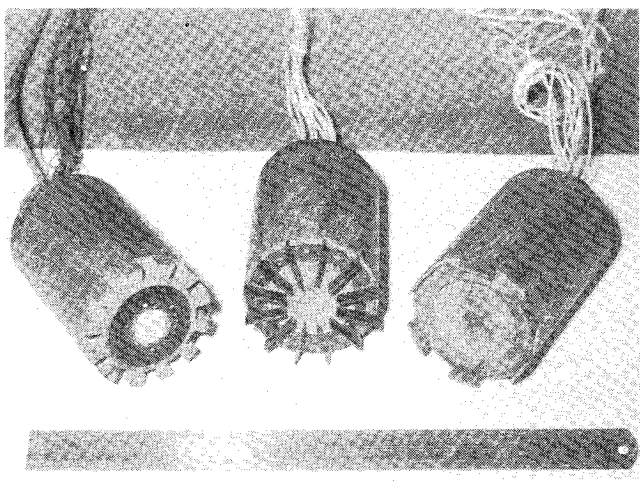

Fig. 2 Photograph of base configurations.

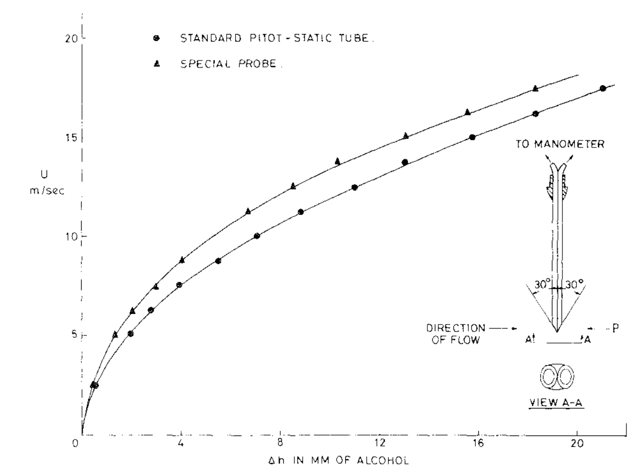

Fig. 3 Special probe calibration.

sidewall of the tunnel as shown. The strut had a thin symmetrical airfoil section and was swept back at an angle of about 45 deg. It was provided with internal grooves through which tubings of 1 mm diam connected to the pressure tappings were drawn. The model was held rigid and was free from vibrations during the experiments.

In all, three base modifications were considered, with the plain blunt base being used as a datum for comparison. The first modification consisted of a base with six circumferential fins (Fig. 1b). The length, breadth, and thickness of each fin were 10, 20, and 1.5 mm, respectively. The second was a base with 12 castellations or cut in grooves (Fig. 1c). The grooves were cut parallel to the axis and radially inward. The length, width, and depth of the grooves were 10 mm each. In addition, another model was used that had six castellations. This had a provision to vary the depth of the groove from 5 to 20 mm in steps of 5 mm. In order to investigate the pressure variation in the grooves with the change in depth of the groove, pressure tappings were provided on the sidewalls of the groove. Thirdly, a base with 12 radial fins (Fig. 1d) was considered. Each fin had a length, breadth, and thickness of 20, 10, and 1.5 mm, respectively.

All the configurations generally had 12 tappings on the base, equally spaced on a circle of radius 31 mm ($r/R = 0.825$) in addition to the central tapping. A reasonable indication of the base pressure could thus be obtained. Figure 2 shows a photograph of these base configurations.

Total and static pressures were measured using probes of standard design. The probes were made up of 0.93 mm o.d. hypodermic tubing. For the static probe, the orifices were 0.35 mm in diameter, equispaced in a radial plane. In addition, a special probe was designed to locate the rear stagation point in the recirculating region behind the base. With this probe, it was possible to obtain the velocity head directly as it could read the difference of total and static pressures at any location. The probe was made of 0.93-mm diam hypodermic tubes attached together and with their mouths chamfered at 30 deg. The mouth of the tube facing the flow direction would read the total pressure, whereas the one opposite to it would read the static pressure. The velocity head could, therefore, be read directly. The probe was calibrated before use with a standard pitot-static tube and Fig. 3 shows the calibration curve. Using this probe, the velocities in the near wake could be measured to an accuracy of about 5%.

The experiments were conducted in an open-circuit low-speed wind tunnel with a test section of 610×610 mm at a freestream velocity of 25 m/s. The Reynolds number, based on freestream conditions and the base diameter, was 1.25×10^5.

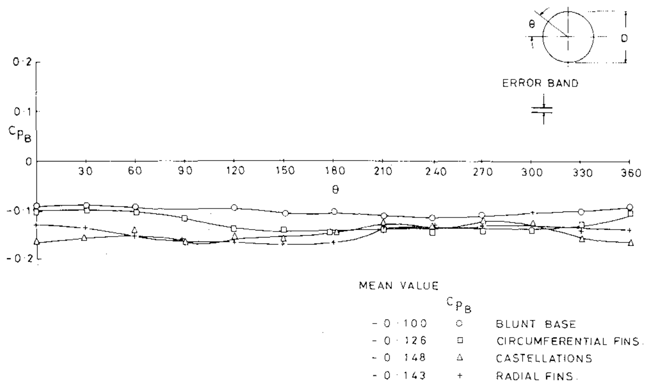

Fig. 4 Pressure distribution on the base.

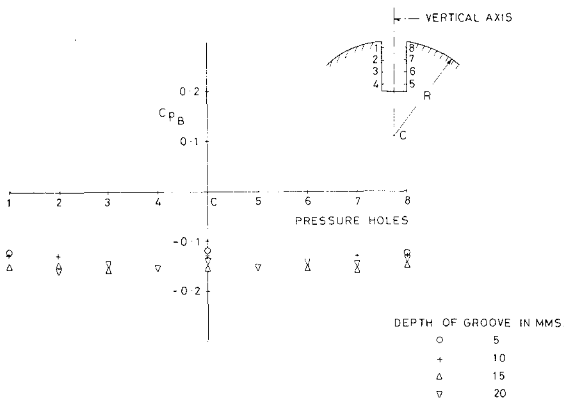

Fig. 5 Variation of C_{pB} vs depth of castellations.

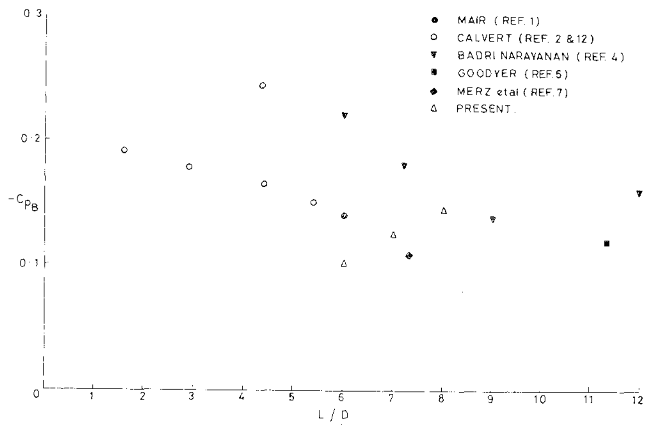

Fig. 6 Variation of C_{p_B} with L/D ratio.

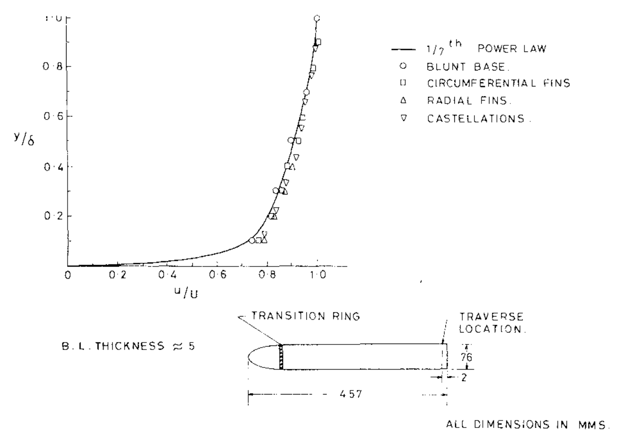

Fig. 7 Boundary-layer profiles near the base.

Solid and wake blockage were estimated to be about 1.87% and this was considered not serious enough to warrant any correction to the results due to blockage effects.

Throughout, the pressure measurements were made using a projection manometer with an accuracy of 0.25 mm of alcohol. This gave an overall accuracy of ± 0.008 in C_p.

Results and Discussion

Figure 4 shows the base pressure distribution of an axisymmetric body of revolution with a blunt base and for modified base geometries. It is seen that in the presence of modifications the base pressure has decreased, which implies an attendant increase in base drag. For the base with castellations and radial fins the base pressure is much lower. For the base with circumferential fins, the decrease in base pressure is not very significant in comparison with the blunt base. The results also show that there are no serious effects due to strut interference. As the base pressure decreases in the presence of all modifications, it would mean that for an axisymmetric base flow, vortex suppression devices like castellations etc. will not be effective as drag reducing devices in the manner they have been shown to be in two-dimensional base flows.[9] This is because a large part of the low-pressure region of the base of an axisymmetric body of revolution is associated with the diffusion of momentum across the shear layers and not in the dynamics of cast-off vortices.

Figure 5 shows the results obtained when the depth of the groove of castellations was varied. It is seen that the pressure decreases with increasing depth. It was also observed that pressures measured on the sidewalls of the groove were not significantly different from the pressure measured at the center of the base. This is in contrast with the two-dimensional castellated base wherein the pressure inside the groove (cut out) is significantly different from that measured outside the groove.[10,11]

A plot of the base pressure coefficient against the length-to-diameter ratio is shown in Fig. 6. The results from Refs. 1, 2, 4, 5, 7, and 12 (available in the open literature) are also shown in the same figure. The results shown in this figure for L/D of 7 and 8 were obtained from a subsidiary experiment conducted at the same freestream conditions and by varying the length of the central cylindrical portion of the model, keeping the base diameter constant. It is interesting to note that the maximum base pressure is observed for the finess ratio of around 6, and hence the base drag would be minimum. This result is consistent with the minimum drag for an axisymmetric body of finess ratio 6, as observed from the results quoted in Ref. 13. Another point to note is that while the present results and those of Refs. 1, 2, and 12 show a consistent trend, those of Refs. 4 and 5 are at variance. A possible reason for the discrepancy could be that in both these cases the base pressure has been measured using a pressure probe rather than by means of a pressure orifice drilled into the base.

Figure 7 shows the boundary-layer profiles near the base for all the base geometries. The profiles are quite close to the 1/7th power law profile. The boundary-layer thickness was about 5 mm. The existence of the turbulent velocity profile was also confirmed by plotting the measurements in terms of a log-log relation.

The pressure distribution obtained on the body is shown in Fig. 8. It is seen that although there is a somewhat steep decrease in pressures near the base, pressure distribution on the forebody is fairly independent of modifications to the base. This would mean that any change in total drag is mainly due to the change in base drag, which is a consequence of modification to the base geometry. An additional feature which is revealed is that the so-called "upstream influence" of

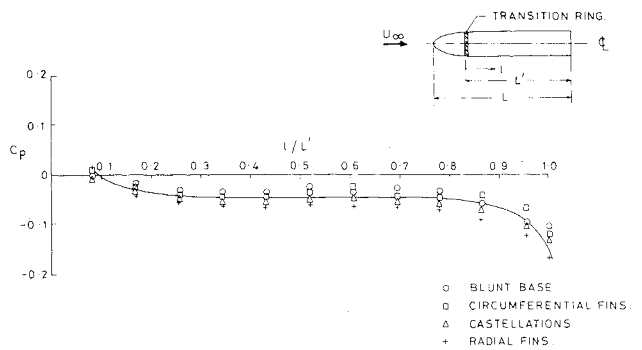

Fig. 8 Pressure distribution along the body.

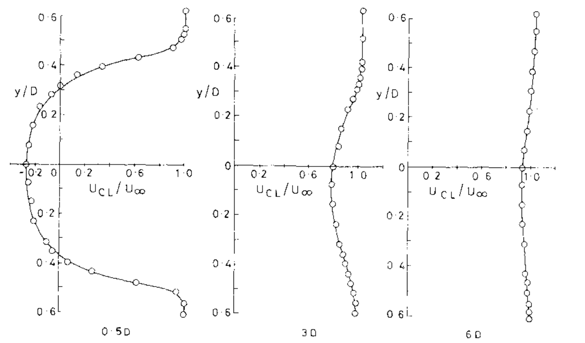

Fig. 11 Typical velocity profiles in the wake.

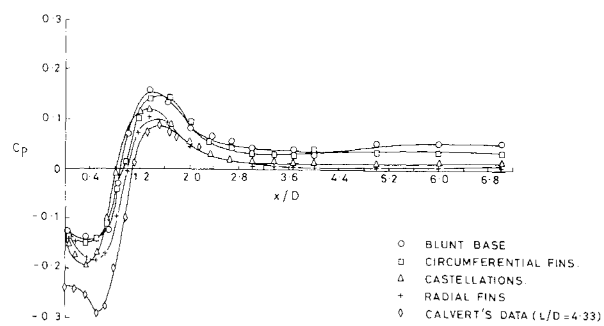

Fig. 9 Static pressure variation along the wake centerline.

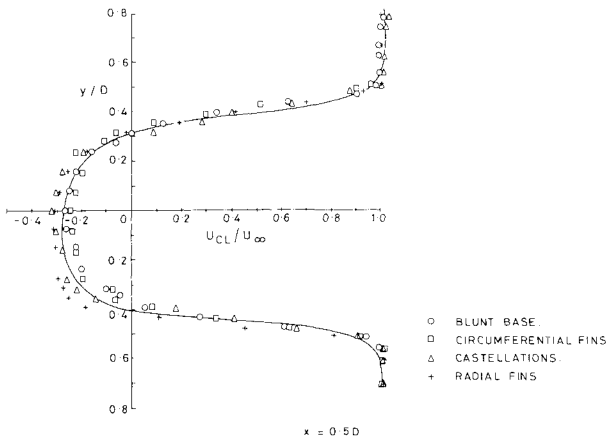

Fig. 12 Velocity profiles in the recirculation region.

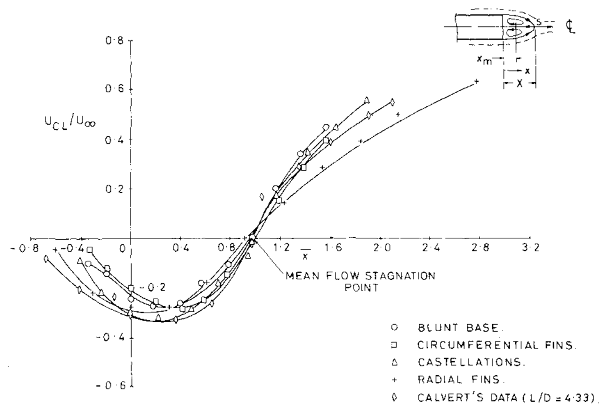

Fig. 10 Mean velocity variation along the wake centerline.

the separation process at the base extends to about 1 base diam ahead of the base. This is in contrast to the observations of Ref. 7, wherein the upstream influence of the base was found to extend as far as 3 base diam. For the present measurements, therefore, all the calculations have been referenced to a flow state existing at least 2 diam ahead of the base and so are believed to be free from any upstream influence of the base.

From earlier investigations (for example, Refs. 2, 6, and 7), it is clear that behind the blunt base of an axisymmetric body there is a fairly steady recirculating bubble flow with a stagnation point located downstream of the base. The dynamic pressure at this location should, therefore, be zero. The special velocity head probe described earlier was used to locate the rear stagnation point. It was found that for all base configurations tested, the rear stagnation point was at $x/D \simeq 1$ within the limits of experimental error.

The variation of static pressure along the wake centerline with the plain blunt base and in the presence of modified bases is shown in Fig. 9. In all cases, the static pressure reaches a minimum value slightly downstream of the base, rises to a maximum (above freestream static pressure) downstream of the mean flow stagnation point, and tends toward the freestream value far downstream. The measurements, however, could only be taken as far downstream as 7 diam from the base. The minimum pressure for all the base geometries is seen to occur at $0.30 \leq x/D \leq 0.50$. The maximum negative pressure is observed for the base with castellations and radial fins, compared with the blunt base and the base with circumferenctial fins. It is also seen that the pressure recovery downstream of the stagnation point is less in the case of base with castellations and radial fins. Results of Ref. 2 obtained along the wake centerline behind the blunt base of an axisymmetric body of revolution are also shown in Fig. 9. The trend is seen to be the same as has been observed in the present measurements.

Figure 10 shows the variation of mean velocity along the wake centerline. These results were obtained using the special velocity head probe. We note that the rear stagnation point is at $\bar{x} \simeq 1$. Figure 10 also shows Calvert's[2] results ($L/D = 4.33$) which is consistent with our observations. Also, the effect of modifications to the base on rear stagnation point location is not very significant, although velocity variations upstream and downstream of the stagnation point are appreciable. Particularly, it may be noted that the reversed velocities in the bubble seem to be comparatively higher for the castellated and radial-finned base. Calvert's data show higher reversed velocities in the recirculating zone, which might explain the reason for his obtaining a much lower base pressure.

The velocity profiles in the wake fall into two groups—those upstream of the stagnation point and those downstream of it. Figure 11 shows some profiles obtained at various distances behind the base. It is seen that the profiles are reasonably symmetrical. This is a further confirmation that strut interference has not been serious. Figure 12 shows the profiles obtained in the recirculation region ($x = 0.5D$). It is noted that large reversed velocities exist and are, in general, of the order of approximately 30% of the freestream velocity.

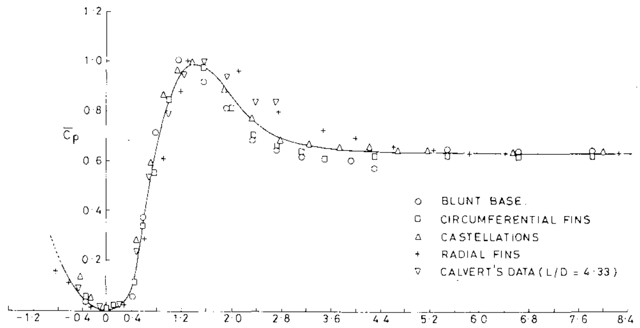

Fig. 13 Near-wake similarity for an axisymmetric body of revolution.

Similar observations have also been reported by Merz et al.[7] It is also interesting to note that although the velocities in the recirculating region are affected due to modifications to the base, the size of the recirculating region is not significantly affected.

The longitudinal wake similarity data are shown in Fig. 13. The parameters $\bar{C}_p$ and $\bar{x}$ were first suggested by Calvert.[2] Calvert's results are also shown on the same figure. It is interesting to note that up to the stagnation point, there is good correlation, while there is some scatter beyond. Our data are in quite good agreement with Calvert's results up to the stagnation point. The few data points that Calvert has beyond the stagnation point also show some deviation from the present data. Perhaps, this is an indication that these similarity parameters are valid from the base up to the stagnation point within the near-wake region. It may also be noted that the pressure peak is at $\bar{x} \simeq 1.4$, and the pressure coefficient at the stagnation point is $\bar{C}_p \simeq 0.85$. The base-pressure coefficient for the data corresponds approximately to $\bar{C}_p = 0.20$. Slight extrapolation of the curve to $\bar{C}_p = 0.3$ corresponds to $\bar{x} \simeq -1.0$, in agreement with Calvert's results.

Conclusions

The present investigation has shown that:

1) The wake behind a plain blunt base of an axisymmetric body of revolution is steady with a closed recirculation region forming a bubble. The wake width in the recirculation region was found to be less than the base diameter.

2) Neither the size of the recirculating bubble nor the position of the rear stagnation point was significantly affected by modifications to the base geometry. The rear stagnation point was located at $x/D \simeq 1.0$.

3) The base pressures, however, were affected by modifications to the base geometry and tended to increase the base drag. The base with castellations was found to give maximum drag (an increase of nearly 50%), while that with circumferential fins produced only a small increase over that for the plain base. Our observations that modifications to the base increase the base drag is consistent with earlier measurements of Goodyer.[5]

4) The similarity parameters proposed by Calvert for the near-wake region of axisymmetric bodies in low-speed flow correlated the present data quite well.

5) Finally, the present measurements have shown that those base modifications which have been shown to yield substantial drag reductions in two-dimensional flows will not necessarily do so in three-dimensional flows. This is because of the quite different nature of the flow in two- and three-dimensional wakes.

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