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Wake development in turbulent subsonic axisymmetric flows

J. L. F. Porteiro, V. Perez-Villar

Abstract The development of the wake velocity and turbulence profiles behind a cylindrical blunt based body aligned with a subsonic uniform stream was experimentally investigated as a function of the momentum thickness of the approaching boundary layer and the transfer of mass into the recirculating region. Measurements were made just outside of the recirculating region at distances of 1.5, 2 and 3 diameters downstream of the cylinder. Results indicate that, even at these short distances from the cylinder base, the velocity profiles are similar. They also show that the width of the wake increases with the thickness of the boundary layer while the velocity at the centerline decreases. Near wake mass transfer was found to alter centerline velocities while the width of the wake was not significantly altered. Wake centerline velocity development as a function of boundary layer thickness is presented for distances up to three diameters from the base.

List of symbols

b	Dimensionless half-wake radius
D	Base diameter
r	Radial distance from centerline
R	Base radius
U	Axial velocity
U_{max}	Maximum axial velocity
W	Base mass transfer rate
x	Axial distance from base (posit.:downstream; negat.:upstream)
$\%T$	Turbulence level (%) $\%T=\frac{\sqrt{(\overline{u'^2})}}{U}*100$
Γ	Near-wake mass transfer coefficient; positive values imply blowing, negative values imply suction $\Gamma=\frac{W}{\pi R^2\rho_\infty U_\infty}$
δ_1^*	Boundary layer displacement thickness at $x=-3D$
δ^*	Dimensionless boundary layer displacement thickness $\delta^*=\frac{\delta_1^*}{R}$
Θ_1	Boundary layer momentum thickness at $x=-3D$
Θ	Dimensionless boundary layer momentum thickness $\Theta=\frac{\Theta_1}{R}$
ρ	Density

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1 Introduction

The complex flowfield generated by the separation and recirculation of flow behind a bluff body immersed in a viscous subsonic stream, while qualitatively understood (Hoerner 1958; Chang 1970; Tanner 1973), has generally resisted reliable analytical treatment. Figure 1 illustrates the time averaged flowfield produced by an axisymmetric cylinder aligned with the flow. The approaching boundary layer is unable to negotiate the abrupt change in geometry of the base and consequently separates from the body. The separated flow forms a free shear layer which entrains mass from the region immediately behind the base, resulting in a pressure reduction in this region. As the sheer layer approaches the flow centerlines; its velocity decreases, the streamline curvature becomes more pronounced, and the static pressure increases. The portion of the shear layer with sufficient kinetic energy to overcome this pressure rise realigns itself with the centerline, passes on downstream, and develops into a viscous wake. The portion without sufficient kinetic energy curves inwards towards the base, realigns itself with the centerline and recirculates. It is clear that changes in the thickness of the approaching boundary layer will alter the shear layer and

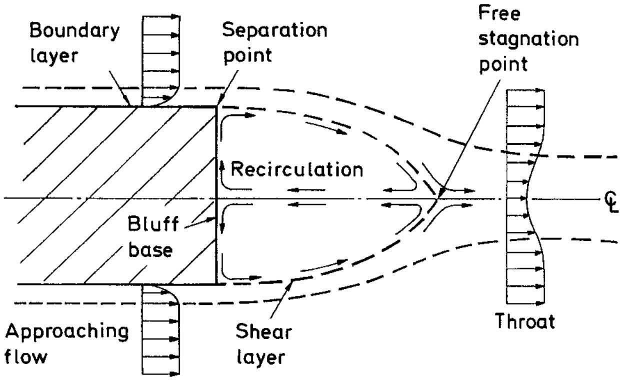

Fig. 1. Near-wake flowfield schematic (no near-wake mass transfer)

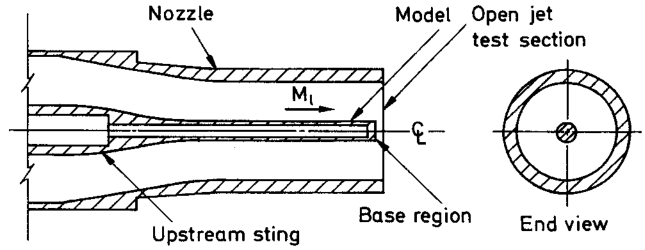

Fig. 2. Facility test section

recirculating flow region. The influence of boundary layer thickness on near wake properties such as base pressure has been well established experimentally both in subsonic (Koh 1971; VanWagenen 1968) and supersonic (Kurzweg 1951; Lehnert and Schermerhorn 1966) flow. In a similar manner, altering the mass balance of the near wake through mass suction or injection is an effective way of altering the structure of the recirculating region and controlling the base pressure (Przirembel 1979; Przirembel and Riddle 1975; Porteiro et al. 1983; Porteiro, 1986).

The purpose of the present experimental investigation was to study the influence of these two processes in the development of the wake velocity and turbulence profiles as a means of furthering our understanding of the mechanisms through which they modify base drag. The determination of the dependency of the velocity profiles on the momentum thickness of the approaching boundary layer is also of importance for the development of an analytical model of the flow (Page and Ostowari 1988).

2
Experimental apparatus and technique

This experimental investigation was conducted in an open jet facility designed and constructed for interference-free studies of turbulent, axisymmetric near-wake at subsonic speeds. As shown in Fig. 2, its support sting was designed as an integral part of the nozzle to produce uniform flow over a 1.9 cm diameter cylindrical model. The nozzle has an overall contraction ratio of 8 : 1 and an exit diameter of 10.16 cm. A detailed study of the characteristics of the tunnel showed that the tunnel provides an excellent flow field for near-wake investigations at subsonic Mach numbers.

Boundary layer blowing and suction were used to alter the thickness of the approaching boundary layer. This was carried out through a porous metal support sleeve extending from the model support sting to 3 diameters upstream of the model base. The porous metal sleeve was 8.25 cm long, 0.159 cm thick, and 1.9 cm outside diameter. Base mass transfer took place through a porous metal base plate 1.9 cm in diameter and 0.159 cm thick. Measurements were made to insure that the boundary layer remained axisymmetric for all blowing rates (up to boundary layer separation) and for all suction rates. Measurements were taken at the base at 4 positions, 90° apart; and 3 diameters upstream of the base, 180° apart. These measurements showed the boundary layer to be symmetrical in all cases.

Boundary layer velocity measurements were made at a location 3 diameters upstream of the base with a miniature total pressure probe. The probe position could be determined to within 0.025 mm in 152.4 mm total travel. Total pressure measurements were taken at 27 radial locations chosen to provide detailed information on the velocity profile.

The total and static pressures on the centerline of the wake behind the model were measured. This was accomplished by extending either a straight total or static pressure probe from the blunt base through a hole in the center of the base. Both probes consisted of a straight piece of stainless steel tubing with an O.D. of 0.89 mm. The tip of the total probe was open and rounded while the tip of the static probe was plugged and rounded. The static probe had an orifice 0.56 mm in diameter located on the side wall 0.60 cm from the tip. The location of the probes was changed by manually sliding them in and out of the base. The position was determined with a depth micrometer accurate to 0.025 mm. The pressure sensed by the probes was measured on an alcohol manometer readable to 0.05 mm of water.

Wake velocity surveys were made with a constant temperature hot wire anemometer. The probe position could be determined within 0.025 mm in either the vertical or axial direction. All test were conducted at a nominal Mach number of 0.11.

3
Results and discussion

The influence of the thickness of the approaching boundary layer on wake development was studied for increasing values of the momentum thickness until the magnitude of the boundary layer blowing caused boundary layer separation. Results obtained under those conditions are identified with the label "Separated boundary layer". The effects of several rates of base blowing and suction were also investigated. Hot wire velocity measurements were made at locations 1.5, 2 and 3 base diameters downstream of the base.

The influence of the boundary layer momentum thickness is shown in Fig. 3 and 4. Boundary layer thickness alters both centerline velocity and the general shape of the velocity profile. Thicker boundary layers induce lower centerline velocities and produce a wider wake. Upstream separated boundary layers behave as very thick boundary layers. The increase in width of the wake can be directly attributed to the physical increase in

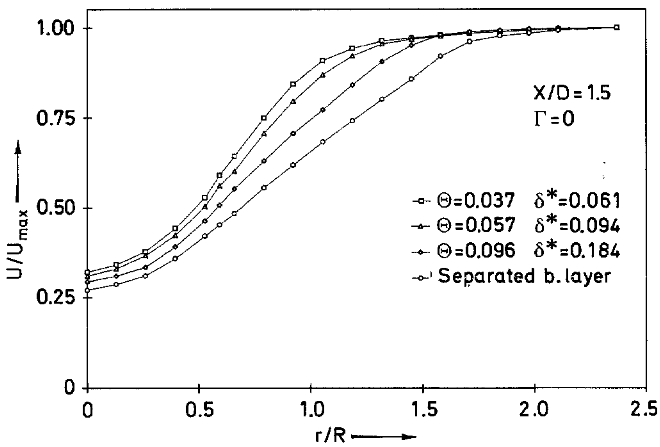

Fig. 3. Influence of boundary layer thickness on velocity profiles. ($x/D = 1.5$)

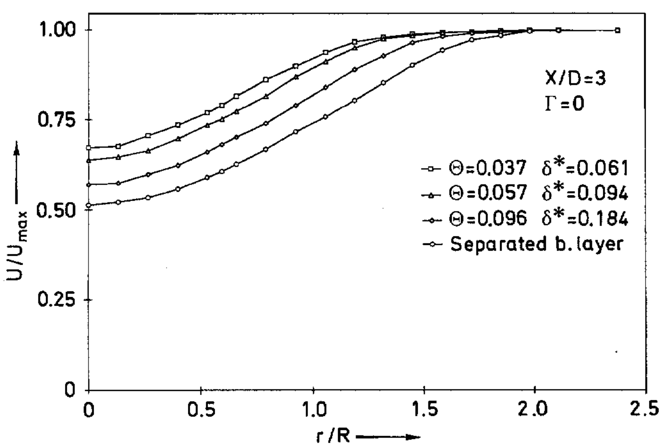

Fig. 4. Influence of boundary layer thickness on velocity profiles. ($x/D = 3$)

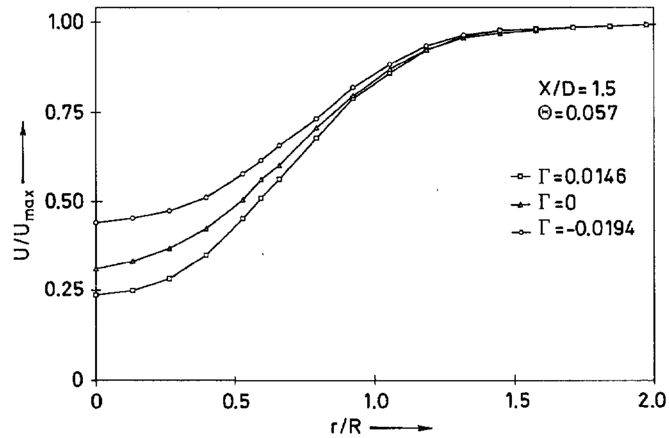

Fig. 5. Velocity profile development as a function of near wake mass transfer. ($x/D = 1.5$)

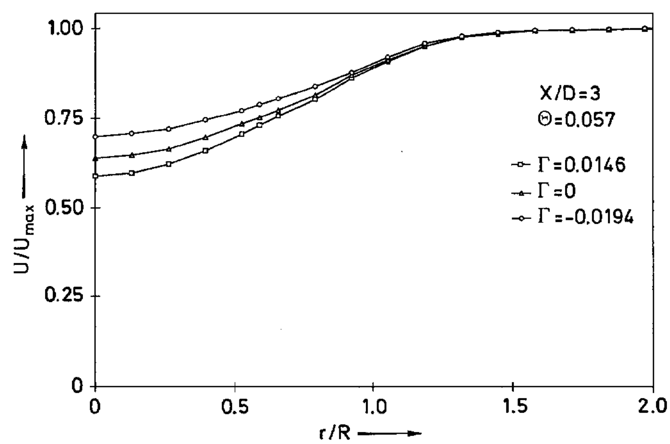

Fig. 6. Velocity profile development as a function of near wake mass transfer. ($x/D = 3$)

the thickness of the boundary layer. The displacement thickness grows by a factor of 3 from the thinnest to the thickest layer, from 6% to 18% of the radius of the cylinder. In terms of the wake width at the separation point this is equivalent to an increase in the radius of the cylinder and results in a wider wake downstream. The effects of the boundary layer thickness on centerline velocity are more complex. It has been shown by Porteiro et al. (1983) that increasing the thickness of the boundary layer moves the stagnation point closer to the base. Since the distance between the base and the point where the measurements were taken was the same for all boundary layer thicknesses, the length over which the centerline velocity is allowed to grow before being measured (i.e. the distance between the stagnation and measurement points) increases with the boundary layer thickness. In this way, if the centerline velocity growth rate was to remain constant for all cases, longer development lengths should result in higher centerline velocities, and wake centerline velocity should increase with boundary layer thickness. As shown in Figs. 3 and 4 thicker boundary layers, despite a longer development length result in lower centerline velocities, clearly indicating that centerline velocity growth rates are not constant and that they are much larger for thin boundary layers than for thick boundary layers. It is clear from these data that the dominant parameter in centerline velocity growth is the velocity gradient in the radial direction. This is also supported by the fact that centerline velocity growth from 1.5 to 2 diameters is larger than that from 2 to 3 diameters (see Fig. 10).

The effect of near-wake mass transfer is presented in Figs. 5 and 6. The main effect of the mass transfer is to alter the centerline velocity while the width of the wake is not changed significantly. Base bleed decreases the centerline velocity while base suction has the opposite effect. It is apparent that the changes in centerline velocity due to the near-wake mass transfer are a direct consequence of the changes in the free stagnation point location that such transfer brings about. As shown by Porteiro et al. (1983), base bleed moves the stagnation point location away from the base in a linear way while base suction has the opposite effect. As in the boundary layer case, the distance between the base and the point where the measurements were taken was the same for all base transfer rates and, therefore, the length over which the centerline velocity is allowed to grow before being measured is a function of the base mass transfer rate, increasing with increasing

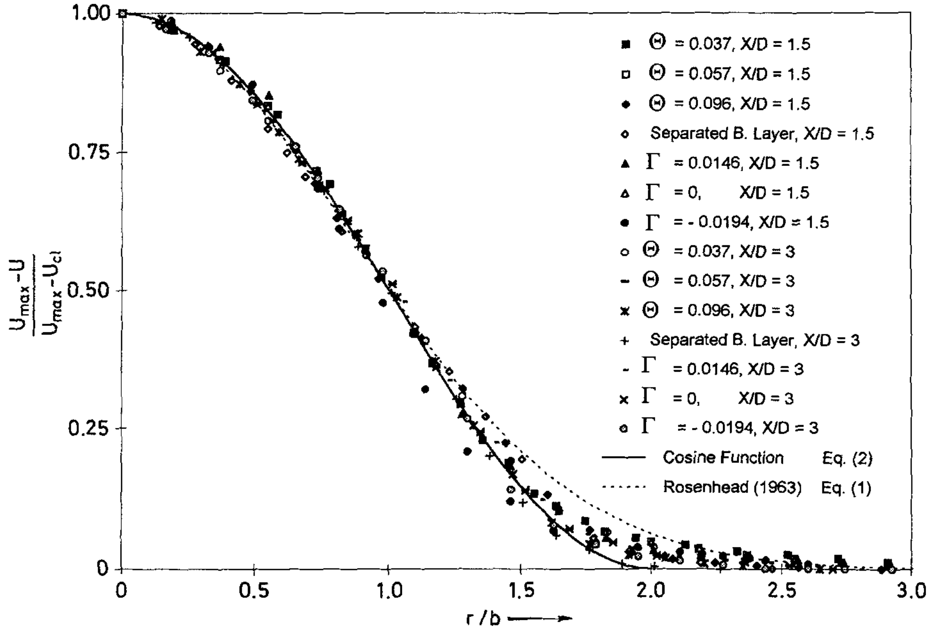

Fig. 7. Velocity profile similarity for developing wakes

suction rates and decreasing with increasing base bleed rates. Since base mass transfer rates do not significantly alter the width of the wake, velocity gradients are similar for all cases and wake development length is the controlling parameter in centerline velocity growth, longer development lengths resulting in higher centerline velocities.

While there is no significant change in wake width from a distance of 1.5 to 3 diameters from the base for any of the velocity profiles shown in Figs. 3–6, centerline velocity increases significantly in all cases. In Figs. 3 and 4 it can be observed that profiles with higher centerline velocities (those with thinner boundary layers) exhibit greater centerline velocity growth than those with lower initial centerline velocities (corresponding to velocity profiles resulting from thicker boundary layers). For Figs. 5 and 6 the opposite is true as centerline velocity growth is large for those profiles with lower initial centerline velocity. In all cases it is clear that centerline velocity growth from 1.5 to 3 diameters is directly related to velocity gradients in the wake.

The similarity of the velocity profiles given in velocity defect form is studied in Fig. 7. This figure also shows a comparison between the experimental data, Rosenhead's formulation for the axisymmetric wake (Rosenhead 1963) in the form:

$$\frac{U_{max}-U}{U_{max}-U_{CL}}=\exp\left(-a\left[\frac{r}{b}\right]^2\right),\ \text{where } a=0.69315 \tag{1}$$

and the cosine formulation given by Ostowari and Page (1989) in the form:

$$\frac{U_{max}-U}{U_{max}-U_{CL}}=1-0.5\left(1-\cos\left[\frac{\pi r}{4b}\right]\right) \tag{2}$$

The data presented is for profiles measured at 1.5 and 3 diameters downstream of the base that were obtained through boundary layer blowing and/or base mass transfer. The degree of similarity is remarkable despite the fact that two different techniques of near wake modification are present and that the velocity profiles were measured at locations very close to the rear stagnation point of the recirculating flow. The agreement of the experimental data with the analytical solution given by Eq. (1) is excellent for values of r smaller than the half-wake width b. For the case of Eq. (2), agreement is excellent within the range of applicability of the equation ($r \leq 2b$) making it an useful tool for the analysis of turbulent wakes.

Figures 8 and 9 present the evolution of the turbulence levels in the wake as a function of the thickness of the boundary layer. While all profiles exhibit the same centerline turbulence levels (35%) at the 1.5 diameters station, the values at 3 diameters range from 12% to 15%, thinner boundary layers resulting in lower turbulence levels. It is quite possible that the higher values of the turbulence for values of r/R greater than 1 shown on Fig. 8 might be the result of the boundary layer blowing mechanism used since boundary layer thickness is increased by mass injection through the porous sleeve located before and up to $x/D=3$. The influence of base mass transfer is presented in Fig. 10 and 11. At 1.5 diameters downstream centerline turbulence levels range from 27% to 42%, the lower levels being obtained with base suction and the higher one with base blowing. It should be noted that profiles with higher centerline velocities had lower turbulence levels. At 3 diameters centerline turbulence level profiles were similar to those obtained for attached boundary layers without base mass transfer.

The development of near- and developing-wake centerline velocities as a function of the boundary layer thickness is shown in Fig. 12. It can be seen that thin boundary layers induce higher centerline velocities than thick boundary layers.

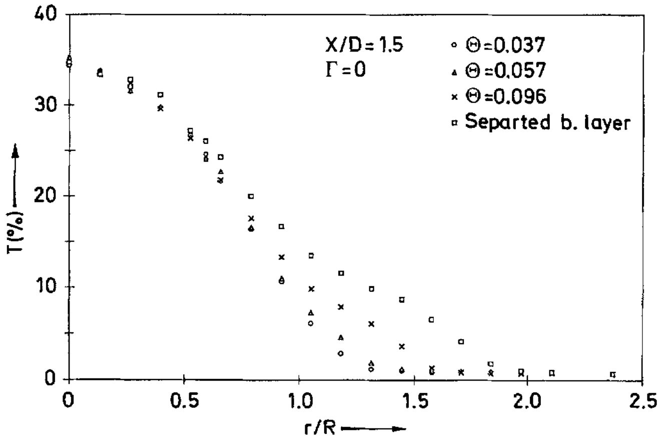

Fig. 8. Turbulence levels as a function of approaching boundary layer thickness. ($x/D=1.5$)

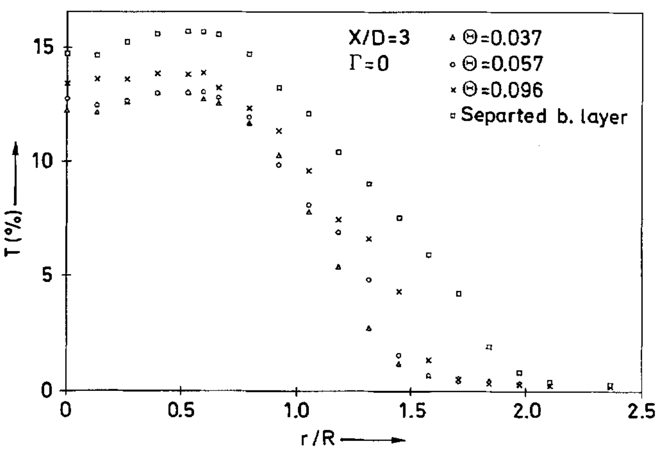

Fig. 9. Turbulence levels as a function of approaching boundary layer thickness. ($x/D=3$)

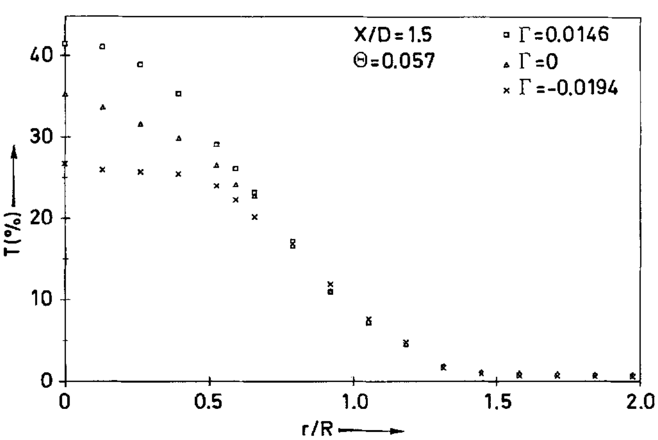

Fig. 10. Variation of turbulence levels with near wake mass transfer. ($x/D=1.5$)

This is true both inside the recirculation region, where velocities are negative or towards the base, as well as outside, where they are positive. It is also interesting to note that the rate of growth of the centerline velocity decreases as boundary

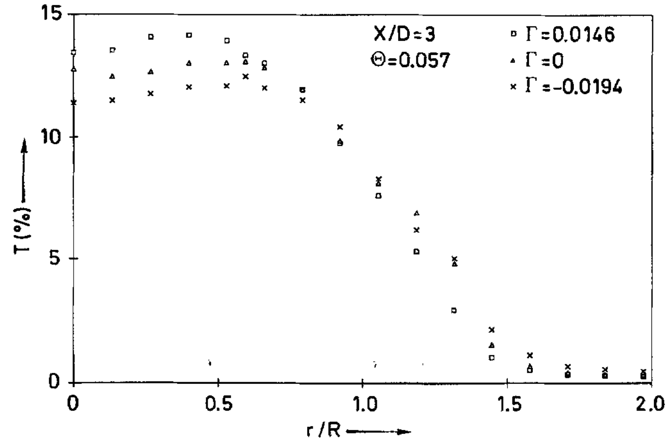

Fig. 11. Variation of turbulence levels with near wake mass transfer. ($x/D=3$)

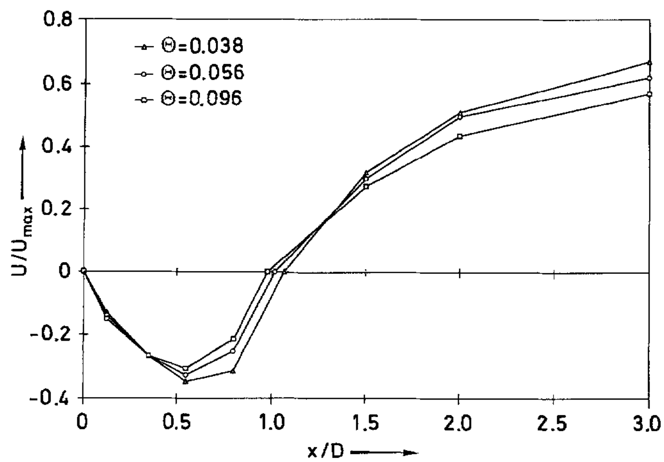

Fig. 12. Centerline velocity development in the recirculating and developing wake regions

layer thickness increases. This is consistent with the concept that the main controlling factor in velocity growth is the steepness of the velocity profile, since thinner boundary layers give rise to narrower wakes and steeper profiles. For the natural boundary layer case ($\Theta=0.059$, no boundary layer blowing, no base mass transfer) the recirculating region is about one diameter long, the maximum (negative) velocity is approximately 33% of the freestream velocity and it is found at $x/D=0.65$. Outside the recirculating region, centerline velocity grows to 31% of freestream in the first half diameter of travel, to 49% in the second half diameter and then more slowly, to 64% in the next diameter of travel.

4
Summary and conclusion

Near wake and boundary layer mass transfer are very effective mechanisms in altering the development of the velocity profiles outside the recirculating region, by altering their width and centerline velocity. Their influence on turbulence levels is less pronounced. While there was no significant growth in the width of the wake from 1.5 to 3 diameters downstream of the base, centerline velocity grows very rapidly from the stagnation point, (approximately one diameter downstream) to 2 diameters downstream and at a much slower pace from 2 to 3 diameters downstream. All velocity profiles showed a remarkable degree of similarity that was not destroyed by either base or boundary layer mass transfer and were in good agreement with analytic solutions of the flow.

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