Modification of Subsonic Wakes Using Boundary Layer and Base Mass Transfer

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The influence of boundary-layer thickness and near-wake mass transfer on the turbulent near wake of a cylindrical blunt-based body aligned with a uniform freestream was experimentally investigated. Tests were conducted at $M=0.11$ and 0.06 in a wind tunnel utilizing an upstream support system. Results indicate that the thickness of the approaching boundary layer has a dominant influence on base pressure. Base pressure increases with the thickness of the boundary layer. Base mass transfer into the near-wake increases base pressure, while base suction has the opposite effect. Both boundary-layer thickness and base mass transfer have a significant influence on the size, pressure, and velocity fields of the near wake.

Nomenclature

C_p = pressure coefficient $= 2(P-P_s)/\rho_\infty U_\infty^2$
C_{p_b} = base pressure coefficient
C_q = boundary-layer mass transfer coefficient $=\rho_w U_w/\rho_\infty U_\infty$ (positive: blowing; negative: suction)
D = model diameter
H = boundary-layer shape factor, ratio of the displacement thickness to the momentum thickness
M = Mach number
M_{CL} = near-wake centerline Mach number
m_B = base mass transfer rate
P = pressure
P_b = base pressure
P_s = static reference pressure (at $X/D=-3$)
R_0 = model radius
U = axial velocity
$U_{\max}$ = maximum axial velocity
X = axial distance from base (positive: downstream; negative: upstream)
$X_{s.p.}$ = location of rear stagnation point
Γ = base mass transfer coefficient $= m_B/\pi R_0^2 \rho_\infty U_\infty$ (positive: blowing; negative: suction)
θ = dimensionless boundary-layer momentum thickness $=\theta_I/R_0$
θ_I = boundary-layer momentum thickness at the reference point (at $X/D=-3$)
ρ = density

Subscripts

∞ = freestream condition
w = condition at the wall

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Introduction

THE separation of flow at or near the base of a bluff body moving through a real fluid leads to the development of a free shear layer, the creation of a trailing stagnation point or region, and the recirculation of flow behind the base. This recirculation region is usually referred to as the near wake of the body and has a significant influence on base drag, base heat transfer, and the configuration of the far wake. The near wake is dominated by the mixing processes associated with the free shear layer which is characterized by large velocity gradients and intense shear that lead to the production of turbulence. A schematic of the various flow components which characterize the wake of a bluff axisymmetric body is shown in Fig. 1.

Despite its practical importance, the subsonic near-wake problem has received relatively little attention in comparison with its supersonic counterpart. While qualitatively understood,[1-3] until recently it has resisted reliable analytical treatment. Analytical results[4-7] indicate a strong dependency of the base pressure on the momentum thickness of the approaching boundary layer. While this influence of the momentum thickness on base pressure has been well established experimentally both in supersonic[8,9] and subsonic[4,10] flows, there are only a very limited number of experiments[11] in which both the base pressure and the thickness of the boundary layer were measured.

Altering the mass balance of the near wake has been proved effective in the control of base pressure in two-dimensional flow. However, other than the work of Przirembel[12] and Przirembel and Riddle,[13] there have been no studies of the effect of base bleed and suction on base pressure in subsonic axisymmetric flow.

The present experimental investigation was prompted by two apparent needs. One was the acquisition of reliable, consistent data relating approaching boundary-layer thickness to base pressure. This is of paramount importance for the development of an appropriate analytical model of the flow. The second was the investigation of the effectiveness of using variations in the thickness of the boundary layer and in the mass balance of the near wake to control base flow.

Experimental Apparatus and Technique

This experimental investigation was conducted in a second generation Rutgers Axisymmetric Near-Wake Tunnel (RANT II). This tunnel is an open-jet facility designed and con-

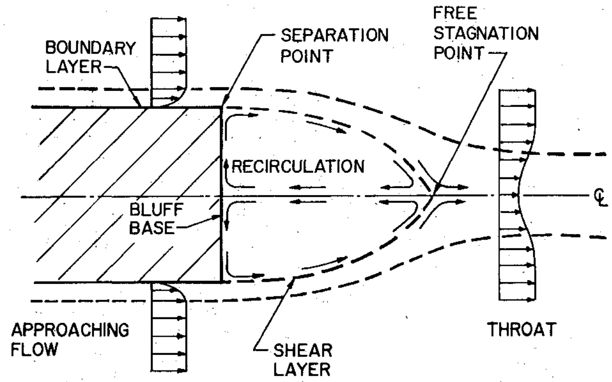

Fig. 1 Near-wake flowfield schematic (no near-wake mass transfer).

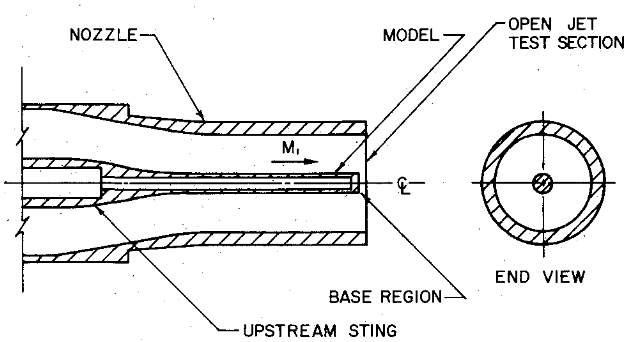

Fig. 2 RANT II test section diagram.

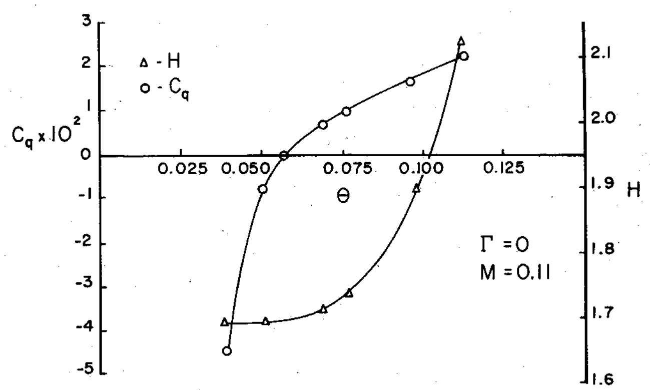

Fig. 3 Boundary-layer parameters vs boundary-layer blowing and suction.

structed for interference-free studies of turbulent, axisymmetric near wakes at subsonic speeds. As shown in Fig. 2, the unique feature of RANT II is an upstream sting that 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. This is the same facility used by Merz et al.[14] in his study of subsonic axisymmetric near wakes. A more complete description of this facility may be found in Ref. 11. A detailed study of the characteristics of the tunnel carried out by Merz[11] showed that the tunnel provides an excellent flowfield for near-wake investigations at subsonic Mach numbers.

The tunnel was modified and a test model developed in order to allow boundary-layer control and mass transfer through the base. No modifications affecting tunnel flow characteristics were made and the models used for testing had the same external dimensions as Merz's model, thus making applicable the available wealth of information about the tunnel flowfield.

Base flow control required the simultaneous and independent supply of different combinations of bleed air and suction to both the boundary layer and the near wake. Boundary-layer blowing and suction was carried out through a porous metal 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. The porosity of the sleeve was 40 μm.

Base mass transfer took place through a porous metal plate of 1.9 cm diameter, 0.159 cm thickness, and 100 μm porosity. Pressure regulators were used to stabilize bleed air pressure and Dwyer flow meters were used for metering. Suction flow rates were metered using Brooks flow meters. All flow meters were calibrated with sonic nozzles and a Statham P-24-250A-350 pressure transducer, which had been precalibrated with a Texas Instruments calibration unit. A more complete description of the boundary-layer and base flow control equipment can be found in Ref. 15.

Preliminary 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 four positions, 90 deg apart, and 3 diameters upstream of the base, 180 deg apart. These measurements showed the boundary layer to be symmetrical in all cases.

The tunnel stagnation pressure was monitored using a Kiel probe located in the tunnel plenum chamber. The probe signal was measured with a Statham ± 3.45 kPa g. transducer and an X-Y recorder. A water manometer readable to 0.13 cm of water was used as a check of the transducer readings.

Boundary-layer velocity measurements were made at a location 3 diameters upstream of the base with a United Sensor miniature total pressure probe and a Statham ± 3.45 kPa g. transducer. The probe was zeroed by electrical continuity and moved across the test section with a traversing mechanism. 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 pressure acting on the blunt base of the model was measured with a static pressure tap located at the center of the base. Measurements were taken simultaneously with the boundary-layer measurements and also in the absence of the boundary-layer probe. An alcohol micromanometer providing accurate readings to 0.05 mm of water was used. It should be noted, however, that a larger experimental error should be expected.

Reference static pressure measurements were also taken at an axial location 3 diameters upstream of the base. This location was shown by Merz et al.[14] not to exhibit base flow effects. This, as will be reported later, was not the case for this study. The readings were taken on the model surface at locations 180 deg apart and on the nozzle wall. An alcohol micromanometer readable to 0.05 mm was used. The static pressure was assumed to be constant across the boundary layer.

The Pitot and static pressures on the centerline of the wake behind the model were measured. This was accomplished by extending either a straight Pitot 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 Pitot 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 the alcohol manometer previously described.

This investigation was carried out with nominal Mach numbers of 0.11 and 0.06. The corresponding Reynolds numbers were 2.57 and 1.4×10^6/m. Nominal stagnation pressures were 102.18 and 101.58 kPa absolute and the value of the stagnation temperature 280 ± 10 K. The approaching boundary layers were turbulent.

Experimental Results and Discussion

The analysis of the wind-tunnel stagnation pressure revealed a peak-to-peak variation of about 2.5% for the average test run. It was also found that boundary-layer bleed and suction had a slight, but noticeable, influence on the stagnation pressure. To a much lesser extent, this was also the case for high rates of near-wake mass transfer. Maximum stagnation pressure increase due to boundary-layer blowing was under 3% and maximum decrease due to suction was under 2%. Variations due to near-wake mass transfer were, in all cases, very small and well under 1%.

Boundary layers were measured for 72 combinations of boundary-layer and near-wake mass transfer rates at $M=0.11$ and for 48 combinations at $M=0.06$. In both cases, boundary-layer separation determined the upper limit for boundary-layer blowing. The reference static pressure and the total pressure data from the boundary-layer measurements were reduced to velocity profiles by assuming constant static pressure across the boundary layer and isoenergetic flow for the tunnel. The values obtained for the thickness of the boundary layer ranged between 0.56 and 0.87 base radii. Boundary-layer velocity profiles included 15-17 data points, allowing the determination of the momentum and energy thickness by direct numerical integration of the experimental data. The influence of boundary-layer blowing and suction on the dimensionless momentum thickness and boundary-layer shape factor is shown in Fig. 3. A least squares method was used to fit the measured velocity profiles to a power law. The fit was good in general except for those resulting from blowing rates close to those needed for separation. The power law exponent N was found to be between 8.24 and 1.94 at $M=0.11$ and between 20.96 and 1.93 at $M=0.06$. The lowest values were obtained for boundary layers with blowing rates close to the rates needed for separation at the measuring point.

Static and base pressures were measured for the same combination of boundary-layer and base mass transfer rates used in the boundary-layer measurements. The static reference pressure decreased steadily as the thickness of the boundary layer increased. On the other hand, the base pressure increased with the momentum thickness. Figure 4 summarizes the combined effects of these two pressures by showing the variation of the pressure coefficient as a function of the dimensionless boundary-layer thickness. The graph clearly indicates a decrease in the absolute value of the base pressure coefficient with increasing momentum thickness. The decreases are almost linear for thin boundary layer, but seem to accelerate as the momentum thickness increases. Changes in static reference pressure had a significant effect on C_{p_b}. This effect was proportional to the amount of mass being transferred to or from the boundary layer. Maximum changes in base pressure coefficient were 40% for very thick boundary layers and 26% for very thin boundary layers. At $M=0.06$ similar results were obtained. The values of the base pressure coefficient were slightly higher.

Positive base mass transfer rates produced an increase in both the base pressure and the static pressure at the reference point. Negative mass transfer rates produced the opposite effects. For positive transfer rates, the increase in base pressure is larger than the increase in reference static pressure and an increase in the value (i.e., a decrease in the absolute

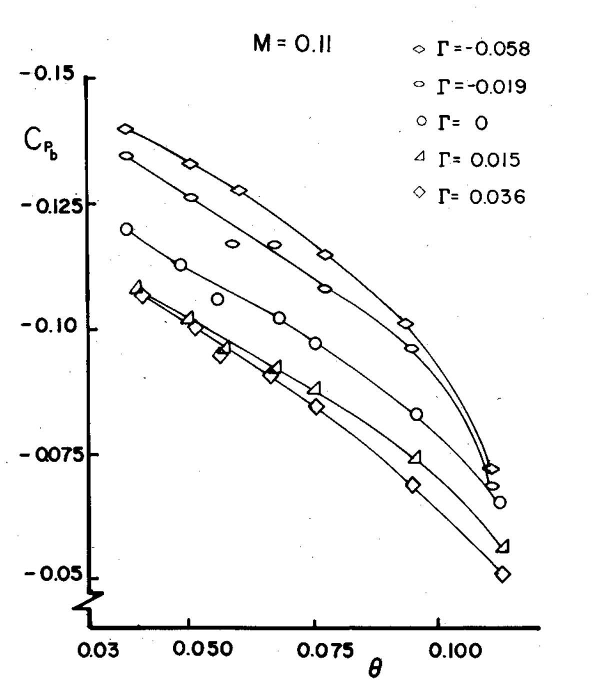

Fig. 4 Base pressure coefficient vs boundary-layer momentum thickness.

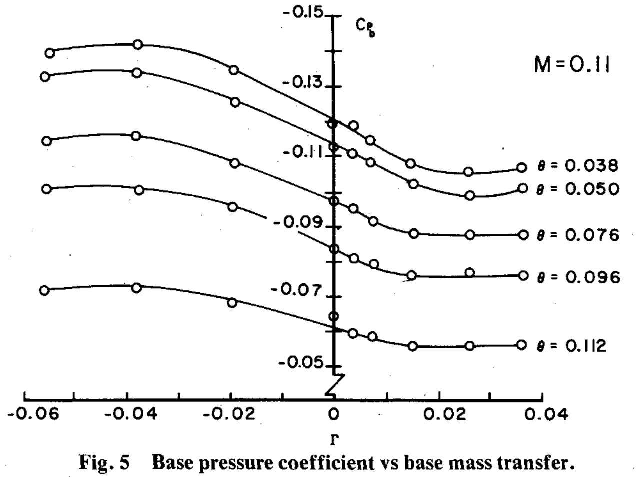

Fig. 5 Base pressure coefficient vs base mass transfer.

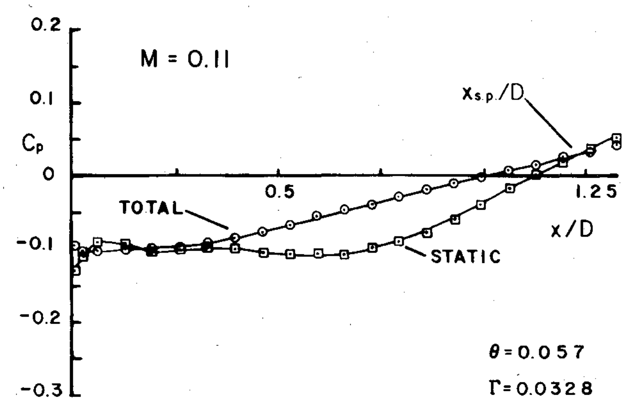

Fig. 6 Near-wake pressure distributions (high base bleed).

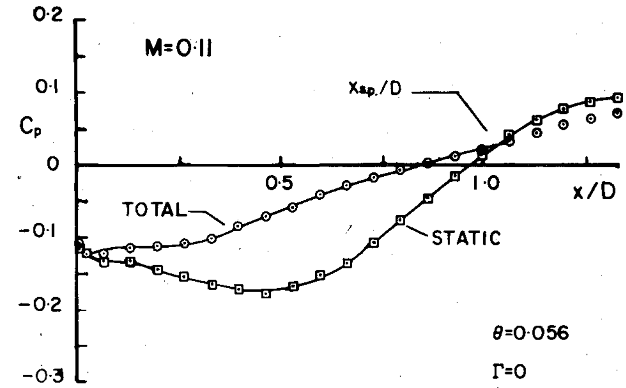

Fig. 7 Near-wake pressure distributions (no base mass transfer).

value) of the base pressure coefficient results. For negative transfer rates, an increase in the absolute value is the result.

Maximum changes in the base pressure coefficient due to changes in static reference pressure were of the order of 12% for base suction and 30% for base blowing.

The effects of mass transfer to the near wake on the base pressure coefficient are shown in Fig. 5. It can be seen that for low and moderate positive transfer rates the absolute value of the base pressure coefficient decreases significantly. For higher values, the magnitude of the base pressure coefficient stabilizes or increases slightly. This rise in the magnitude of the base pressure coefficient, however, may not be entirely due to a decrease in the base pressure, but may in part be due to the formation of a small recirculating bubble behind the static pressure probe located at the base. If this is the case, the probe would be measuring the pressure inside the recirculating bubble which may be significantly different from the static pressure at the base.

A steady increase in the magnitude of the base pressure coefficient takes place for moderate and low suction rates. For high suction rates, the magnitude of the base pressure coefficient decreases. Again, this may not be a totally accurate indication of an increase in base pressure. The base pressure probe may be measuring the total pressure at the base on the centerline of the recirculating flow. Results obtained at $M = 0.06$ were similar to those obtained at $M = 0.11$.

The influence of base mass transfer and boundary-layer thickness on the centerline static and total pressure distributions is presented in Figs. 6-10. In all cases, the behavior of the pressure coefficients is similar. In general, the static pressure decreases from its value at the base to reach a minimum value in the proximity of the middle of the recirculation region. From that point it increases steadily to a value higher than the reference value.

The total pressure, after a slight initial decrease, increases almost linearly with distance reaching, in almost all cases, values higher than that of the static reference pressure.

The effect of base mass transfer is illustrated in Figs. 6-8. Base bleed increases the values of both static and total pressure and smoothes out the pressure distributions. For high bleed rates, such as in Fig. 6, the flowfield close to the base can be very complicated. In this case, the static and total pressure curves seem to indicate the existence of two bubbles close to the base.

Base suction effects are shown in Fig. 8. The total pressure rises slightly due to base suction, while the static pressure decreases dramatically reaching a minimum at about the midcavity location and then increases very rapidly to a level well above the static reference pressure. Figures 9 and 10 illustrate the effect of boundary-layer thickness on centerline static and total pressure. Thicker boundary layers raise the value of both static and total pressure. This effect is especially noticeable when base suction takes place.

The average rear stagnation point location can be obtained from the time-averaged static/total pressure plots as the point

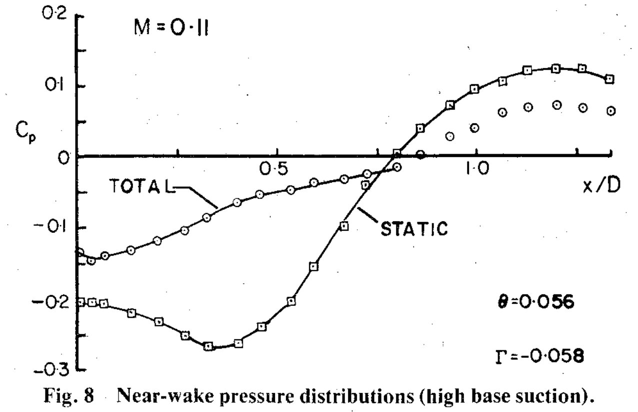

Fig. 8 Near-wake pressure distributions (high base suction).

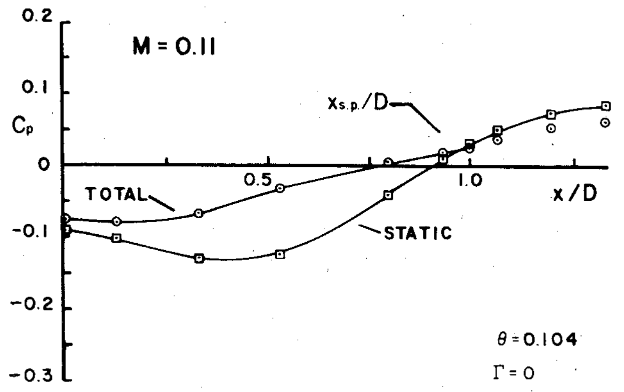

Fig. 9 Near-wake pressure distributions (no base mass transfer, thick boundary layer).

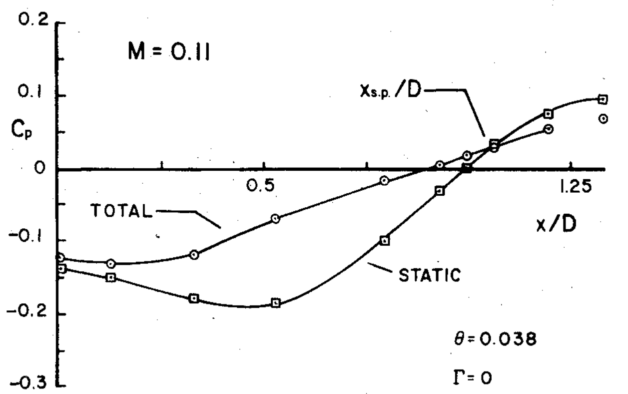

Fig. 10 Near-wake pressure distributions (no base mass transfer, thin boundary layer).

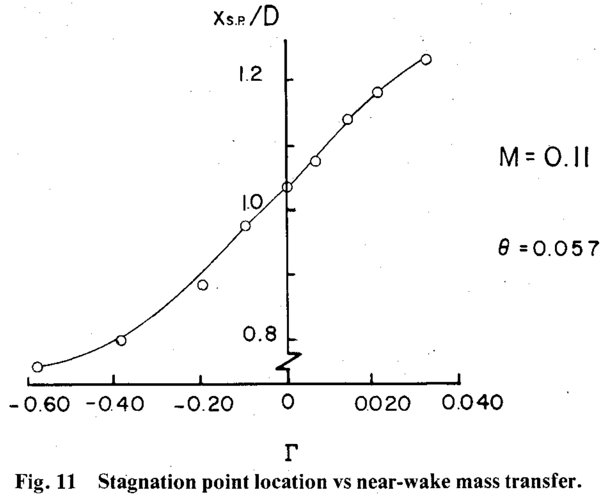

Fig. 11 Stagnation point location vs near-wake mass transfer.

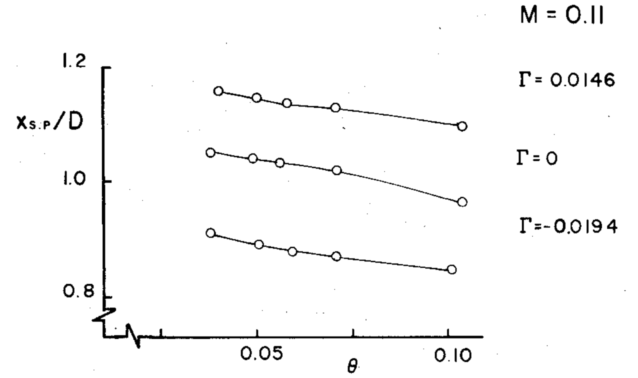

Fig. 12 Stagnation point location vs boundary-layer momentum thickness.

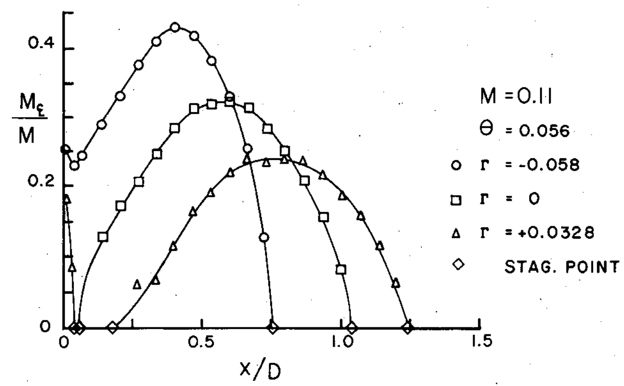

Fig. 13 Centerline velocity distributions as a function of base mass transfer.

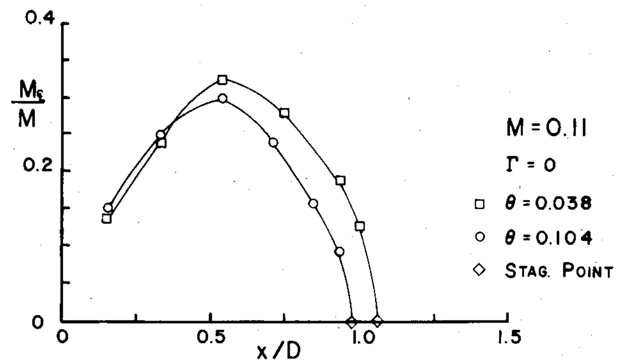

Fig. 14 Centerline velocity distribution (no mass transfer, thick and thin boundary layers).

where the static and total pressures are equal. The change of the rear stagnation point location as a function of base mass transfer is shown in Fig. 11. The rear stagnation point location varies almost linearly with the mass transfer rate except at high suction rates. The result is in agreement with the findings of Przirembel and Riddle.[13]

Figure 12 represents the variations of the rear stagnation point with the momentum thickness of the boundary layer. This variation is very small. Thick boundary layers were found to move the stagnation point closer to the base. This finding is in disagreement with the results obtained by Van Wagenen.[4] His results wre obtained by traversing the centerline with a total pressure probe in both directions and choosing the point where the readings were equal as the stagnation point. This method may lead to errors since the probe disturbs the flow in a different way in each direction.

The centerline velocity profiles are shown in Figs. 13 and 14. These profiles were computed from the centerline pressure distributions. It can be seen that base bleed decreases centerline velocities, while base suction has the opposite effect. The influence of the boundary-layer thickness is slightly more complex. Increases of the momentum thickness are accompanied by a general decrease in centerline velocities except for positive or no bleed. In these cases, the velocities of the points close to the base are higher for thick boundary layers than for thin boundary layers.

Figure 14 does not include the values of the centerline velocity close to the base since more detailed information would be needed to represent the velocity variations in that location.

The results obtained for the cases without base mass transfer are in good agreement with those of Merz et al.[14] The predicted values for the maximum centerline velocity are slightly higher than the present experimental values. The centerline velocity distributions were found to follow the empirical correlation derived by Merz.

Conclusion

The influence of the boundary-layer thickness and base mass transfer on the turbulent near wake of an axisymmetric blunt-based model has been investigated. The experiments were carried out in a special wind tunnel with no significant support interference. The experiments were conducted at Mach numbers of 0.11 and 0.06. Corresponding Reynolds numbers were 2.57 and 1.4×10^6/m.

The following are the major results of this study:

1) The characteristics of the approaching boundary layer have a dominant influence on the base pressure. Tripling the momentum thickness of the boundary layer reduces the magnitude of the base pressure coefficient to half of its original value.

2) Mass transfer into the near wake increases the base pressure. Reductions of 12% in the absolute value of the base pressure coefficient were obtained.

3) Base mass transfer has a great influence on the location of the rear stagnation point. Displacements of 0.2 base diameters away from the base were achieved through base bleed. When base suction was used, a maximum displacement toward the base of 0.3 base diameters was obtained.

4) Boundary-layer thickness has little influence on the stagnation point location. Tripling the momentum thickness of the boundary layer moved the stagnation point closer to the base by less than 0.1 base diameters.

5) Increasing the thickness of the boundary layer of the approaching flow resulted in an overall increase in both total and static pressure on the near-wake centerline.

6) Base bleed increased the total and static pressures on the near-wake centerline, smoothing out the pressure distribution. Base suction had the opposite effect.

7) Changes in the boundary-layer thickness influenced the near-wake centerline velocity, i.e., increasing the thickness resulted in lower centerline velocities.

8) Base bleed also reduced the centerline velocities. Base suction resulted in increased velocities.

Acknowledgments

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References

[1] Hoerner, S. F., *Fluid Dynamic Drag*, published by the author, New Jersey, 1958.

[2] Chang, P. K., *Separation of Flow*, Pergamon Press, London, 1970.

[3] Tanner, M., "Theoretical Prediction of Base Pressure for Steady Base Flow," *Progress in Aerospace Sciences*, Vol. 14, Pergamon Press, 1973, pp. 177-225.

[4] Van Wagenen, R., "A Study of Axially-Symmetric Subsonic Base Flow," Ph.D. Thesis, Dept. of Mechanical Engineering, University of Washington, Seattle, 1968.

[5] Chow, W. L. and Spring, D. J., "Viscid-Inviscid Interaction of Incompressible Separated Flows," *Journal of Applied Mechanics*, Vol. 98, No. 3, Sept. 1976, pp. 387-395.

[6] Liu, J. S. K. and Chow, W. L., "Base Pressure Problems Associated with an Axisymmetric Transonic Flow Past a Backward Facing Step," University of Illinois, Urbana, Rept. ME-TR 395-5, Nov. 1977.

[7] Page, R. H., "Calculation of Turbulent Axisymmetrical Subsonic Bluff Body Wakes with Influence of Mass Transfer," Paper presented at 2nd Symposium on Turbulent Shear Flows, Imperial College, London, July 1979.

[8] Kurzweg, H. H., "Interrelationship Between Boundary Layer and Base Pressure," *Journal of the Aeronautical Sciences*, Vol. 18, Nov. 1951, pp. 743-748.

[9] Lehnert, R. and Schermerhorn, V. L., "Correlation of Base Pressure and Wake Structure of Sharp and Blunt Nosed Cones with Reynolds Number Based on Boundary Layer Momentum Thickness," *Journal of the Aerospace Sciences*, Vol. 26, Pt. 2, Oct. 1966, pp. 185-186.

[10]Koh, J. C. Y., "Wind Tunnel Technique for Providing Simulation of Flight Base Flow," *Journal of Spacecraft and Rockets,* Vol. 8, Oct. 1971, pp. 1095-1096.

[11]Merz, R. A., "The Turbulent Near Wake of an Axisymmetric Blunt Based Body at Subsonic Speeds," Ph.D. Thesis, Mechanical, Industrial and Aerospace Engineering Dept., Rutgers University, New Brunswick, N. J., June 1975.

[12]Przirembel, C. E. G., "The Effect of Base Bleed/Suction on the Subsonic Near Wake of a Bluff Body," *Symposium on Aerodynamics of Transportation,* 1979 ASME Fluids Engineering Division Conference, Niagara Falls, N. Y., June 1979, pp. 43-51.

[13]Przirembel, C. E. G. and Riddle, R. A., "The Effect of Mass Removal from a Subsonic Axisymmetric Near Wake," *Proceedings of the 14th Midwestern Mechanics Conference,* University of Oklahoma Press, Norman, Okla., 1975, pp. 547-562.

[14]Merz, R. A., Page, R. H., and Przirembel, C. E. G., "Subsonic Axisymmetric Near-Wake Studies," *AIAA Journal,* Vol. 16, July 1978, pp. 656-661.

[15]Porteiro, J. L. F., "Subsonic Axisymmetric Base Flow Control Using Boundary-Layer Thickness and Near-Wake Balance Variations," Ph.D. Thesis, Mechanical, Industrial and Aerospace Engineering Dept., Rutgers University, New Brunswick, N. J., Oct. 1980.