Axisymmetric Transonic Turbulent Base Pressures

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Abstract

RECENT studies of incompressible and transonic separated flow problems[1-3] led to the development of a model accounting for the viscid-inviscid interaction within these flow regimes. It is stipulated that the inviscid flowfield is produced from an equivalent body whose geometry can be characterized by certain parameters. The inviscid flow so established guides the viscous flow processes of mixing and recompression along the wake, including the subsequent reattachment and flow redevelopment in the sense of boundary-layer concept. The viscid-inviscid interaction is manifested by the fact that the characteristic parameters required to establish the corresponding inviscid flow are determined through the viscous flow considerations. Extension of this approach to study the base pressure of a transonic flow past a backward facing step in axisymmetric configuration is reported and discussed.

Contents

For an axisymmetric transonic flow past a backward facing step, as depicted in Fig. 1, the viscous layer is usually very thin, as a result of the high-characteristic Reynolds number, $\rho_\infty u_\infty H/\mu_\infty$, and the equivalent inviscid body should assume a profile more or less traced by the dividing streamline. As an initial approximation, this inviscid body profile R_b is described by:

$$\begin{array}{ll} R_b = ShR^* & \text{for } Z \leq 0 \\ R_b = Sh(R^* - Z^3) & \text{for } 0 \leq Z \leq 1 \\ R_b = Sh(R^* - 1) & \text{for } Z \geq 1 \end{array}$$

where R_b, Z are already normalized by Z_s. Sh ($Sh = H/Z_s$) is the shape parameter of the equivalent body and $R^* = R_0/H$. It should be noted that the equivalent body has a third-order polynomial within the wake region, so that continuity of slope and curvature at the step is asssured. Furthermore, the location of the inviscid rear stagnation point ($Z = 1$, $R_b = R_s$), with a given step height H, is yet unknown.

For a given approaching flow condition, the corresponding inviscid transonic flow can be established for a specific value of Sh by solving numerically the full axisymmetric potential equation.[4,5] Figure 2 shows a typical surface pressure coefficient of the equivalent body from such calculations. The pressure decreases initially until a minimum pressure is reached. A steep rise in pressure occurs thereafter as the flow approaches the inviscid rear stagnation point. Beyond this point, the pressure decreases quickly toward the original freestream value. With the established inviscid flowfield, the viscous flow analyses such as the turbulent boundary-layer growth ahead of the step, the turbulent mixing after separation, recompression, and reattachment may be performed. They are discussed in detail in Ref. 4.

It has been found again that the point of reattachment behaves as a saddlepoint singularity for the system of equations describing the process of viscous flow recompression. This behavior can be employed to determine the correct value of the shape parameter Sh for the given flow condition including the boundary-layer thickness at the step, compatible with the characteristic Reynolds number. If the flow solution were obtained through iterations with different shape parameters, the cost of the computer time to establish the corresponding inviscid flowfields would be excessive. Instead, actual calculations were carried out to determine the correct momentum thickness ratio δ_I^{**}/H of the boundary layer at the step compatible with the given flow conditions and the specific selected shape parameter. It has also been learned that the pressure coefficient at the step can no longer be interpreted as the base pressure coefficient. As the initial flow Mach number increases toward sonic value, the base pressure becomes lower while the absolute value of the pressure coefficient at the step approaches zero. Since the base is exposed to the recirculating flow, the base pressure for the present problem has been defined as the static pressure of the wake flow prior to the beginning of recompression. Figure 3

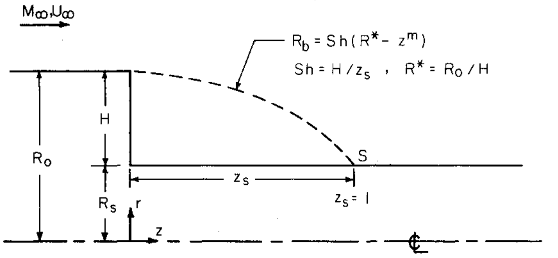

Fig. 1 The corresponding inviscid body of a transonic flow past an axisymmetric backward facing step.

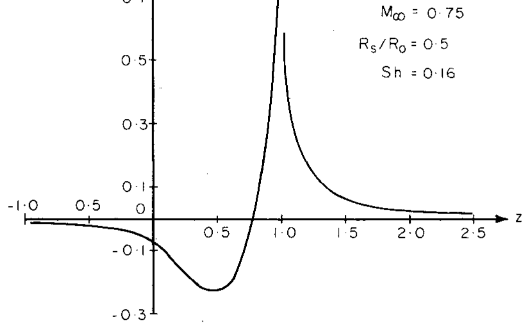

Fig. 2 Surface pressure coefficients on the equivalent body.

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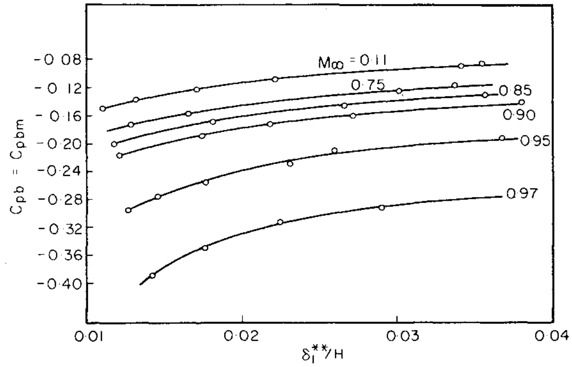

Fig. 3 Variation of C_{pbm} vs δ_l^{**}/H as a function of Mach number for zero sting radius ratio.

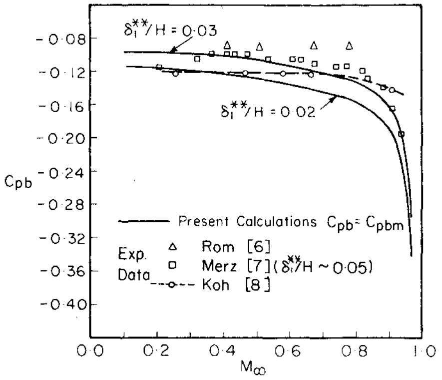

Fig. 4 Comparison of base pressure with experimental data for zero sting radius ratio.

shows the influences of the Mach number and the Reynolds number on base pressures so defined. Drastic decrease of base pressures has been observed as the sonic initial flow condition is approached. Figure 4 shows the comparison of the base pressure with the available experimental data.[6-8] Unfortunately, other than the data from Merz et al.,[7] the information on the initial momentum thickness ratios under the testing conditions of these data is not available. Figure 5 shows a specific geometry of the established wake flow.

It should be mentioned that the results obtained so far constitute only the first approximation of the problem. The profile of the corresponding inviscid body geometry compatible with the established viscous flow should be at a distance of the displacement thickness of the viscous layer away from the viscous dividing streamline, and thus the profile would no longer coincide with the solid wall upstream of the step and downstream of reattachment. Higher order approximations to the corresponding inviscid body geometry can be carried out after the viscous flowfield downstream of reattachment is also established. It is believed, however, that the base pressure results obtained and presented here would not be significantly modified. It is also appropriate to add that "perturbation of the corresponding inviscid body geometry"[9] yields meaningful results to separated flow problems in subsonic and transonic flow regimes.

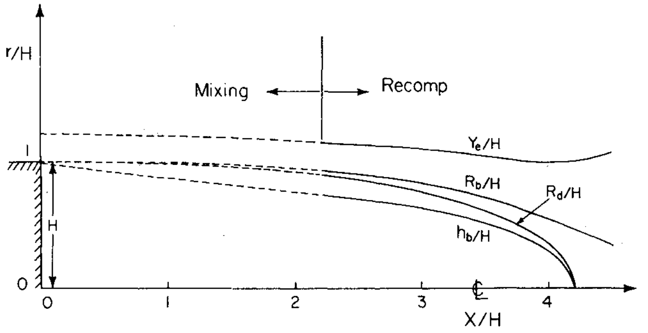

Fig. 5 Geometry of the wake region for $M_\infty = 0.75$, $R_s/R_0 = 0$, $\delta_l^{**}/H = 0.023$, $SH = 0.195$.

Acknowledgment

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References

[1] 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.

[2] Warpinski, N.R. and Chow, W.L., "Viscid-Inviscid Interaction Associated with Incompressible Flow Past Wedges at High Reynolds Numbers," Rept. ME-TR-395-4, Dept. of Mechanical and Industrial Engineering, Univ. of Illinois at Urbana-Champaign, Feb. 1977, NASA CR-135246.

[3] Chow, W.L. and Shih, T.S., "Transonic Flow Past a Backward Facing Step," *AIAA Journal,* Vol. 15, Sept. 1977, pp. 1342-1343.

[4] Liu, J.S.K. and Chow, W.L, "Base Pressure Problems Associated with an Axisymmetric Transonic Flow Past a Backward Facing Step," Rept. ME-TR-395-5, Dept. of Mechanical Engineering, Univ. of Illinois, Tech. Rept. prepared for the Research Grant U.S. Army DAAG 29-76-G-0199, Nov. 1977, ADA 050658.

[5] Chow, W.L., Bober, L.J., and Anderson, B.H., "Numerical Calculations of Transonic Boattail Flow," NASA TN D-7984, June 1975.

[6] Rom, J., Reichenberg, V.M., and Salomon, M., "Wind Tunnel Measurements of the Base Pressure on an Axially Symmetric Model in Subsonic, Transonic, and Supersonic Speeds at High Reynolds Numbers," Technion-Israel Institute of Technology, T.A.E. Rept. No. 134, Sept. 1972.

[7] Merz, R.A., Page, R.A., and Przirembel, C.E.G., "Subsonic Axisymmetric Near-Wake Studies," *AIAA Journal,* Vol. 16, July 1978, pp. 656-662.

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

[9] Chow, W.L., Warpinski, N.R., and Liu, J.S.K., "Perturbations of the Corresponding Inviscid Body Geometry in Separated Flows," Paper presented at Eighth U.S. National Congress of Applied Mechanics, U.C.L.A., June 1978.