[2]Jarvinen, P. O. and Hill, J.A.F., "Universal Model for Underexpanded Rocket Plumes in Hypersonic Flow," *12th JANNAF Liquid Propulsion Meeting*, Las Vegas, Nev., 1970.

[3]Dash, S. M. and Thorpe, R. D., "A New Shock-Capturing/Shock-Fitting Computational Code for Analyzing Supersonic Inviscid Flows (The SCIPPY Code)," Aeronautical Research Associates of Princeton, Inc., Princeton, N.J., Rept. No. 366, Nov. 1978.

[4]Wilson, K. H., Personal communication, Lockheed Palo Alto Research Laboratory, Nov. 1978.

[5]Dash, S. M. and Pergament, H. S., "A Computational Model for the Prediction of Jet Entrainment in the Vicinity of Nozzle Boattails (The BOAT Code)," NASA CR3075, 1978.

[6]Dash, S. M. and Pergament, H. S., "The Analysis of Low Altitude Rocket and Aircraft Plume Flowfields: Modeling Requirements and Procedures," *Proceedings of the JANNAF 10th Plume Technology Meeting*, CPIA Publication 291, Sept. 1977.

[7]Fishburne, E. S., "A.R.A.P. SPECRA and STARAD Computer Codes for Exhaust Plume Radiation," Aeronautical Research Associates of Princeton, Inc., Princeton, N.J., Reports to be published.

[8]Dash, S. M., Pearce, B. E., Pergament, H. S., and Fishburne, E. S., "The Prediction of Rocket and Aircraft Exhaust Plume Structure. Requirements in IR Radiation Signature Studies," AIAA Paper 79-0095, New Orleans, La., Jan. 1979.

[9]Dash, S.M., Pergament, H. S., and Thorpe, R. D., "A Modular Approach for the Coupling of Viscous and Inviscid Processes in Exhaust Plume Flows," AIAA Paper 79-0150, New Orleans, La., Jan. 1979.

Readers' Forum

Brief discussions of previous investigations in the aerospace sciences and technical comments on papers published in the AIAA Journal *are presented in this special department. Entries must be restricted to a maximum of 1000 words, or the equivalent of one* Journal *page including formulas and figures. A discussion will be published as quickly as possible after receipt of the manuscript. Neither the AIAA nor its editors are responsible for the opinions expressed by the correspondents. Authors will be invited to reply promptly.*

Comment on "Wall Shear Stress Measurements in a Shock-Wave Boundary-Layer Interaction"

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MAJOR advances have been made in establishing numerical solutions to turbulent boundary-layer separation problems, yet there are still many serious discrepancies between predicted flow characteristics and experimental results. The acquisition of accurate skin friction measurements in reverse flow regions is of primary importance in evaluating numerical techniques as well as in adding to the basic understanding of separated flow phenomena.

Recent studies by Murthy and Rose[1] provided valuable data concerning the reliability of various skin friction measuring devices. Their attempts to provide correlations of experimental skin friction values with numerical solutions of Baldwin and Rose[2] and Baldwin and MacCormack,[3] however, may have biased their results. The skin friction gages used by Murthy and Rose could not distinguish between positive and negative skin friction values, but they assumed the reverse flow skin friction coefficients to be negative in order to correspond with the negative values predicted by numerical techniques. Plotting the data in this manner resulted in a significant jump between positive and negative values at the separation and reattachment points, as shown in Fig. 1. If the skin friction coefficients in the reverse flow region had instead been plotted as positive values, it could then be assumed that an appreciable error existed in all of the data points.

Considering flow conditions for the test case ($Re_\delta = 0.97 \times 10^6$, $\delta = 1.7$ cm, $T_0 = 270$K, $T_w = 60°$C, and $M_\infty = 2.9$), one can arrive at a unit Reynolds number of 5.6×10^5/cm and $T_w/T_\infty = 3.1$. Using the boundary-layer relationship of Johnson and Kaufman,[4] $\delta/x = 0.3122 (Re_x)^{-0.1622}$, to describe the boundary-layer thickness as a function of the local Reynolds number, based upon distance from the wind tunnel throat x, one can calculate a local Reynolds number at interaction to be 5.6×10^7. The technique of Truitt,[5] after Van Driest,[6] can then establish a local skin friction coefficient of approximately 0.0011 for the undisturbed flow. This is slightly lower than the value recorded by Murthy and Rose (0.0014) but corresponds to the upstream skin friction coefficient measured by Settles et al.[7] at comparable conditions. If one thus assumes an error of approximately 0.0003 in the measurements of Murthy and Rose, their data can then be plotted as shown in Fig. 2.

It is suggested that Fig. 2 might be a more accurate representation of the skin friction measurements of Murthy and Rose, even though it indicates negligible skin friction values in the reverse flow region and implies that significant inaccuracies might exist in the numerical solutions. It is assumed that the rather large fluctuations in the sensor gage

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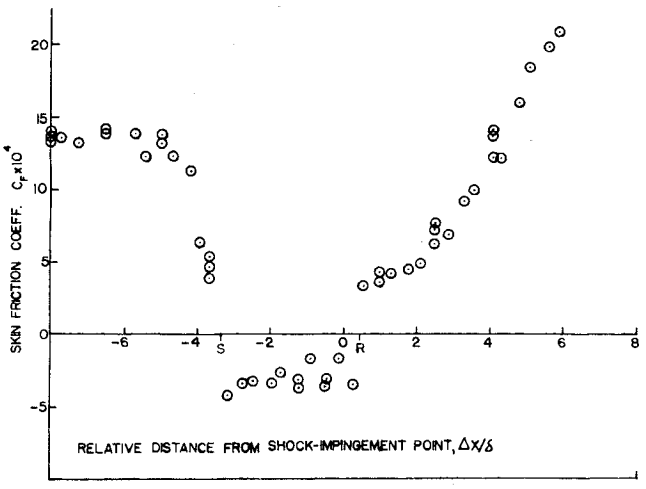

Fig. 1: Skin-friction distribution from Murthy and Rose[1] with shock generator angle = 13 deg and $M_\infty = 2.9$.

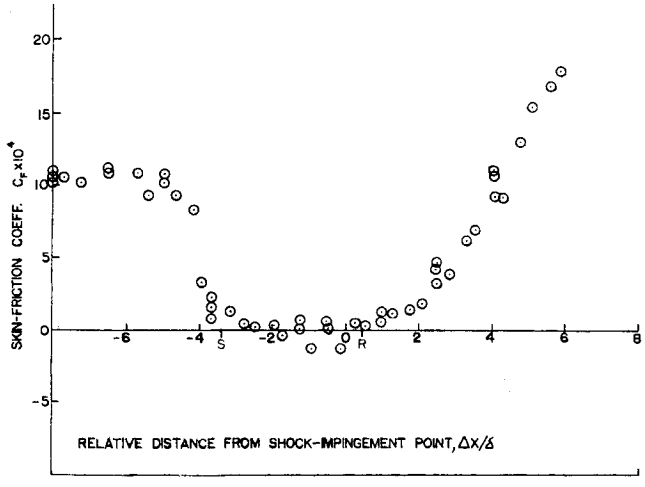

Fig. 2: Revised skin-friction distribution with shock generator angle = 13 deg and $M_\infty = 2.9$.

outputs in the separated flow regions are of the order of magnitude of the skin friction coefficients in that region. This would account for the alternating positive and negative skin friction coefficients that resulted along the separated flow region.

References

[1] Murthy, V.S. and Rose, W.C., "Wall Shear Stress Measurements in a Shock-Wave Boundary-Layer Interaction," *AIAA Journal*, Vol. 16, July 1978, pp. 667-672.

[2] Baldwin, B.S. and Rose, W.C., "Calculations of Shock Separation Boundary Layers," *Proceedings of Conference on Aerodynamic Analysis Requiring Advanced Computers*, Langley Research Center, March 1976, pp. 401-411.

[3] Baldwin, B.S. and MacCormack, R.W., "Modifications of the Law of the Wall and Algebraic Turbulence Modelling for Separated Boundary Layers," AIAA Paper 76-350, San Diego, Calif., 1976.

[4] Johnson, C.B. and Kaufman, L.G., II, "Interference Heating from Interactions of Shock Waves with Turbulent Boundary Layers at Mach 6," NASA TN D-7649, Sept. 1974.

[5] Truitt, R.W., *Fundamentals of Aerodynamic Heating*, Ronald Press, New York, 1960, pp. 222-223.

[6] Van Driest, E.R., "Turbulent Boundary Layer in Compressible Fluids," *Journal of Aeronautical Sciences*, Vol. 18, Mar. 1951, pp. 145-160, 216.

[7] Settles, G.S., Vas, I.E., and Bogdonoff, S.M., "Details of a Shock-Separated Turbulent Boundary Layer at a Compression Corner," *AIAA Journal*, Vol. 14, Dec. 1976, pp. 1709-1715.

Reply by Authors to R.D. Kirchner

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THE essence of Kirchner's Comment centers around the initial value of the skin friction coefficient. The original study of this flow was done by Reda and Murphy,[1] who reported a value for the coefficient of 0.0013, as determined by a Preston tube. In an independent analysis of this flow, Rubesin et al.[2] confirmed this value by a technique for examining the pitot profiles obtained in the study of Ref. 1. The use of semiempirical relationships to deduce the skin friction coefficient, as suggested by Kirchner, is questionable when applied to the flow in the NASA Ames Research Center's 8 × 8 in. wind tunnel, since it is a highly asymmetric, sliding-block, variable Mach number design. Any relationship between the NASA tunnel flow and that at Princeton used by Settles et al.[3] is purely coincidental. If anything is known about the skin friction in the Reda and Murphy flow, it is this upstream value. Therefore, its value must stand at 0.0013, as was used to calibrate our gages.

The negative coefficients were chosen to agree with the separation and reattachment points deduced by oil flow studies, in addition to being chosen to correspond with the numerical predictions. Kirchner's interpretation of our data would shorten the separation length to about half of that observed experimentally.

Even if one were to suppose that the upstream value of skin friction coefficient had a value of 0.0011, correct interpretation of the gage outputs would not produce Kirchner's Fig. 2 This is because the contribution to the measured data from the initial value results in a multiplying factor and not a zero shift, as assumed by Kirchner. The reason is that the measured Nusselt number in the absence of flow (i.e., skin friction = 0) must remain unaltered in any correction procedure. The calibration curve of Nusselt number vs skin friction thus rotates about its zero skin friction intercept. With this fact, the only allowable change to our data is a multiplicative one involving the ratio of assumed initial skin friction values, i.e., 0.0011/0.0013. As an example, a value of 0.0003 we reported would become 0.00025 after the correct application of a correction.

Kirchner also suggests that the alternating positive and negative skin friction coefficients in the separated flow region of his corrected data are attributable to the relatively large fluctuations in that region. As stated in our paper, the gages could not distinguish between positive and negative values; therefore, they cannot directly support any observation about the alternating nature of skin friction values. Kirchner's observation arises purely from the manner in which he has applied a correction to our data.

Unfortunately for both Kirchner and the authors, no one

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