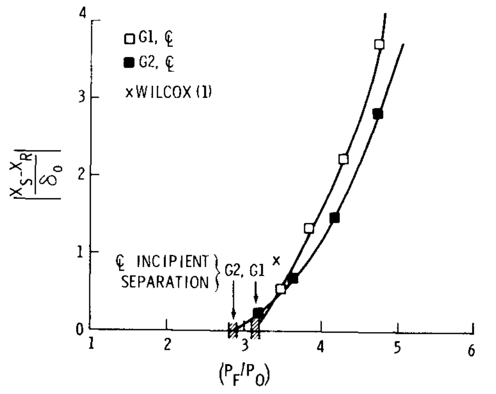

Fig. 3 Length of separated flow vs over-all pressure rise.

sonic line), consistent with experimental observations. The predicted shape of the pressure distribution was also in agreement with experimental observation (i.e., the presence of inflection points and an over-all pressure rise somewhat below that dictated by inviscid theory). In addition, the predicted pressure rise to separation was in close agreement with the experimentally established level ~ 2.0.

With regard to this last point, the free-interaction concept[4] dictates that, for supersonic flow, the pressure rise to separation is independent of the mode of inducing separation; Fig. 1 substantiates this concept (i.e., P_S/P_o independent of P_F/P_o). Flow up to the separation point can be reasoned to be relatively independent not only of the over-all pressure rise and the geometry used to create the viscous-inviscid interaction, but also of any three-dimensional effects which occur downstream of the separation line (the physical location of the separation line, relative to the rest of the flowfield would, however, be sensitive to such three-dimensional effects). The region of flow between the start of the pressure rise and the separation point is physically small ($\sim 1\delta_o$) and is coincident with the very beginning of the adverse pressure gradient. Agreement between predicted and measured P_S/P_o levels, regardless of three-dimensional effects, is thereby expected.

The level of agreement between theory and experiment is reduced when one views those quantities indicative of the over-all scale of the interaction region. The predicted pressure rise to reattachment is greater than measured; the upstream influence length is less than measured, while the predicted length of separated flow is nearly double that measured for an equivalent over-all pressure rise; the predicted sonic line leaves the vicinity of the wall at an angle steeper than observed experimentally; finally, the absolute displacement of the sonic line from the surface is more nearly in agreement with the G1, $\alpha = 11°$, data, rather than

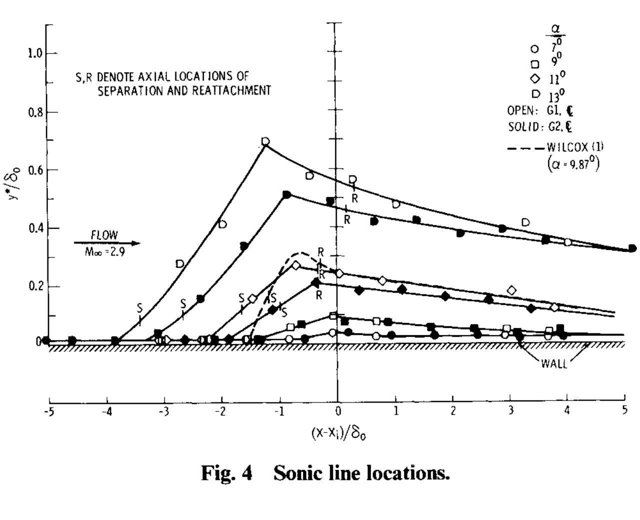

Fig. 4 Sonic line locations.

falling somewhere between the $\alpha = 9°$ and $\alpha = 11°$ data, as might be expected for an $\alpha = 9.87°$ computation.

Combined results of Refs. 2 and 3 have shown that the abovementioned quantities are dependent on sidewall/corner boundary-layer effects; the extent of influence has been shown to be most prominent for those cases where the test boundary layer is well separated ($|X_S - X_R| > 1\delta_o$).

Exhibited levels of agreement, and disagreement, between the predictions of Ref. 1 and the data of Refs. 2 and 3, do not conclusively prove, or disprove, the merits of such a calculation scheme. It should be noted, however, that the particular shock strength chosen for analysis ($\alpha \approx 10°$) generated, experimentally, only a small region of reverse flow (less than $1\delta_o$), and, accordingly, the interaction flowfield was found to be less removed from a nominally two-dimensional state than those flowfields investigated at higher incident shock strengths. It is felt, therefore, that experimental limitations may not be the total cause for those areas of disagreement noted herein.

References

[1] Wilcox, D. C., "Calculation of Turbulent Boundary-Layer Shock-Wave Interaction," *AIAA Journal*, Vol. 11, No. 11, Nov. 1973, pp. 1592–1594.

[2] Reda, D. C. and Murphy, J. D., "Shock Wave-Turbulent Boundary Layer Interactions in Rectangular Channels," *AIAA Journal*, Vol. 11, No. 2, Feb. 1973, pp. 139–140.

[3] Reda, D. C. and Murphy, J. D., "Shock Wave-Turbulent Boundary Layer Interactions in Rectangular Channels, Part II: The Influence of Sidewall Boundary Layers on Incipient Separation and Scale of the Interaction," *AIAA Journal*, Vol. 11, No. 10, Oct. 1973, pp. 1367–1368.

[4] Chapman, D. R., Kuehn, D. M., and Larson, H. K., "Investigation of Separated Flows in Supersonic and Subsonic Streams with Emphasis on the effect of Transition," Rept. 1356, 1958, NACA.

Reply by Author to D. C. Reda

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Reda's comments pertaining to my listing of his data focus mainly upon size of the separation bubble $(x_R - x_s)/\delta_0$, and the value of the surface pressure at reattachment, p_R/p_0. The source of the discrepancies between the values Reda quotes and those quoted in my Note[1] is a matter of interpretation of the Reda-Murphy data presented in Ref. 2. Specifically, while the curves shown in the abovementioned comment are based upon centerline measurements, I have chosen to include both centerline and off-centerline data in my comparisons to provide a measure of experimental data scatter. The computed surface pressure distribution is shown in Fig. 1; open symbols denote measured pressures at separation and reattachment. Surface pressure for the Reda-Murphy $G1, \alpha = 10°$ flowfield indicates that $p_R/p_0 \simeq 2.31$ on the tunnel centerline while p_R/p_0 is as high as 2.50 away from the centerline. The calculated value of p_R/p_0 of 2.63 differs, as quoted in the Note, by 5% from the off-centerline value. Similarly, I interpreted the extent of the separated region as lying between the separation point farthest upstream and the reattachment point farthest downstream. With this interpretation, the length of the Reda-Murphy separated region is $(x_R - x_s)/\delta_0 \simeq 0.86$ compared to 0.91 in the numerical flowfield.

Received March 8, 1974. Numerical results presented in this discussion were generated by the author as a Staff Scientist with Applied Theory, Inc., Los Angeles, Calif.

Index categories: Boundary Layers and Convective Heat Transfer—Turbulent; Jets, Waves, and Viscid-Inviscid Flow Interactions.

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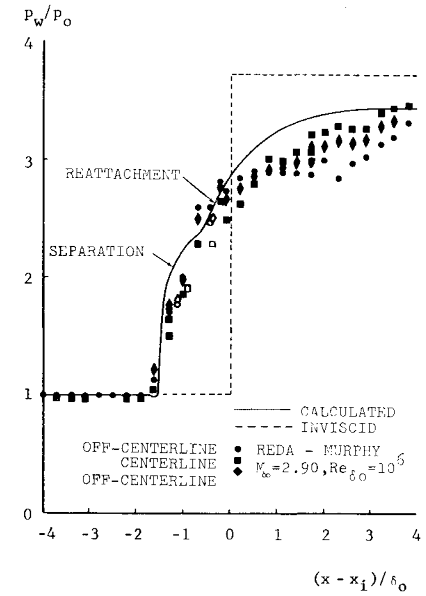

Fig. 1 Comparison of calculated surface-pressure distribution with experimental data; $M_\infty = 2.96$ $\theta = 9.87°$; $Re_{\delta_0} = 2.49 \times 10^5$; open symbols denote pressures measured at separation and reattachment.

All Reda's comments regarding solution accuracy for "quantities indicative of the over-all scale of the interaction region" are qualitative. It is instructive to quantify the actual differences; the level of accuracy is then seen to be quite good.

Pressure Rise to Reattachment

As already noted, p_R/p_0 is within 5% of the Reda-Murphy off-centerline value; more importantly, the computed surface-pressure distribution is within 10% of measured values throughout the interaction region when all Reda-Murphy data are considered.

Upstream Influence Length

Since publishing the Note, I have found that numerical smearing of the incident shock in the freestream caused uncertainty in the location of x_i, and hence x_0, of about $0.15\delta_0$. Reda's Fig. 2 shows a difference between computed and measured $(x_i - x_0)/\delta_0$ of about twice this amount, so that the numerical error accounts for much of the difference between measured and calculated x_0.

Separation Bubble Length

The computed bubble should be larger than the measured bubble because the Reynolds number, Re_{δ_0}, in the numerical flowfield is 2.5×10^5 compared to $Re_{\delta_0} = 1.0 \times 10^6$ for the Reda-Murphy field. That is, Roshko and Thomke[3] have found for Mach 2.95 compression-corner flows that increasing Re_{δ_0} beyond about 10^6 increases the flow's resistance to separation with an attendant reduction in the extent of the separated region. Further verification of this claim is provided by results of two Saffman-model shock-wave boundary-layer interaction flowfields[4] computed since publication of my Note, for a freestream flow deflection angle, θ, of 12.75°; Re_{δ_0} was 2.5×10^5 in one calculation and 1.0×10^6 in the other. The calculations verify that $(x_R - x_s)/\delta_0$ decreases appreciably when Re_{δ_0} is increased from 2.5×10^5 to 1.0×10^6; specifically, the computed separation-bubble length decreases from $3.87\delta_0$ for the lower Re_{δ_0} to $2.81\delta_0$ for $Re_{\delta_0} = 1.0 \times 10^6$.

Sonic Line Angle

The points shown by Reda (Fig. 4) are of doubtful sufficiency to determine the angle at which the sonic line leaves the wall, so that this comparison may have little meaning; data points at $(x - x_i)/\delta_0 = -1.0$ and/or -1.75, for example, would be needed to verify the sketched linear fit to the data. Interestingly, for the $\theta = 12.75°$, $Re_{\delta_0} = 1.0 \times 10^6$ calculation mentioned previously, the computed sonic line leaves the wall at an angle almost identical to that shown in Reda's Fig. 4 when $\alpha = \theta = 13°$, a curve for which sufficient data are available to determine the initial sonic line inclination.

Absolute Displacement of Sonic Line

In light of the preceding comments regarding separation bubble size, the sonic line should be expected to be farther from the wall in the lower-Reynolds-number numerical flowfield than in the experimental flowfield.

In conclusion, the results presented in my Note were not intended to provide a definitive test of the Saffman turbulence model. Rather, the Note only intended to relate to the fluid mechanics community, prior to publication of a more detailed paper, results of a first of its kind calculation of shock-induced turbulent boundary-layer separation and its promising results. The stronger-shock calculations mentioned earlier in this reply do provide a much better test of the turbulence model since both shock strength and Reynolds number more closely match those of the Reda-Murphy 13° freestream flow-deflection interaction.

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[1] Wilcox, D. C., "Calculation of Turbulent Boundary-Layer Shock-Wave Interaction," *AIAA Journal*, Vol. 11, No. 11, Nov. 1973, pp. 1592–1594.

[2] Reda, D. C. and Murphy, J. D., "Shock Wave Turbulent Boundary Layer Interactions in Rectangular Channels," AIAA Paper 72-715, Boston, Mass., 1972.

[3] Roshko, A. and Thomke, G. J., "Supersonic, Turbulent Boundary-Layer Interaction with a Compression Corner at Very High Reynolds Number," Paper 10163, May 1969, McDonnell Douglas, Santa Monica, Calif.

[4] Wilcox, D. C., "Numerical Study of Separated Turbulent Flows," Rept. ATR-73-38-1, Sept. 1973, Applied Theory, Inc., Los Angeles, Calif.

Comment on "Evaluation of Preston Tube Calibration Equations in Supersonic Flow"

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DATA are presented by Allen[1] (documented and notation explained in Ref. 2) for Preston tubes in constant-pressure adiabatic-wall supersonic boundary layers at freestream Mach numbers M_e between 2.0 and 4.6 and Reynolds numbers based on tube diameter and friction velocity, $u_\tau d/\nu_w$, between 6 and 5000. The data cover a greater range than previous measurements (referenced by Allen) and appear to be of good accuracy except at small $u_\tau d/\nu_w$. Unfortunately, the empirical "intermediate temperature" concept used in Allen's preferred data correlation (Ref. 1, Fig. 4) is incompatible with the law-of-the-wall concept on which the Preston tube relies: briefly, the intermediate temperature depends on freestream conditions while the Preston tube

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