separated mode. The scale effect is obviously one of the key parameters.

The c^* efficiencies for the penetrated, mixed, and separated cases averaged out at 93, 97, and 93%, respectively. These figures were not corrected for heat transfer or discharge coefficient, but such corrections would not change the relative standing by more than 1%. At this level of c^*, the 4% difference between the mixed mode and the other modes represents a significant change. Operation under mixed mode conditions results in a uniform propellant spray and optimum combustion efficiency.

References

[1] Rupe, J. H. and Evans, D. D., "Designing for Compatibility in High-Performance *lp* Engines," *Astronautics and Aeronautics*, June 1965, pp. 68–74.

[2] Evans, D. D., Stanford, H. B., and Riebling, R. W., "The Effect of Injector Element Scale on the Mixing and Combustion of Nitrogen Tetroxide-Hydrazine Propellant," TR 32-1178, Nov. 1967, Jet Propulsion Lab., Pasadena, Calif.

[3] Burrows, M. C., "Mixing Reaction of Hydrazine and Nitrogen Tetroxide at Elevated Pressure," *AIAA Journal*, Vol. 5, No. 9, Sept. 1967, pp. 1700–1701.

[4] Breen, B. P. et al, "Injection and Combustion of Hypergolic Propellants," AFRPL-TR 69-48, April 1969, Dynamic Science, a division of Marshall Industries, Monrovia, Calif.

[5] Kushida, R. and Houseman, J., "Criteria for Separation of Impinging Streams of Hypergolic Propellants," TM 33-395, July 1968, Jet Propulsion Lab., Pasadena, Calif.; also paper WSCI-67-38, 1967, Western States Combustion Institute, Seattle, Wash.

Effect of Vortices on Delta Wing Lee-Side Heating at Mach 6

ALLEN H. WHITEHEAD JR.*
NASA Langley Research Center, Hampton, Va.

Nomenclature

L	=	model chord length
M_∞	=	freestream Mach number
p/p_∞	=	ratio of local static pressure to freestream static pressure
R_∞	=	freestream Reynolds number
St_∞	=	local Stanton number based on freestream conditions
x	=	distance down centerline from apex
α	=	angle of attack
θ	=	surface angle from centerline through apex

Subscripts

L	=	model length
x	=	distance down centerline from apex

RECENT investigations[1–3] have indicated pressure and heating levels on the lee surface of a delta wing considerably above that predicted using two-dimensional expansion methods. Examination of the lee-surface flowfield in these studies revealed that this localized high heating and pressure in the central region of the wing is induced by coiled vortex sheets present above the surface when conditions are conducive to separation. Hypersonic experiments indicate that separation and the associated vortex system can initiate either at the leading edge or at the base of an inboard shock system. The major difference in the flowfield when the flow separates at the leading edge is that the vortex structure appears further outboard than when the vortex initiates at the base of an inboard separation. The nature of the flow in the centerline region is dependent on the spanwise location of the vortex.[1] In previous hypersonic experiments on the lee surface the flow was separated inboard of the leading edge.[1,2] The present investigation was undertaken to determine if severe heating persists over the lee surface when the flow separates at the leading edge. Furthermore, the present study, conducted in the Langley 20-in. Mach 6 tunnel, extends over a much wider Reynolds number range than previous tests.

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* Aerospace Engineer, Applied Fluid Mechanics Section, Aero-Physics Division. Associate Member AIAA.

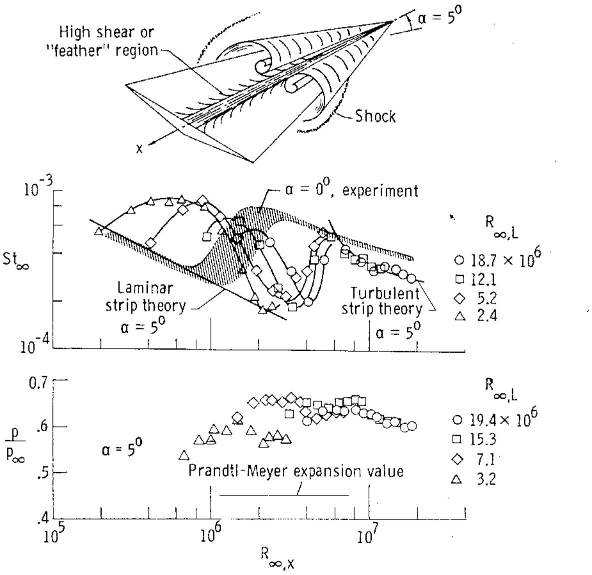

Fig. 1 Flowfield, centerline heating, and pressure distribution on lee surface of 75° swept wing; M_∞ = 6, α = 5° (unless otherwise labeled), L = 26.1 in.

The present delta wing was sting-mounted and had a sharp leading edge (<0.003 in.) with a sweep of 75° and a 14.6° wedge angle (measured normal to the leading edge). The leading-edge shock was calculated to be detached at all angles of attack. An oil-flow technique was used to indicate direction and relative magnitude of the surface shear forces, and to indicate the location of separation and reattachment. In this method, random dots of an oil and lampblack mixture are applied to the model surface prior to the run. The vapor-screen technique gave additional evidence of the vortical structure above the lee surface. Temperature data were reduced to Stanton numbers by methods similar to those described in Ref. 4 and assuming a turbulent recovery factor of 0.895. Local Mach numbers used in determining turbulent recovery temperatures were obtained from measured static and freestream total pressures.

Previous tests show peak heating on the lee surface of a delta wing coincident with a high shear area in the centerline region identified by a feather-like oil flow trace.[1] This high shear region was also revealed in the present experiments by the oil flow results as indicated by the sketch of Fig. 1.

The effect of a Reynolds number variation from 2.4 to 18.7 million on the lee-surface centerline heating is shown in the lower portion of Fig. 1. The data depart initially from laminar theory[5] and then rise to a peak whose value and location are unit Reynolds number dependent. The heating decreases beyond this peak to near-laminar values with further increases in $R_{\infty,x}$. An abrupt rise in heating then occurs and, subsequently, the data achieve the level and trend expected of a turbulent boundary layer. The peak Stanton number values obtained on the centerline at the low Reynolds numbers are almost double the values found on the centerline

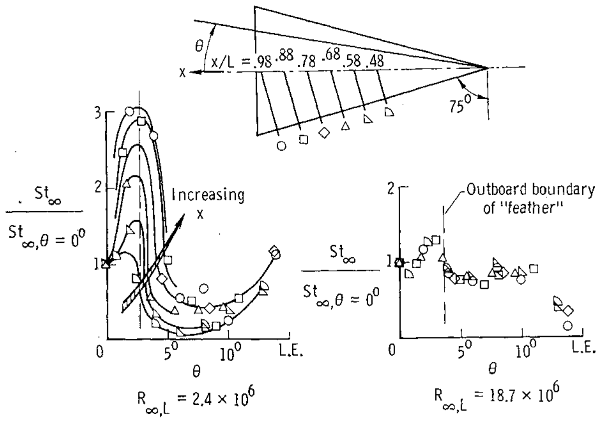

Fig. 2 Heating off-centerline on lee surface of delta wing; $M_\infty = 6$, $\alpha = 5°$, $L = 26.1$ in.

with a turbulent boundary layer. Furthermore, these peak values are 10–15% higher than the largest Stanton number values obtained on the centerline at $\alpha = 0°$ at a comparable freestream unit Reynolds number. (The $\alpha = 0°$ data extending over the same freestream Reynolds number range show in the figure as a shaded region.)

Beyond about $R_{\infty,x} = 6 \times 10^6$, a portion of the data at the two highest unit Reynolds numbers correlates with a slope and level predicted by the modified Spalding-Chi turbulent strip theory[6] using Prandtl-Meyer pressure values (virtual origin taken as the position of peak heating). Past investigations indicate this simple flat-plate heating calculation generally predicts the trend of turbulent centerline heating in this high shear region, but comparison of this prediction with other delta wing data[1] suggests fortuitous agreement of the level of the data. If only a limited amount of this centerline data had been available (i.e., if data had existed only for $R_{\infty,x} < 10^6$), a conclusion might have been that transitional flow existed. Examining the heating data beyond the peak ($10^6 < R_{\infty,x} < 4 \times 10^6$), however, indicates a departure from flat-plate boundary-layer properties. Similar behavior is exhibited by the chordwise heating from the leading edge of a 90° corner alined with the flow.[7] The flowfields over the lee side of the delta wing and that over the 90° corner are somewhat analogous because both geometries generate vortices as a result of interacting flow components.

The centerline pressure distribution also exhibits a variation with Reynolds number, but the variation is much smaller than that found for the heat transfer (15% compared to over 400% variation of the heating from maximum to minimum value at a given unit Reynolds number). Furthermore, the peak pressure values do not occur at the same Reynolds number as the peak heating values. The mean value of the centerline pressure data is some 40% higher than the two-dimensional Prandtl-Meyer expansion value. The observed pressure variation is indicative of the complex flow phenomena present on the lee surface. For $R_{\infty,x} > 10^7$, the dependence of the pressure and heating data on unit Reynolds number appears to vanish.

Heating values on the remainder of the lee surface are examined through normalizing off-centerline Stanton numbers by the centerline value along a line perpendicular to the leading edge (see sketch in Fig. 2). The six chordwise stations nearest the trailing edge were selected; the most forward station examined was located at about the half-chord station from the apex ($x/L = 0.48$). Heating data in the region where the centerline data are known to be turbulent are shown on the righthand side of Fig. 2 ($R_{\infty,L} = 18.7 \times 10^6$). In this case the data off the centerline correlate as a function of surface ray angle θ. This high Reynolds number conical correlation has been observed on delta wings at lower Mach numbers.[3] Moving out spanwise from the centerline, the Stanton number increases until the exterior boundary of the high shear region is reached (the "feather" region determined by the oil-flow techniques). Beyond this boundary, the heating falls to a nearly constant value until near the leading edge where the heating decreases to a low value.

At the lowest unit Reynolds number ($R_{\infty,L} = 2.4 \times 10^6$) shown on the left of Fig. 2, no such simple conical correlation was found. The same general trend exists in the central region at a given x station as that for the higher Reynolds number data, that is, an initial spanwise rise to the boundary of the feather region followed by a sharp drop in the Stanton number further outboard. However, the initial rise from the centerline heating value increases in magnitude as the distance down the plate increases. Near the trailing edge, the heating just off the centerline is three times that at the centerline. The data in Fig. 1 suggests attributing this lack of correlation for these rearward six stations at $R_{\infty,L} = 2.4 \times 10^6$ to the decrease in heating down the centerline. A nearly constant peak heating occurs near the outboard boundary of the high shear region for the six stations examined in Fig. 2 at any given unit Reynolds number.

The heating distribution for stations farther upstream than $x/L = 0.48$ shows a departure from the behavior of the data shown in Fig. 2. At all Reynolds numbers, the heating at forward stations generally peaks at the centerline.

The results of this investigation of the lee-surface heating when separation and the vortex system initiate at the leading edge indicate that high localized heating occurs in the centerline region which can be attributed to the vortices. A study of the effect of a variation in freestream Reynolds number from about 2 to 20 million, based on model length, shows that the maximum values of the Stanton number on the lee surface occur on the centerline at low unit Reynolds numbers. These values are well above laminar flat-plate predictions and exceed all Stanton number values found at zero angle of attack at a comparable freestream Reynolds number. This localized high heating on the lee surface should be considered in the design of hypersonic vehicles, especially for the cruise-type vehicle which operates at low angles of attack. When the centerline region is turbulent, the surface heating across the span can be correlated in conical coordinates. No such correlation exists for the lower Reynolds number data.

References

[1] Whitehead, A. H., Jr. and Keyes, J. W., "Flow Phenomena and Separation over Delta Wings with Trailing-Edge Flaps at Mach 6," *AIAA Journal*, Vol. 6, No. 12, Dec. 1968, pp. 2380–2387.

[2] Cross, E. J., Jr. and Hankey, W. L., "Investigation of the Leeward Side of a Delta Wing at Hypersonic Speeds," AIAA Paper 68-675, Los Angeles, Calif., 1968.

[3] Bertram, M. H., Cary, A. M., Jr., and Whitehead, A. H., Jr., "Experiments With Hypersonic Turbulent Boundary Layers on Flat Plates and Delta Wings," AGARD Specialists Meeting on Hypersonic Boundary Layers and Flow Fields, London, England, May 1–3, 1968.

[4] Holloway, P. F., Sterrett, J. R., and Creekmore, H. S., "An Investigation of Heat Transfer Within Regions of Separated Flow at a Mach Number of 6.0," TN D-3074, Nov. 1965, NASA.

[5] Bertram, M. H. and Feller, W. V., "A Simple Method for Determining Heat Transfer, Skin Friction, and Boundary-Layer Thickness for Hypersonic Laminar Boundary-Layer Flows in a Pressure Gradient," Memo 5-24-59L, June 1959, NASA.

[6] Neal, L., Jr. and Bertram, M. H., "Turbulent Skin Friction and Heat-Transfer Charts Adapted From the Spalding and Chi Method," TN D-3969, May 1967, NASA.

[7] Stainback, C. P., "Heat-Transfer Measurements at a Mach Number of 8 in the Vicinity of a 90° Interior Corner Aligned With the Free-Stream Velocity," TN D-2417, Aug. 1964, NASA.