[8] Cole, J. D. and Aroesty, J., "The Blowhard Problem—Inviscid Flows with Surface Injection," *International Journal of Heat and Mass Transfer*, Vol. 11, No. 7, July 1968, pp. 1167–1183.
[9] Inger, G. R. and Gaitatzes, G. A., "Strong Blowing into Viscous Flows Around Two-Dimensional and Axisymmetric Supersonic Bodies," *AIAA Journal*, Vol. 9, No. 3, March 1971, pp. 436–443.
[10] Ellinwood, J. W. and Mirels, H., "Axisymmetric Hypersonic Flow with Mass Transfer and Large Transverse Curvature," *AIAA Journal*, Vol. 7, No. 11, Nov. 1969, pp. 2049–2056.
[11] Ellinwood, J. W. and Mirels, H., "Axisymmetric Hypersonic Flow with Strong Viscous Interaction," *Journal of Fluid Mechanics*, Vol. 34, Pt. 4, 1968, pp. 687–703.
[12] Fannelop, T. K., "Displacement Thickness for Boundary Layers with Surface Mass Injection," *AIAA Journal*, Vol. 4, No. 6, June 1966, pp. 1142–1147.
[13] Lees, L. and Reeves, B. L., "Supersonic Separated and Reattaching Laminar Flows. I: General Theory and Application to Adiabatic Boundary-Layer/Shock Wave Interactions," *AIAA Journal*, Vol. 2 No. 11, Nov. 1964, pp. 1907–1920.
[14] Chernyi, G. G., *Introduction to Hypersonic Flow*, Academic Press, New York, 1961.

JUNE 1971 AIAA JOURNAL VOL. 9, NO. 6

An Experimental Investigation of the Flowfield around a Yawed Cone

R. H. Feldhuhn* and A. E. Winkelmann†
U.S. Naval Ordnance Laboratory, Silver Spring, Md.

and

L. Pasiuk‡
Naval Ordnance Systems Command
Washington, D.C.

An experimental investigation of the flowfield associated with a highly yawed five degree half-angle cone has been conducted in the wind tunnels at the U.S. Naval Ordnance Laboratory (NOL). The measurements, obtained for the most part at Mach 5, included surface pressure distributions, flow visualization photographs, and leeward side flowfield surveys. Analysis of these results indicates that the flowfield associated with a highly yawed cone at high supersonic velocities resembles that of a circular cylinder in a supersonic crossflow. The essential difference between these flowfields is the presence in the cone flowfield of a "vortical singularity like" gradient which separates the flow traversing the stronger portion of the shock wave on the windward side from the flow traversing the weaker portion of the shock wave on the leeward side.

Nomenclature

L = body length
M = Mach number
M_θ = $V/(\gamma P/\rho)^{1/2}$
P = pressure
P_{T_2} = Pitot pressure
R = distance measured perpendicular to the axis of the cone
R_b = local radius of the cone
Re = Reynolds number, $Re_{\infty,X} = \rho_\infty U_\infty X/\mu_\infty$
S = distance from vertex measured along a conical generator
T = temperature
U_∞ = uniform freestream velocity
V = elevation velocity component in a spherical coordinate system (positive in direction of increasing θ)
W = azimuthal velocity component in a spherical coordinate system
X = distance from tip of cone measured along the axis of symmetry of the cone
α = angle of attack
γ = ratio of specific heats
θ = elevation angle, measured from the axis of the cone, of a spherical coordinate system whose origin is at the apex of the cone
θ_c = cone half angle
μ = absolute viscosity
ρ = gas density
ω = azimuthal angle measured from the windward plane of symmetry

Subscripts

0 = stagnation conditions
∞ = undisturbed freestream conditions

Presented as Paper 70-766 at the AIAA 3rd Fluid and Plasma Dynamics Conference, Los Angeles, Calif., June 29–July 1, 1970; submitted August 10, 1970, revision received January 6, 1971. The investigation was sponsored by ABMDA under order number MIPR-A31699-93-Z546.

* Aerospace Engineer. Member AIAA.
† Aerospace Engineer, presently Graduate Student, Aerospace Engineering Department, University of Maryland. Member AIAA.
‡ Mechanical Engineer. Member AIAA.

I. Introduction

THE determination of the fluid dynamic properties of the flowfields around sharp right circular cones at supersonic and hypersonic velocities has been the subject of numerous experimental and theoretical investigations in the past.[1–13] Generally speaking, these previous investigations have demonstrated the adequacy of available techniques for calculating the inviscid flowfield and laminar boundary-layer properties on a yawed cone at small angles of attack (i.e., $\alpha \lesssim \theta_c$).[3–11] Furthermore, calculations of the inviscid flowfield and laminar boundary-layer properties on the windward side of a highly yawed cone (i.e., $\alpha \gtrsim 1.5\ \theta_c$) have also been completed.[3,7] However, flowfield properties cannot adequately be calculated on the leeward side of highly yawed conical bodies at the present time.[4,8] One reason for the failure to predict the leeward flowfield is the inability to properly model the flow in this region. This is in part a result of a scarcity of definitive experimental measurements on the leeward side of highly yawed configurations. Uncertainties which exist concerning the general structure of the flowfield (i.e., streamline pattern, entropy distribution, conical nature of the inviscid flowfield, viscous effects, etc.) have subverted analytical attempts to specify the entire flowfield around highly yawed conical bodies.

The objective of the investigation discussed herein is to provide a description of the flowfield on the leeward side of highly yawed circular cones at supersonic and hypersonic velocities. The experimental measurements were obtained as part of a more general study of the aerothermodynamic characteristics of yawed bodies of revolution at high supersonic Mach numbers.[14–16] A description of the flowfield around a yawed cone was obtained from analysis of surface pressure distributions, flow-visualization photographs and flowfield surveys. Measurements of the fluid and thermodynamic properties in the flowfield on the leeward plane of symmetry of a yawed cone were obtained with a calibrated five-hole cone probe, a Pitot probe and an equilibrium temperature probe.

II. Experimental Considerations

Surface pressure, flowfield surveys, and flow visualization experiments were conducted in the NOL Supersonic Tunnel No. 2 at a nomimal Mach number of 5. Additional flow visualization experiments were conducted in the Hypersonic Tunnel at a nominal Mach number of 6. These facilities are two-dimensional, open-jet, air wind tunnels with test section heights of approximately 16 in. and running times on the order of five minutes for the conditions of the present experiments. Descriptions of these facilities are presented in Refs. 17 and 18.

Several sharp five-degree half-angle cones, each 14.287 in. long, were constructed for the experiments in the Supersonic Tunnel No. 2. A model with 15 static pressure orifices along each of two conical rays, 180° apart, was utilized during the flowfield surveys and surface pressure experiments. Surface pressure distributions along the most windward and leeward generators of a yawed cone were obtained over an angle of attack range between 0° and 40°. Circumferential surface pressure distributions and leeward flowfield surveys were obtained at an angle of attack of 24°. The leeward flowfield surveys were conducted in a plane perpendicular to the axis of the cone (i.e., a cross-flow plane) located 9.11 in. from the vertex of the cone. Leeward flowfield

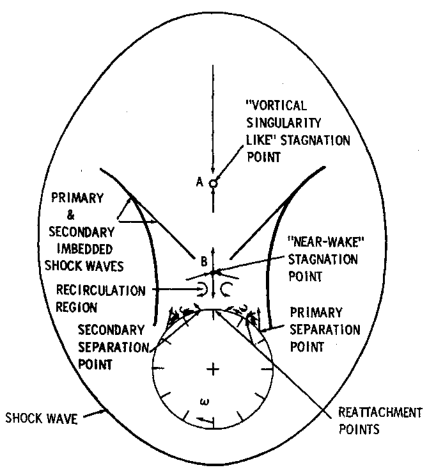

Fig. 1 Flowfield around a cone at a large angle of attack.

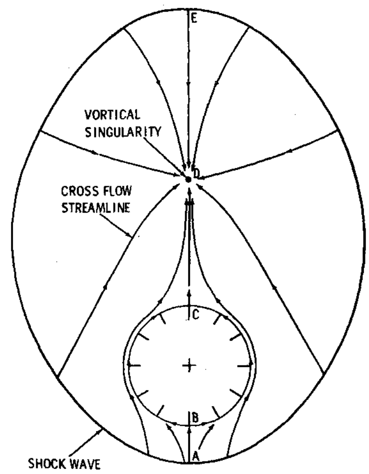

Fig. 2 Inviscid flowfield around a cone at a large angle of attack.

measurements were made with a simple Pitot probe (O.D. = 0.063 in.), a calibrated five-hole cone probe (o.d. = 0.187 in.), and an equilibrium temperature probe (o.d. = 0.050 in.). Additional details concerning the Supersonic Tunnel No. 2 experiments are presented in Refs. 15 and 16.

An indication of the local shear direction on a yawed cone was deduced from the surface oil flow pattern that was established after a slightly blunted conical model ($\theta_c = 5°$, $L = 13.967$ in., Tip Radius/Base Radius = 0.025) was exposed to a Mach 6 flow in the Hypersonic Tunnel. The details of the Mach 6 investigation which included force, pressure and heat transfer measurements for highly yawed axisymmetric configurations as well as the oil flow visualization studies referred to herein are presented in Ref. 14.

Nominal wind-tunnel testing conditions in the aforementioned facilities for these experiments are:

Supersonic Tunnel No. 2

Mach No.	Reynolds No./ft	$P_{0\infty}$	$T_{0\infty}$
5.07	4.4×10^6	100 psia	635°R
5.07	2.2×10^6	50 psia	635°R

Hypersonic Tunnel

Mach No.	Reynolds No./ft	$P_{0\infty}$	$T_{0\infty}$
5.93	2.4×10^6	147 psia	960°R

III. Results and Discussion

Flowfield Model

A sketch illustrating the structure of the flowfield around a yawed cone which best describes the experimental observations of the present investigation is shown in Fig. 1. For the purposes of description the lines shown in Fig. 1 can be thought of as the intersection of the three-dimensional flowfield around a yawed cone with a crossflow plane or a spherical surface (i.e., a surface of constant radius in a spherical coordinate system whose origin is at the vertex of the cone). The directions indicated by the arrows are the resultant velocity directions associated with the elevational (V) and circumferential (W) velocity components of the spherical coordinate system centered at the apex of the cone. A general description of the flowfield is stated below with supporting information provided in subsequent sections.

The flow on the windward side of a yawed cone is dominated by the inviscid conical flowfield between the shock wave and the thin viscous boundary-layer adjacent to the surface. In this region, the pressure gradient in the circumferential direction is favorable. On the leeward side of the cone, this pressure gradient which is initially favorable becomes adverse. Circumferentially downstream of the local pressure minimum, the boundary layer separates from the surface of

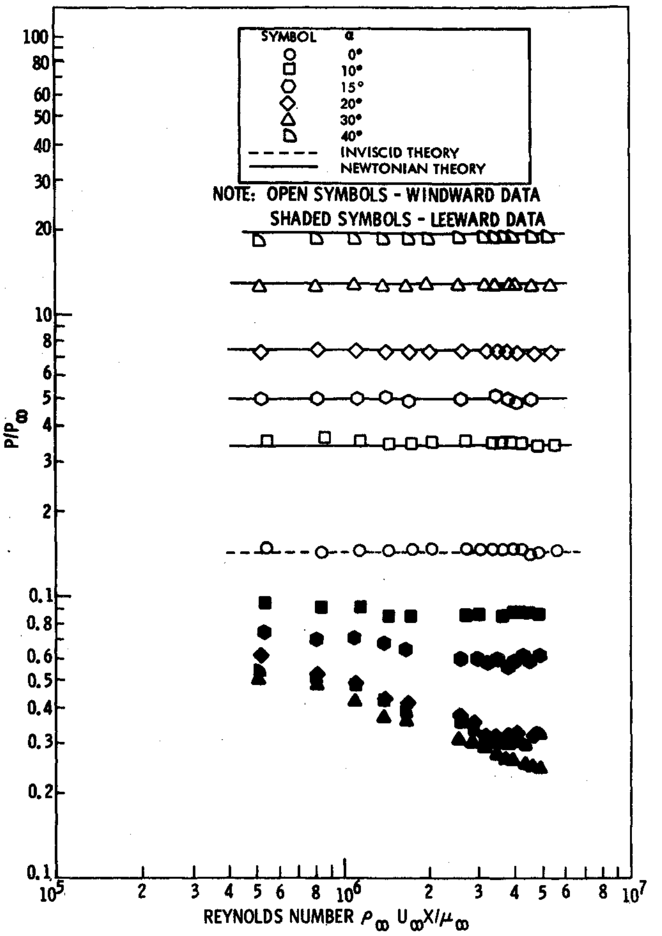

Fig. 3 Longitudinal surface pressure distribution (M_∞ = 5.07, Re_∞/ft = 4.8 × 10^6).

the cone along a conical generator. In the region of the separation line, an interaction is established between the flow that has separated from the surface and the approaching inviscid flow. If the resultant Mach number associated with the elevational and circumferential velocity components exceeds one, the interaction establishes an imbedded shock wave system on the leeward side of the cone. The separated flow "stagnates" on the plane of symmetry at point B of Fig. 1 (i.e., $V = W = 0$). For the purposes of description, one can refer to a dividing surface between the separation line and the locus of points B on successive cross-flow planes. The fluid above this dividing surface moves toward the "vortical singularity like" stagnation point located at point A in Fig. 1. A second imbedded shock wave can be created from the compressive turning of the fluid off the plane of symmetry as it moves toward point A.[10,12] The fluid below this dividing surface establishes a region of recirculating flow which has a stagnation point at the surface of the cone on the leeward plane of symmetry. Near the surface of the cone, this fluid flows away from the plane of symmetry and again separates at approximately 10° to 15° from the plane of symmetry. A second reattachment occurs approximately 35° degrees from the plane of symmetry.

The leeward flowfield model illustrated in Fig. 1 differs from that which is determined on the basis of an inviscid analysis[1,2,5] of the flowfield (Fig. 2) primarily because viscous interaction effects on the leeward side cannot be adequately accounted for in an inviscid model. For the inviscid model of the flowfield around a highly yawed cone, illustrated in Fig. 2, the crossflow streamline ABCD is an isentrope with a value of entropy equal to that behind the enveloping shock wave at the plane of symmetry on the windward side of the cone. A contact discontinuity (vortical singularity) is noted at point D. Across the vortical singularity there is a discontinuous change in entropy to a value which is associated with the shock wave in the plane of symmetry on the leeward side at point E. The discontinuity corresponds to one of the two stagnation points (i.e., $V = W = 0$) in the conical inviscid flowfield on the leeward side of the cone. (The other being in the plane of symmetry at the surface of the cone.) The flow model which is proposed in Fig. 1 includes an additional stagnation point, point B, on the leeward plane of symmetry, a recirculation region, and an imbedded shock wave system which are unaccounted for by the inviscid analyses conducted to date. For the freestream conditions associated with the present experiments, it appears to be unjustifiable to assume that the leeward flowfield is conical. The remaining discussion is intended to illustrate some of the experimental observations which led to the above comments and the flowfield model illustrated in Fig. 1.

Viscous-Inviscid Interaction

From an analytical viewpoint, one can presume that the flowfield established around a sharp cone, in a steady supersonic flow, is conical as long as the flow can be considered as inviscid and the local Mach number is supersonic. (If the local Mach number is subsonic, the cone must be infinitely long in order to assume conicity of the flowfield.) The conical nature of the flowfield is in part due to an absence of a suitable length dimension with which one can nondimensionalize the variables of the inviscid flowfield. In a nonideal gas, viscous phenomena interact with the inviscid flow and therefore introduce nonconical effects into the flowfield. The fact that parts of the flowfield around yawed conical bodies are determined by an interaction between viscous and inviscid phenomena has been recognized.[10,12,19] However, while the importance of the interaction has been noted, it also has been observed that the flowfield is "essentially conical."[9,10,19] That is to say, that previous experimental measurements have not indicated a strong dependence of the measured flowfield properties with distance from the apex. Clearly, some insight as to how the flowfield depends upon the distance from the apex and/or Reynolds number would be useful in trying to provide a description of the entire flowfield around yawed conical bodies for future analysis.

The surface pressure measurements illustrated in Figs. 3 and 4 provide some very useful information in this regard. The significant points to note in these results are the independence of the measurements on the windward side of the cone upon Reynolds number, the dependency of the measurements on the leeward side upon Reynolds number and the location of a local minimum in the static pressure distribution

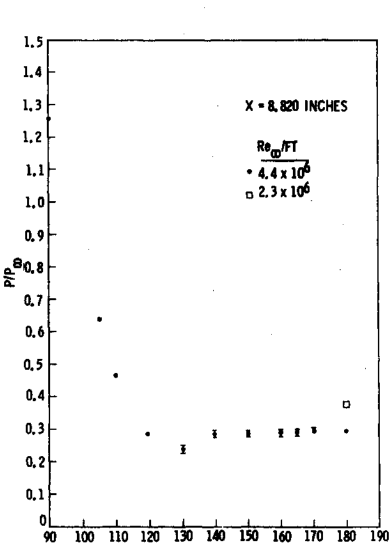

Fig. 4 Circumferential surface pressure distribution — α = 24°.

at an angle of 130° from the windward plane of symmetry.§ The invariance with respect to Reynolds numbers on the windward side is to be expected as the local Reynolds numbers are moderately high, the cone is sharp and the local Mach number is supersonic. The windward pressure measurements coupled with schlieren photographs, which indicate that the shockwave is straight and the boundary-layer thickness on the windward side is thin compared to the local radius of the cone, are the basis for stating that the flowfield on the windward side of a highly yawed cone is conical. The conical inviscid flowfield on the windward side of yawed circular cones can be calculated by techniques which are mathematically similar to those employed in the calculation of the flowfield associated with blunted bodies at supersonic velocities.[3–6]

A variation of the leeward static pressure with distance is indicated in Fig. 3. Although each data point illustrated in this figure was obtained at one pressure orifice at one Reynolds number per foot, additional measurements obtained at $Re_\infty/\text{ft} \approx 2 \times 10^6$, illustrated in Ref. 16, indicate that the leeward pressure is dependent upon Reynolds number, as indicated in Fig. 3, rather than upon distance normalized by the finite length of the cone (X/L). It is also observed that the leeward pressure distribution is less sensitive to angle of attack for angles of attack in excess of 20°. The dependence of the static pressure distribution upon the Reynolds number is a clear indication that viscous phenomena influence the development of the leeward flow field of a highly yawed cone. Additional measurements of surface pressure distributions along the most leeward meridian generator of slender cones ($\theta_c \leq 10°$) inclined at large angles of attack in hypersonic flows[10,20–22] illustrate that the static pressure distribution in this region is Mach number and Reynolds number dependent. These previous measurements were independently obtained over a freestream Mach number range $8 \leq M_\infty \leq 41$ and Reynolds number range $10^4 \lesssim Re_{\infty,x} \lesssim 8 \times 10^6$ (Ref. 15). A reasonable correlation of these results with those obtained during the present investigation was found by plotting the leeward static pressure distribution as a function of the viscous interaction parameter (Fig. 5). It is worthwhile to note that experimental studies of separated laminar two-dimensional flowfields at lower supersonic Mach numbers[23] indicate a dependence of the static pressure in the separated flow region with Reynolds number (based upon local conditions and length measured to the point of separation) raised to the $-\frac{1}{4}$ power. Furthermore, extrapolation of these studies[23] to higher supersonic Mach numbers indicates a dependence with the local Mach number at the point of separation raised to the $\frac{3}{2}$ power. The trend illustrated by the data in Fig. 5 is consistent with these previous results. In view of the scarcity of high Mach number and Reynolds number data and an absence of a quantitative analysis for

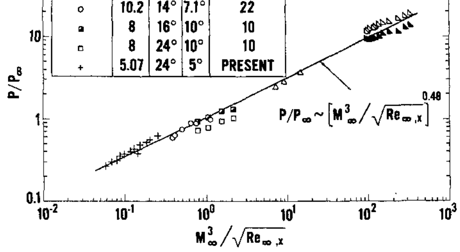

Fig. 5 Correlation of leeward pressure distributions — $\omega = 180°$.

§ Measurements in Ref. 14 indicate that $\omega|_{dp/d\omega = 0°} \approx 125°$ for $\alpha \geq 20°$.

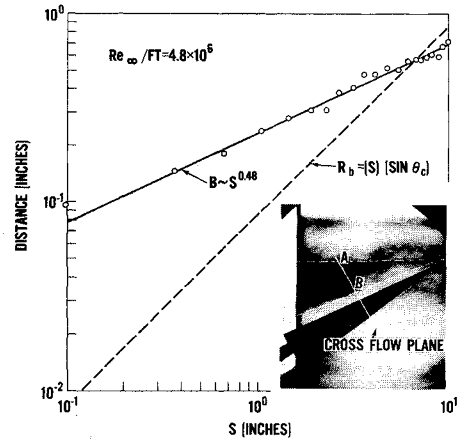

Fig. 6 Schlieren photograph — $\alpha = 30°$.

the flowfield on the leeward side of a highly yawed cone, the correlation presented in Fig. 5 might be viewed as fortuitous. With this reservation noted, the pressure measurements are interpreted as reflecting the viscous interaction nature of the flow field on the leeward side of a highly yawed cone.

An additional indication of nonconicity within the leeward flowfield of highly yawed cones was illustrated in schlieren photographs. Such photographs indicate the existence of two density gradients on the leeward plane of symmetry. This observation is illustrated in Fig. 6 for the case of a five-degree cone at an angle of attack of 30°. The density gradients illustrated in the schlieren photo insert are denoted by the letters A and B. These gradients respectively correspond to the "vortical singularity like" and the "near-wake" stagnation points noted in Fig. 1. Observation of the schlieren photographs indicated that while the density gradient denoted by A is essentially conical, the density gradient denoted by B developed essentially parabolically with distance measured from the vertex of the cone. The distance associated with point B in Fig. 6 corresponds to the distance between the surface of the cone and the density gradient, measured along a line which is normal to the surface of the cone. The local radius of the cone (R_b) is included in Fig. 6 for the purposes of comparison. It is apparent that the density gradient corresponding to B is displaced from the cone by a distance which is comparable to the local radius of the cone.

Surface Flow Visualization Studies

The approximate location of the points of flow separation and reattachment were determined from the pattern that formed after a coated surface was exposed to the incident flow. For the Mach 5 surface flow visualization experiments, a blackened teflon model was coated with azobenzene, a low melting temperature organic compound. Local regions of high shear and heat transfer can be distinguished (Fig. 7) once the model is exposed to the flow as the removal of the azobenzene is sensitive to the local shear and heat transfer. The local flow direction near the surface of a slightly blunted cone at Mach 6 was observed by placing a mixture of lampblack and silicone oil on the surface (Fig. 8). Both of these techniques provided an indication of the location of flow separation as the coating remained essentially undisturbed circumferentially downstream of the point of flow separation. Measurements made at three stations along the cone after the experiment indicated that to within the degree of accuracy of the measurements (i.e., $\Delta\omega = \pm 5°$), flow separation on a yawed cone occurs along a conical generator. (The conical nature of the separation line is not well illustrated in Fig. 7b as this photo was obtained during the experiment.)

The flow pattern illustrated in the oil flow photograph of the leeward plane of symmetry (Fig. 8) indicates a flowfield

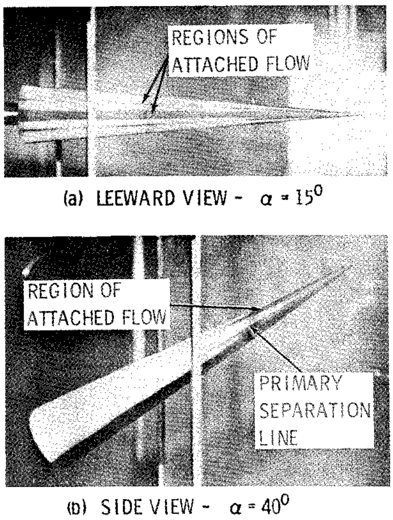

Fig. 7 Azobenzene coated models.

which is characterized by a flow directed away from the plane of symmetry. A similar flow pattern near the leeward plane of symmetry of a yawed circular cone was found in the experimental results of Rainbird,[9] Geoffery et al.,[11] Avduevskii and Medvedev,[12] and George.[13] This leeward pattern is interpreted as reflecting the stagnation point flow pattern in the plane of symmetry on the leeward side of a highly yawed cone (Fig. 1).

The photographs shown in Figs. 7 and 8 qualitatively indicate that there are local maxima in the shear and heat-transfer distributions on the leeward side of highly yawed circular cones. Quantitative measurements of the shear stress[9] and heat-transfer rates[10,14,22] on the leeward plane of symmetry have confirmed this fact. These regions of high shear and heat transfer illustrated in Fig. 7 are referred to as regions of attached flow. In view of the results obtained in the flowfield surveys on the plane of symmetry (to be discussed) which strongly suggest that the fluid on the leeward plane of symmetry has come through the shockwave on the windward side of the cone, it is more proper to refer to these regions as regions of flow reattachment. The definitive measurements of Rainbird[9] of shear stress and shear direction on the leeward side of a yawed cone serve as the basis for defining the second region of maximum shear and heat transfer as a region of reattached flow. In this case it is presumed that a secondary vortex formed in the vicinity of a secondary separation point (Fig. 1) has reattached on the surface of the cone. The angular locations of the primary and secondary separation lines, as well as the regions where local maxima in the shear and heating distributions were noted, are shown in Fig. 9.

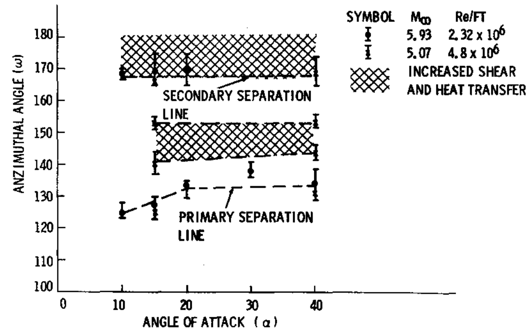

Fig. 9 Location of flow separation.

Optical Flow Visualization Studies

The flowfield around a five-degree cone at an angle of attack of 24° was optically observed with a conventional single pass schlieren system and the resultant photographs were analyzed, as described in Ref. 24, in order to locate the density gradients. A conical model was mounted on a bent sting. The model sting assembly was then rotated at a constant angle of attack around the center line of the wind tunnel. The analysis[24] allows one to define the loci of density gradients in the crossflow plane as the envelope to a series of lines (Fig. 10) which are determined from a series of two-dimensional schlieren photographs. These lines are formed by the intersection of a crossflow plane (X = constant) with a surface that is tangent to the density gradient surface visualized in a schlieren photograph. The tangent surface is uniquely defined by the fact that its normal is perpendicular to the light path of the schlieren system. Although the analysis does not require that the flowfield be conical, this assumption was made in order to simplify data reduction after it was observed that all of the density gradients, with the exception of B as noted in Fig. 6, were essentially conical.

The envelope which defines the outer shock wave in Fig. 10 is clearly defined from the windward side to within 30° of the leeward plane of symmetry. Over this region an ellipse provides a good analytic approximation for the shock shape in the crossflow plane (Ref. 16). The outer shockwave could not be defined all the way to the leeward plane of symmetry because the strength of the shock wave on the leeward side of a cone approaches that of a Mach wave.[10] For the purposes of comparison, one quarter of the trace of an ellipse, defined by the intersection of the crossflow plane and a Mach cone centered at the vertex, is included in Fig. 10.

On the leeward plane of symmetry in Fig. 10, there are two apparent intersections of the tangent lines in the vicinity of $R/R_b = 4.5$ and $R/R_b = 2.0$. A lineal disturbance or a cusped surface would both indicate a similar effect. The probe surveys indicated that the gradient visible at $R/R_b = 2.0$ is associated with a disturbance which extends off the plane of symmetry while the gradient located at $R/R_b = 4.5$ corresponds to a vortical singularity-like stagnation point. That is to say, the point in the flowfield where the fluid that has passed through the shock wave on the windward side

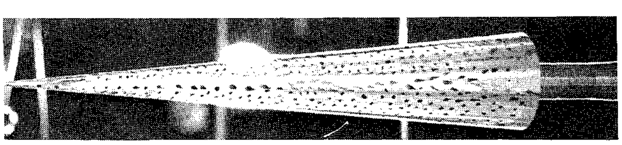

Fig. 8 Leeward surface oil flow pattern — $\alpha = 15°$.

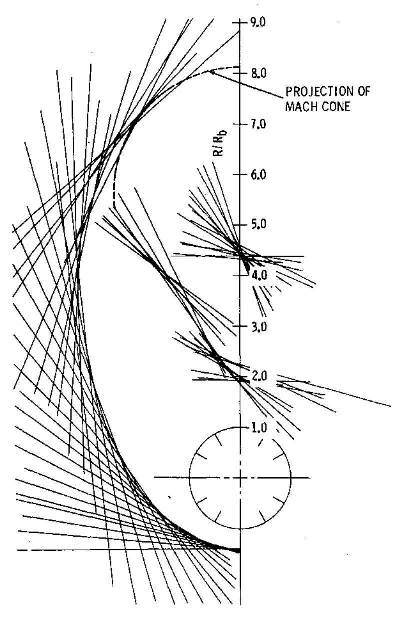

Fig. 10 Tangent lines to density gradients visible in schlieren photographs — ($\alpha = 24°$, X = constant).

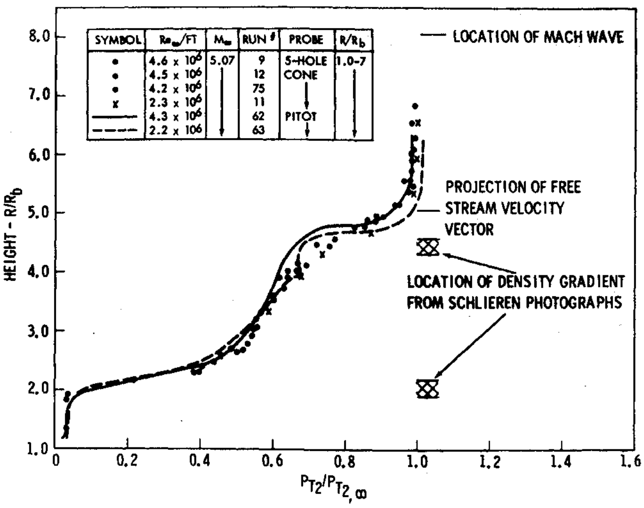

Fig. 11a Pitot pressure — $\alpha = 24°$, $\omega = 180°$, $X = 9.11$ **in.**

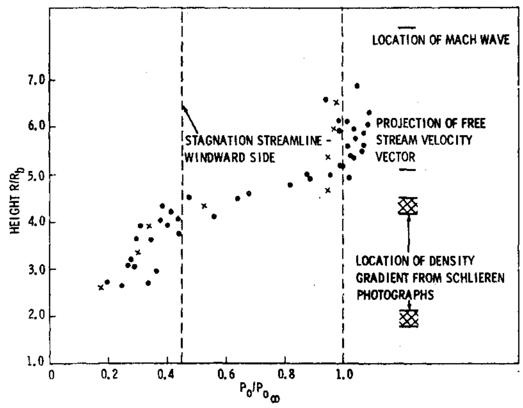

Fig. 11b Stagnation pressure — $\alpha = 24°$, $\omega = 180°$, $X = 9.11$ **in.**

meets that fluid which has passed through the weak shock on the leeward side of the cone. Additional information concerning these points was obtained from flowfield surveys and will be subsequently discussed.

Density gradients located off the plane of symmetry were also visualized (Fig. 10). These disturbances are believed to be associated with the imbedded shock waves within the flowfield on the leeward side of a yawed cone (Fig. 1). The actual shape of the imbedded shock waves could not be determined solely from the schlieren photographs as the analysis[24] only provides the location of lines that are tangent to the density gradient at some unspecified point along the line. In order to determine the shape of the imbedded shock waves, one must know the end points of the envelope. An indication of the shape of the imbedded shock waves was provided by vapor screen photographs obtained with the cone at an angle of attack of 40° (Ref. 15). While there was no direct evidence of a secondary imbedded shock wave observed during the present investigation, its existence is noted in the flowfield model (Fig. 1). Experimental evidence of the existence of a primary and a secondary imbedded shock wave in the leeward flowfield of a highly yawed cone was observed by Tracy[10] and Avduevskii and Medvedev.[12] The similarity between the imbedded shock waves on the leeward side of a cone and the shock wave pattern on the leeward side of a circular cylinder in a supersonic crossflow was noted by these investigators.

Flowfield Surveys ($\omega = 180°$)

Leeward flowfield surveys were made along the line defined by the intersection of the plane of symmetry and a

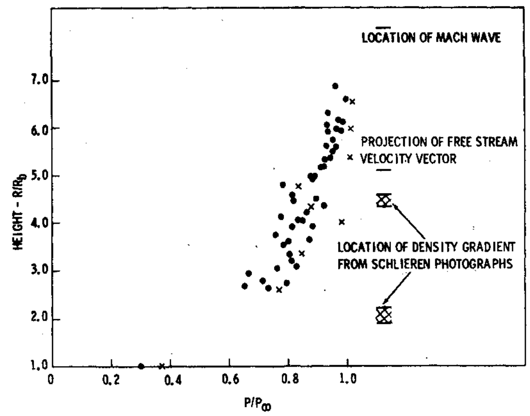

Fig. 11c Static pressure — $\alpha = 24°$, $\omega = 180°$, $X = 9.11$ **in.**

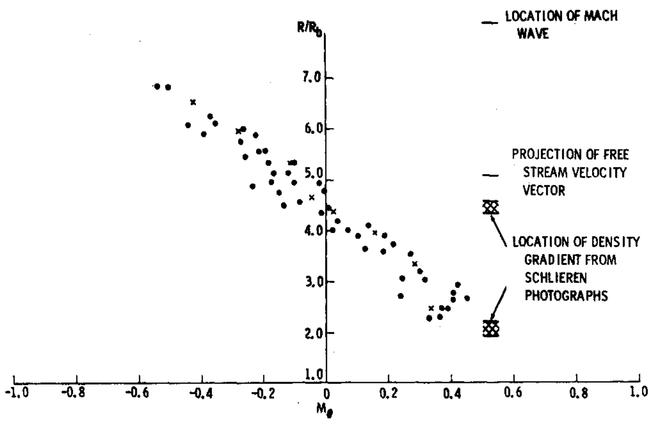

Fig. 11d Elevation velocity component — $\alpha = 24°$, $\omega = 180°$, $X = 9.11$ **in.**

crossflow plane located 9.11 in. from the vertex of the cone. The data obtained with the five-hole cone probe when coupled with the previously obtained probe calibration provided measurements of Pitot pressure, flow direction, Mach number, local stagnation pressure, and local static pressure. Once the flowfield surveys with the five-hole cone probe were completed (i.e., local Mach number and flow direction determined), the stagnation temperature distribution was deduced from the measurements with the equilibrium temperature probe.

The variations of some flowfield properties along the plane of symmetry are shown in Fig. 11. The projection of the freestream velocity vector referred to in these results corresponds to the projection of the freestream velocity vector passing through the vertex of the cone onto the line of traverse. In the vicinity of $R/R_b = 4.5$ one notes there are large decreases in the Pitot (Fig. 11a) and stagnation pressure (Fig. 11b), the static pressure is essentially constant (Fig. 11c), and that the velocity component in the θ direction changes sign (Fig. 11d). In view of the fact that the stagnation temperature is essentially constant in this region (Ref. 16), the large gradient in stagnation pressure is an indication of the existence of a large entropy gradient in the vicinity of $R/R_b = 4.5$. This experimentally defined gradient shows a strong similarity to a vortical singularity which has lifted off the surface of the cone in the leeward plane of symmetry (Fig. 2). However, in view of the fact that the experimental data presented in Fig. 11b indicate a reduction in stagnation pressure which is approximately 30% greater than that associated with the shock wave in the plane of symmetry on the windward side of the cone, the term "vortical singularity-like" stagnation point is utilized in Fig. 1 in order to denote the qualitative similarity between these experimental results and the results of previous analytical investigations. Nonisentropic processes in the vicinity of the boundary layer

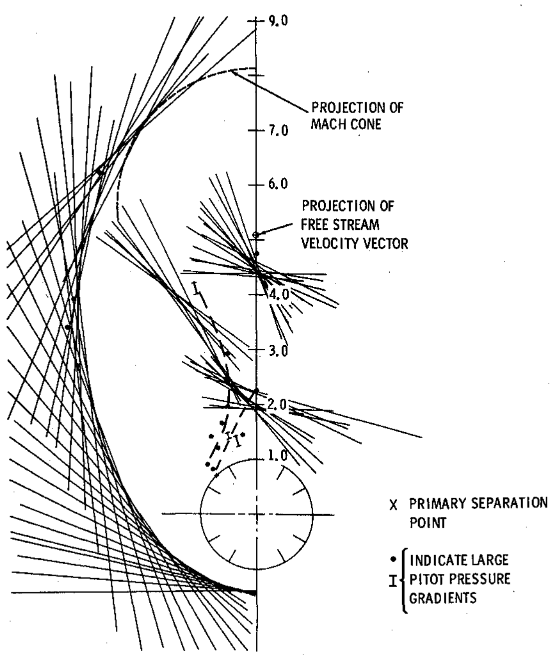

Fig. 12 Location of Pitot pressure gradients ($\alpha = 24°$, $X = 9.11$ in.).

near the cone, the mixing layer just after separation, the imbedded shock wave system, or on the leeward plane of symmetry between $R/R_b = 2.0$ and $R/R_b = 4.5$ can introduce further reductions in stagnation pressure which might possibly account for the noted 30% discrepancy in stagnation pressure.

In the vicinity of $R/R_b = 2.5$ a large gradient was noted in the Pitot pressure (Fig. 11a). Meaningful measurements of Mach number, flow direction, static pressure, and stagnation pressure were not obtained between $R/R_b = 2.5$ and the surface of the cone with the five-hole cone probe because of an inability to successfully align the probe with the local freestream direction (i.e., null the pressure differences between opposing orifices of the probe and repeat the measurements of pressure and probe orientation to the accuracy necessary to extract useful data). This is in part associated with the large relative scale of the probe with respect to the flowfield in this region. The Pitot pressure distribution indicates that the region between the surface of the cone and $R/R_b = 2.0$ is characterized by a relatively low value of Pitot pressure (Fig. 11a). Furthermore, due to the zero slip condition at a solid boundary, the Mach number and stagnation pressure (Fig. 11b) must show significant decreases someplace in this region. The static temperature must increase within this region from its value between $R/R_b = 2.3$ and $R/R_b = 4.5$ by a factor of approximately 4 (Ref. 16). In view of these trends and the observation that the outer boundary of this region developed essentially parabolically (Fig. 6), it is believed to be realistic to refer to the region between point B and the surface of the cone (Fig. 1) as a region where viscous stresses are significant in determining the flowfield.

The proposed flow direction near the surface (negative V velocity component) illustrated on the plane of symmetry in Fig. 1 is based upon the observed shear directions near the leeward plane of symmetry (Fig. 8). Since the θ velocity component was measured to be positive between $R/R_b = 2.5$ and $R/R_b = 4.5$ and is likely to be negative in the vicinity of the body, there will be a third point on the plane of symmetry (i.e., besides $R/R_b = 4.5$ and $R/R_b = 1.0$) where the velocity component normal to the ray is zero. The similarity between the flow in this region and that in the vicinity of the near wake stagnation point of a circular cylinder in crossflow is apparent. It should be emphasized that the proposed flowfield model (Fig. 1) indicates the existence of three "stagnation points" on the leeward plane of symmetry of a highly yawed cone whereas inviscid analyses indicate at most two (Fig. 2). The presence of the additional "stagnation point" is attributed to the effects of viscosity. For the conditions of the present experiments, the viscous region near the surface of the cone is one whose dimensions are comparable to the local body radius (Fig. 6). Furthermore, one observes that there is a static pressure variation across this region (Fig. 11c). In view of these observations any future attempts to apply a boundary-layer type analysis to the leeward flow field in this region should be carefully considered.

Flowfield Surveys ($130° \leq \omega \leq 170°$)

In addition to conducting flowfield surveys in the plane of symmetry of a highly yawed cone, the flowfield off this plane was surveyed with a Pitot probe and the five-hole cone probe. Valid measurements of flow direction, Mach number, static pressure and stagnation pressure were obtained over a relatively small part of the leeward flowfield off the plane of symmetry. These results are discussed in Ref. 16. Pitot pressure distributions were obtained along meridian lines ($X = 9.11$ in., ω = constant) in the region $130° \leq \omega \leq 170°$ with the Pitot probe and/or the Pitot orifice of the five-hole cone probe. A complete illustration of these results is also presented in Ref. 16. In Fig. 12, the location of the Pitot pressure gradients in the crossflow plane are superimposed upon the tangent lines defined from the analysis of the schlieren photographs (Fig. 10). The primary separation point determined from surface flow visualization is also indicated. Curves are faired through the points, determined from Pitot surveys, which are thought to locate the edge of the separated boundary layer and the imbedded shock waves. The flowfield in the vicinity of the separated boundary layer is believed to correspond to the flowfield in the vicinity of the dividing streamline in the wake of a circular cylinder in supersonic crossflow. As noted previously the imbedded shock waves are believed to be associated with the separation and recompression shock waves in the wake of a circular cylinder. The latter flow field is envisioned as a limiting case of the flow on the leeward side of a highly yawed cone as $\alpha \rightarrow 90°$, $\theta_c \rightarrow 0°$, $(S)(\sin\theta_c)$ = constant.

IV. Concluding Remarks

An investigation of the flowfield around a highly yawed slender cone has been conducted in a wind tunnel at a nominal Mach number of 5. The experimental measurements were analyzed and a model is proposed to describe the flowfield. Based upon the available experimental data, the following conclusions are reached: 1) the flowfield on the leeward side of a highly yawed cone is established by an interaction between viscous and inviscid phenomena. 2) The structure of the flowfield on the leeward side of a yawed circular cone shows a strong resemblance to the wake of a circular cylinder in a supersonic crossflow. 3) A "vortical singularity like" gradient which is characterized by a large gradient of stagnation pressure exists on the leeward side of a highly yawed cone. This gradient is one of three "stagnation points" in the plane of symmetry on the leeward side of a highly yawed cone.

The results obtained during the present study suggest additional investigation in the following areas: 1) the leeward flow field around a highly yawed cone in the limits as M_∞ and $Re_{\infty,L} \rightarrow \infty$ and 2) the leeward flowfield around circular cones at small and moderate angles of attack ($0 < \alpha \lesssim 1.5\,\theta_c$).

References

[1] Ferri, A., "Supersonic Flows With Shock Waves," in *High Speed Aerodynamics and Jet Propulsion, Vol. VI,* General

Theory of High Speed Aerodynamics, Princeton University Press, Princeton, N.J., 1954, Sect. H, pp. 670–747.

[2] Smith, J. H. B., "Remarks on the Structure of Conical Flow," RAE TR 69119, 1969, Royal Aircraft Establishment.

[3] Eastman, D. W., "Real Gas Flow Fields About Highly Yawed Cones by the Inverse Method," Boeing D2-20447-1, 1964, The Boeing Co..

[4] Moretti, G., "Inviscid Flow Field about a Pointed Cone at an Angle of Attack," *AIAA Journal*, Vol. 5, No. 4, April 1967, pp. 789–791.

[5] Jones, D. J., "Numerical Solutions of the Supersonic Flow Field for Conical Bodies in a Supersonic Stream," NAE Aero. Rept. LR-507, 1968, National Research Council of Canada.

[6] Ndefo, D. E., "A Numerical Method for Calculating Steady Unsymmetrical Supersonic Flow Past Cones," Rept. AS-69-11, Univ. of Calif., Berkeley, Calif., 1969.

[7] Chang, P. K., Smith, R. A., Casarella, M. J., and Oh, Y. H., "Analysis of Laminar Flow and Heat Transfer on Hypersonic Cone at High Angle of Attack," TR 2, Contract N-00017-67-C-0008, 1968, Dept. of Mechanical Engineering, Catholic Univ. of America, 1968.

[8] Boericke, R. R., "The Laminar Boundary Layer on a Cone at Incidence in Supersonic Flow," *AIAA Journal*, Vol. 9, No. 3, March 1971, pp. 462–468.

[9] Rainbird, W. J., "The External Flow Field About Yawed Circular Cones," AGARD Specialists Meeting, "Hypersonic Boundary Layers and Flow Fields," London, May 1968.

[10] Tracy, R. R., "Hypersonic Flow Over a Yawed Circular Cone," GALCIT Hypersonic Research Project Memo. 69, 1963.

[11] Guffroy, D., Roux, B., Marcillat, J., Brun, R., and Valensi, J., "Etude Theorique et Experimentale de la Couche Limite Autour D'un Cone Circulaire Place en Incidence Dans un Courant Hypersonique," AGARD Specialists Meeting, "Hypersonic Boundary Layers and Flow Fields," London, May 1968.

[12] Avduevskii, V. S. and Medvedev, K. I., "Investigation of the Laminar Flow Separation on a Cone Under Angle of Attack," Izvestia ANSSR, *Fluid and Gas Mechanics*, No. 3, 1966, pp. 117–119.

[13] George, O. L., "An Experimental Investigation of the Flow Field Around an Inclined Sharp Cone in Hypersonic Flow," Sandia Labs., SC-RR-69-57, 1969.

[14] Feldhuhn, R. H. and Pasiuk, L., "An Experimental Investigation of the Aerodynamic Characteristics of Slender Hypersonic Vehicles at High Angles of Attack," NOLTR 68-52, 1968, Naval Ordnance Lab., Silver Spring, Md.

[15] Feldhuhn, R. H. and Winkelmann, A. E., "Separated Flow Phenomena on a Slender Cone at Mach 5," NOLTR 69-36, 1969, Naval Ordnance Lab., Silver Spring, Md.

[16] Feldhuhn, R. H., "An Experimental Investigation of the Flow Field Around a Yawed Cone," NOLTR 69-187, 1969, Naval Ordnance Lab., Silver Spring, Md.

[17] "Aero and Hydro Ballistics Research Facilities," NOLR 1264, 1967, Naval Ordnance Lab., Silver Spring, Md.

[18] Baltakis, F. P., "Performance Capability of the NOL Hypersonic Tunnel," NOLTR 68-187, 1968, Naval Ordnance Lab., Silver Spring, Md.

[19] Cross, E. J., Jr. and Hankey, W. L., "Investigation of the Leeward Side of a Delta Wing at Hypersonic Speeds," *Journal of Spacecraft and Rockets*, Vol. 6, No. 2, Feb. 1969, p. 185–190.

[20] Horstman, C. C. and Kussoy, M. I., "Hypersonic Viscous Interaction on Slender Cones," *AIAA Journal*, Vol. 6, No. 12, Dec. 1968, pp. 2364–2371.

[21] Anderson, J. D., Jr., "Hypersonic Viscous Flow Over Cones at Nominal Mach 11 in Air," ARL 62-387, 1962, Aerospace Research Labs.

[22] Fitch, C. R., Morris, S. D. and Dunkin, O. L., "Force, Pressure, and Heat Transfer Tests on the G. E. Skybolt Nose Cone at Mach 10," AEDC-TDR-62-125, 1962, Arnold Engineering Development Corp., Arnold Air Force Station, Tenn.

[23] 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.

[24] Winkelmann, A. E. and Feldhuhn, R. H., "How to Analyze 2-D Schlieren Photographs to Obtain the Density Gradient Structure of 3-D Flow Fields," NOLTR 69-80, 1969, Naval Ordnance Lab., Silver Spring, Md.