AN ENGINEERING AERODYNAMIC HEATING METHOD FOR HYPERSONIC FLOW

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Abstract

A capability to calculate surface heating rates has been incorporated in an approximate three-dimensional inviscid technique. Surface streamlines are calculated from the inviscid solution, and the axisymmetric analog is then used along with a set of approximate convective-heating equations to compute the surface heat transfer. The method is applied to blunted axisymmetric and three-dimensional ellipsoidal cones at angle of attack for the laminar flow of a perfect gas. The method is also applicable to turbulent and equilibrium-air conditions. The present technique predicts surface heating rates that compare favorably with experimental (ground-test and flight) data and numerical solutions of the Navier-Stokes (NS) and viscous shock-layer (VSL) equations. The new technique represents a significant improvement over current engineering aerothermal methods with only a modest increase in computational effort.

Nomenclature

\( A, B, D, \bar{J} \) geometric factors
\( e_x, e_y, e_{\phi} \) tangential unit vectors on body surface
\( e_x, e_y, e_{\phi} \) unit vectors of cylindrical coordinate system
\( e_{\xi}, e_{\eta}, e_{\rho} \) unit vectors of shock-oriented coordinate system
\( f, \bar{f} \) shock radius
\( h_{\xi}, h_{\beta} \) scale factors of shock-oriented coordinate system
\( h_{\xi}, h_{\beta} \) scale factors of streamline coordinate system

\( M \) Mach number
\( n \) coordinate normal to shock
\( \bar{n} \) coordinate normal to body
\( p \) static pressure
\( q \) heat-transfer rate
\( R \) radius of curvature
\( u, v, w \) velocity components of shock-oriented coordinate system
\( V \) velocity magnitude
\( \mathbf{V} \) velocity vector
\( x, y, z \) cylindrical coordinate system
\( \alpha \) angle of attack
\( \beta \) shock angle relative to freestream velocity
\( \gamma \) body angle relative to freestream velocity
\( \delta \) shock angle in circumferential direction
\( \epsilon \) body angle in circumferential direction
\( \eta \) stream function ratio, \( \Psi/\Psi_s \)
\( \phi \) inclination angle of surface streamlines
\( \kappa_{\xi}, \kappa_{\beta} \) shock curvatures
\( \xi, \beta \) shock coordinates
\( \xi, \beta \) streamline coordinates
\( \rho \) density
\( \sigma \) shock angle, \( \phi - \delta \)
\( \tau \) body angle, \( \phi - \delta \)
\( \Phi, \Psi \) stream functions

Subscripts

\( b \) body
\( s \) shock
\( w \) wall
\( \infty \) freestream conditions

Introduction

The thermal design of hypersonic vehicles involves accurately and reliably predicting the convective heating over the surface of the vehicle. Such results may be obtained by numerically solving the Navier-Stokes (NS) equations, or one of their various subsets such as
the parabolized Navier-Stokes (PNS)\textsuperscript{2} and viscous shock-
layer (VSL) equations\textsuperscript{3,4} for the flowfield surrounding the
vehicle. However, due to the excessive computer storage requirements and run times of these detailed
approaches, they are impractical for the preliminary design
environment where a range of geometries and flow par-
parameters are to be studied. On the other hand, engineer-
ing inviscid-viscous methods\textsuperscript{5-8} have been demonstrated to
adequately predict the heating over a wide range of
generics and aerothermal environments. Various ap-
proximations in the inviscid and boundary-layer regions
reduce the computer time needed to generate a solution.
This reduction in computer time makes the engineering
aerothermal methods ideal for parametric studies.

Two of the simpler engineering aerodynamic heating
methods that are currently used are AER OHE A T\textsuperscript{5,6} and
INCHES.\textsuperscript{7} Both use the axisymmetric analog concept\textsuperscript{9}
which allows axisymmetric boundary-layer techniques to
be applied to three-dimensional (3-D) flows provided the
surface streamlines are known. AEROHEAT calculates
approximate surface streamlines based solely on the body
gometry. INCHES uses an approximate expression for the
scale factor in the windward and leeward planes which
describes the spreading of surface streamlines. Circum-
ferential heating rates are then generated by an empirical
relation. Another area of approximation is the surface
pressure distribution employed by the engineering meth-
ods. AEROHEAT assumes modified Newtonian theory
which is inaccurate for slender bodies, while INCHES
uses an axisymmetric Maslen technique.\textsuperscript{10} The defici-
cies and limitations of these approximations to the surface
streamlines and pressures in the engineering aerothermal
methods, along with their corresponding effects on the
surface heat transfer, have been documented in Refs. 11
to 13.

An approximate 3-D inviscid method\textsuperscript{14,15} has been
developed that is more accurate than modified Newton-
ian theory and has a wider range of applicability than the
axisymmetric Maslen technique. The inviscid tech-
nique uses two stream functions that approximate the
actual stream surfaces in the shock layer and a modified
form of the Maslen second-order pressure equation.\textsuperscript{16} The
method has been shown to calculate the inviscid flowfield
about 3-D blunted noses as well as 3-D afterbodies reasonably
accurately and much faster than numerical solutions of the
inviscid (Euler) equations.\textsuperscript{14}

In this paper, the approximate inviscid technique em-
ploys the axisymmetric analog to predict laminar and
turbulent surface heating rates using the approximate
convective-heating equations of Zoby et al.\textsuperscript{17} Both perfect
gas and equilibrium-air flows are considered. Improved
surface streamlines are calculated based on both the body
gometry and surface pressure distribution. Surface heat-
ing rates are presented for spherically-blunted and asym-
metric ellipsoidal cones at angle of attack. Comparisons
are made between results of the present technique, VSL
and NS solutions, and available experimental data to
demonstrate the accuracy and capability of the present
engineering technique.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Shock wave geometry: side view.}
\end{figure}

\section*{Analysis}

This section describes the 3-D inviscid technique, the
procedure for computing inviscid surface streamlines, and
the application of the axisymmetric analog. Approxima-
tions and coupling issues are also discussed.

\section*{Inviscid Method}

Since a detailed description of the approximate 3-D
inviscid method has been presented previously,\textsuperscript{14,15} only
a brief outline of the inviscid method is given here.

\subsection*{Coordinate Systems}

The three-dimensional shock surface can be repre-
sented by
\begin{equation}
    r_s = f(x, \phi)
\end{equation}
where \((x, r, \phi)\) are wind-oriented cylindrical coordinates
with corresponding unit vectors \((e_x, e_r, e_\phi)\). The \(z\)-axis is
aligned with the freestream velocity vector and is normal
to the shock surface at the origin. Two angles, \(\delta(\phi, x, \phi)\)
and \(\phi, (x, \phi)\), describe the shock wave shape and are de-
defined as
\begin{equation}
    \tan \delta = \frac{1}{f \dot{f} \phi} \quad \tan \phi = \frac{\dot{f} \phi \cos \delta}{\dot{f}}
\end{equation}
An additional angle is given by \(\sigma = \phi - \delta\). All angles
are shown in Figs. 1 and 2. For the special case of axis-
symmetric flow, \(r_s = f(x), \phi = (x), \delta = 0, \text{and } \sigma = \phi\).

Next, a shock-oriented curvilinear coordinate system
\((\xi, \beta, \eta)\) is defined where \(\xi \text{ and } \beta\) represent coordinates of
a point on the shock surface and \(\eta\) is the inward distance
normal to the shock. Differential arc lengths along each
coordinate direction at the shock are \(h_\xi d\xi, h_\beta d\beta, \text{ and}
\)
where \( h_\xi \) and \( h_\beta \) are scale factors for the corresponding coordinates. This coordinate system is well-suited for hypersonic flow (\( M_\infty \gg 1 \)) and thin shock layers.

The unit vectors, \( e_\xi \) and \( e_\beta \), are tangent to the shock surface and are chosen such that \( e_\xi \) is in the direction of the tangential velocity just inside the shock surface. The unit vector \( e_n \) is then defined to be perpendicular to \( e_\xi \) and \( e_\beta \). In cylindrical coordinates, the unit vectors of the curvilinear coordinate system are given by

\[
\begin{align*}
    e_\xi & = \cos \phi \, e_r - \sin \phi \, e_\theta \\
    e_\beta & = \sin \phi \, e_r + \cos \phi \, e_\theta \\
    e_n & = \sin \phi \, e_r - \cos \phi \, e_\theta
\end{align*}
\]

(3)

Although this curvilinear coordinate system is orthogonal at the shock surface, it is nonorthogonal within the shock layer for a general three-dimensional shock. However, for thin shock layers, orthogonality may be assumed everywhere.

The velocity is defined in terms of the unit vectors at the shock as

\[
    \mathbf{V} = u e_\xi + v e_n + w e_\beta
\]

(4)

From the definition of \( e_\xi \) and \( e_\beta \), the crossflow velocity component at the shock, \( w_s \), is equal to zero.

**Governing Equations**

The governing equations for 3-D inviscid flow are simplified by assuming that the velocity component \( w \) is equal to zero not only at the shock but throughout the shock layer. This yields two stream functions, \( \Phi \) (which is equal to \( \beta \) here) and \( \Psi \), which approximate the actual stream surfaces in the shock layer. The stream function \( \Psi \) is analogous to the Stokes stream function for axisymmetric flow.

Approximate expressions for the pressure and normal velocity component are then obtained by transforming the normal momentum and continuity equations to streamline coordinates and evaluating the flow variables at the shock. Along a line normal to the shock, these expressions are

\[
\begin{align*}
    p(\eta) & = p_s + p_1 (\eta - 1) + p_2 (\eta^2 - 1) \\
    v(\eta) & = v_s + v_1 (\eta - 1)
\end{align*}
\]

(5)

(6)

where

\[
\begin{align*}
    p_1 & = \frac{\Psi_s u_s \kappa_\xi}{h_\beta} \\
    p_2 & = -\frac{\Psi_s v_s \tan(\kappa_\xi + \kappa_\beta)}{2h_\beta} \\
    v_1 & = \frac{\Psi_s \tau_s}{h_\beta \cos(\kappa_\xi + \kappa_\beta)}
\end{align*}
\]

and

\[
    \eta = \frac{\Psi - \Psi_s}{\Psi_s}
\]

Defining \( \Psi = 0 \) to be the body surface gives \( \eta = 1 \) on the shock and \( \eta = 0 \) on the body. Note that Eq. (5) reduces to Maslen’s second-order pressure equation\(^6\) for axisymmetric flow if the scale factor \( h_\beta \) is equal to the shock radius \( r_s \).

**Method of Solution**

Since the inviscid method is an inverse one, the shock shape must be varied until the correct body shape is produced. The resulting iteration procedure is handled differently in each region of the flow.

In the stagnation region of a blunt body traveling at hypersonic speeds, the flow is subsonic and the shock shape for the entire subsonic-transonic region must be determined globally. A 3-D shock given by longitudinal conic sections blended in the circumferential direction with an ellipse is assumed. The parameters describing the shock are iterated until the body shape \( (\Psi = 0) \) generated by the approximate inviscid method matches the actual body shape at several discrete points. In this study, six shock parameters are varied until the calculated body is matched to the actual body at six locations.

Once past the transonic region, the inviscid flow is totally supersonic and a marching scheme is well posed. The shock surface from the transonic region forms a starting solution for the marching procedure. The shock variables are extrapolated in \( \xi \) along a number of constant \( \beta \) lines which circle the shock. On each line, the shock curvature \( \kappa_\xi \) is locally iterated until the calculated body shape matches the correct body. The shock variables are then advanced downstream to the next \( \xi \)-location and the process repeated.

**Axisymmetric Analog**

The 3-D boundary-layer analysis is simplified by using the axisymmetric analog\(^3\) as is done in most engineering aerothermal methods. The 3-D boundary-layer
equations are first written in a streamline coordinate system. The crossflow velocity component tangent to the surface but normal to the streamline is then assumed to be zero. This simplification reduces the 3-D boundary-layer equations to the axisymmetric form provided the distance along the streamline is substituted for the surface distance and the scale factor describing the divergence of the streamlines is interpreted as the axisymmetric body radius. Axisymmetric boundary-layer methods can then be employed in the existing 3-D inviscid technique.

**Inviscid Surface Streamlines**

Before applying the axisymmetric analog, inviscid surface streamlines are computed from the approximate inviscid solution. Inviscid surface streamlines may be calculated from the surface pressure distribution or from the velocity components. The approximate inviscid method used here predicts accurate surface pressures, but the direction of the velocity on the surface is not accurate. Therefore, in the present method, streamlines are calculated from the surface pressures.

A streamline coordinate system \((\xi, \beta, \bar{n})\) is defined where \(\bar{n}\) is the distance normal to the body surface and \(\bar{n}\) is the distance normal to the body. The bars indicate the variables apply to the body and not the shock. Differential arc lengths along each coordinate direction at the body are \(h_\xi d\xi, h_\beta d\beta,\) and \(h\bar{n}\) where \(h_\xi\) and \(h_\beta\) are scale factors for the corresponding coordinates. If the body surface is represented by \(n = f(x, \phi)\) in wind axes with the axial coordinate parallel to the freestream velocity and passing through the stagnation point, the vector normal (outward) to the body surface is given by

\[
e_\sigma = -\sin \tilde{\beta} e_x + \cos \tilde{\beta} (-\sin \tilde{\delta} e_\phi)
\]

The body angles are defined in the same fashion as the shock angles and are

\[
\tan \tilde{\delta} = \frac{1}{\bar{n}} \frac{\partial f}{\partial \phi}, \quad \tan \tilde{\beta} = \frac{1}{\bar{n}} \frac{\partial f}{\partial x} \cos \tilde{\delta}
\]

The tangential unit vectors at the surface, \(e_\xi\) and \(e_\beta,\) are similar to the tangential unit vectors at the shock. From Ref. 5, they are given as

\[
e_\xi = \cos \tilde{\delta} e_x + \sin \tilde{\delta} e_\phi
\]

\[
e_\beta = -\sin \tilde{\beta} e_x + \cos \tilde{\beta} e_\phi
\]

where

\[
e_x = \cos \tilde{\delta} e_x + \sin \tilde{\delta} (-\sin \tilde{\delta} e_\phi)
\]

\[
e_\phi = \sin \tilde{\delta} e_x + \cos \tilde{\delta} e_\phi
\]

and the angle \(\tilde{\theta}\) represents the orientation of the surface streamlines. Note that the vectors, \(e_x\) and \(e_\phi,\) are identical in form to the unit vectors, \(e_\xi\) and \(e_\beta,\) defined at the shock.

The orientation of the inviscid surface streamlines, given by \(\tilde{\theta},\) is found by applying the momentum equations along the body surface using the pressure distribution generated by the inviscid solution. By writing the momentum equations in streamline coordinates, taking the scalar product with \(e_\xi,\) and substituting the unit vectors, Eqs. (9) and (10), this may be expressed as

\[
\frac{1}{h_\xi} \frac{\partial \tilde{\theta}}{\partial \xi} = -\sin \tilde{\beta} \frac{\partial \tilde{\delta}}{\partial \xi} -\rho e_\xi \frac{1}{h_\beta} \frac{1}{\partial \beta}
\]

(13)

where \(\tilde{\delta} = \phi - \tilde{\delta}.\) The scale factor \(h_\beta\) can be determined by noting that for an orthogonal curvilinear coordinate system

\[
\frac{\partial}{\partial \xi} (h_\xi e_\xi) = \frac{\partial}{\partial \beta} (h_\xi e_\xi)
\]

Taking the scalar product of this equation with \(e_\xi\) and again substituting the unit vectors, Eqs. (9) and \(10,\) yields

\[
\frac{1}{h_\xi} \frac{\partial \ln h_\beta}{\partial \xi} = \frac{1}{h_\xi} \frac{\partial \tilde{\theta}}{\partial \beta} + \sin \tilde{\beta} \frac{\partial \tilde{\delta}}{\partial \beta}
\]

(14)

Equations (13) and (14) may be integrated along a surface streamline to obtain the streamline direction \(\bar{\theta}\) and the scale factor \(h_\beta.\) Although the surface streamlines can be determined after the inviscid solution has already been calculated, it was found to be more convenient to compute the inviscid solution and the surface streamlines simultaneously. Before applying these equations along shock coordinates, transformation operators relating derivatives with respect to the streamline coordinates \((\xi, \beta)\) to derivatives with respect to the shock coordinates \((\xi, \beta)\) are needed. In the approximate inviscid method, the curvilinear coordinate system is assumed to be orthogonal throughout the shock layer. This assumption simplifies the analysis but does not change the form of the approximate pressure and velocity relations, Eqs. (5) and (6), since the flowfield variables are evaluated at the shock where the coordinate system is orthogonal. However, at the body surface, the correct coordinate directions need to be considered. Following the approach of Ref. 15 and using the nonorthogonal directions at the surface, the transformation operators are

\[
\frac{\bar{J}}{h_\xi} \frac{\partial}{\partial \xi} = (B e_\xi \cdot e_\xi - D e_\xi \cdot e_\beta) \frac{1}{h_\xi} \frac{\partial}{\partial \xi} + (-D e_\xi \cdot e_\xi + A e_\xi \cdot e_\beta) \frac{1}{h_\beta} \frac{\partial}{\partial \beta}
\]

(15)

and

\[
\frac{\bar{J}}{h_\beta} \frac{\partial}{\partial \beta} = (B e_\beta \cdot e_\xi - D e_\beta \cdot e_\beta) \frac{1}{h_\xi} \frac{\partial}{\partial \xi} + (-D e_\beta \cdot e_\xi + A e_\beta \cdot e_\beta) \frac{1}{h_\beta} \frac{\partial}{\partial \beta}
\]

(16)

where

\[
A = 1 - n_h \kappa_\xi
\]
These operators can be used to calculate the pressure derivative in Eq. (13) as well as allow Eqs. (12) and (14) to be integrated with respect to the shock coordinate $\xi$. The calculations were performed using the same technique used previously. The results are presented in Figs. 3 and 4, demonstrating the ability of the present method to calculate surface heating rates. The comparison with experimental data is shown in Figs. 3 and 4, and the results are in good agreement with experimental measurements. The present method is shown to be accurate and efficient for calculating surface heating rates.
The pressure gas, laminar solution over a blunted ellipsoidal cone.

The results from the present laminar and turbulent model. Excellent comparison between the calculated values is obtained from the present solution around the ellipsoidal cone. The calculated heating rates in the transition region are based on the Dhaawan data shown in Fig. 8. Results from the present method are compared with heat-transfer data obtained from a blunt cone at equilibrium-ambient and turbulent conditions.

Ellipsoidal Cones

In order to demonstrate the significant improvement in the prediction of heating rates for low and high heat fluxes, the surface heating rates over a 5 deg sphere-cone at an altitude of 150,000 ft. The freestream Mach number is 1.9 and the nose radius in the side planes are 0.5 and 0.9 deg respectively. The freestream and dynamic heating methods/ the surface heating rates in the transition region are based on the Dhaawan data shown in Fig. 8. Results from the present method are compared with heat-transfer data obtained from a blunt cone at equilibrium-ambient and turbulent conditions.

Comparison of circumferential surface heating rates for 5 deg sphere-cone.

Comparison of surface heating rates with the VSL results shown in Fig. 8. Results from the present method are compared with heat-transfer data obtained from a blunt cone at equilibrium-ambient and turbulent conditions.

The surface heating rates over a 5 deg sphere-cone.

Figure 7. Comparison of surface heating rates for 0 deg sphere-cone.

Figure 6. Comparison of circumferential surface heating rates for 12 deg sphere-cone.
Comparison of surface heating rates for a 2:1 ellipsoidal cone.

Figure 12.

Comparison of circumferential surface heat.

Figure 13.

Comparison of circumferential surface heat.

Figure 14.

Comparison of surface heating rates for a 2:1 ellipsoidal cone.
Comparison of circumferential surface heat-distribution for $2:1$ ellipsoidal cone.

Figure 17. Comparison of circumferential surface heat-distribution for $2:1$ ellipsoidal core.

Comparison of thermal surface heat-distribution for $2:1$ ellipsoidal core.

Comparison of surface heating rates for $2:1$ ellipsoidal core.

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References

Concluding Remarks

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hypersonic flow fields is applied to the solution of the NS and
turbulent equations.
numerical methods with
major cost and efficiency advantages.

Figure 18. Comparison of experimental surface heat rates for 3-D blunt-nosed cone.

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Concluding Remarks

-2-D bodies significantly enhance physical capabilities over present engineering methods. The applications to
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