INVISCID-SURFACE-STREAMLINE PROGRAM FOR USE IN PREDICTING SHUTTLE HEATING RATES

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INTRODUCTION

The previous papers in this session have indicated that a number of methods are currently under development for computing the "exact" three-dimensional flow field about real configurations. However, even when these methods are available, they will require large computational times on present-generation computers. Thus, there is still a need to develop approximate methods to solve three-dimensional flow problems. This paper describes an inviscid-surface-streamline program (for predicting shuttle heating rates) which uses approximate methods to obtain a solution. The basic method used herein is described in detail in reference 1.

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SYMBOLS

H	scale factor in β-direction
L	length of delta-wing orbiter model, 0.323 meter
M_∞	free-stream Mach number
p	static pressure
q_{REF}	heat-transfer rate at stagnation point of a scaled 0.3048-meter-radius sphere
q_w	heat-transfer rate at wall
$q_{w,s}$	heat-transfer rate at stagnation point
r_N	nose radius of blunt cone, 0.925 cm
$R_{\infty,N}$	free-stream Reynolds number based on nose radius
u,v	velocity components in boundary layer in ξ- and β-directions, respectively
V_∞	free-stream velocity
x	axial distance from nose
α	angle of attack
β	coordinate normal to streamline on surface
η	coordinate normal to surface
ξ	coordinate along a surface streamline
φ	circumferential angle measured from lower surface plane of symmetry

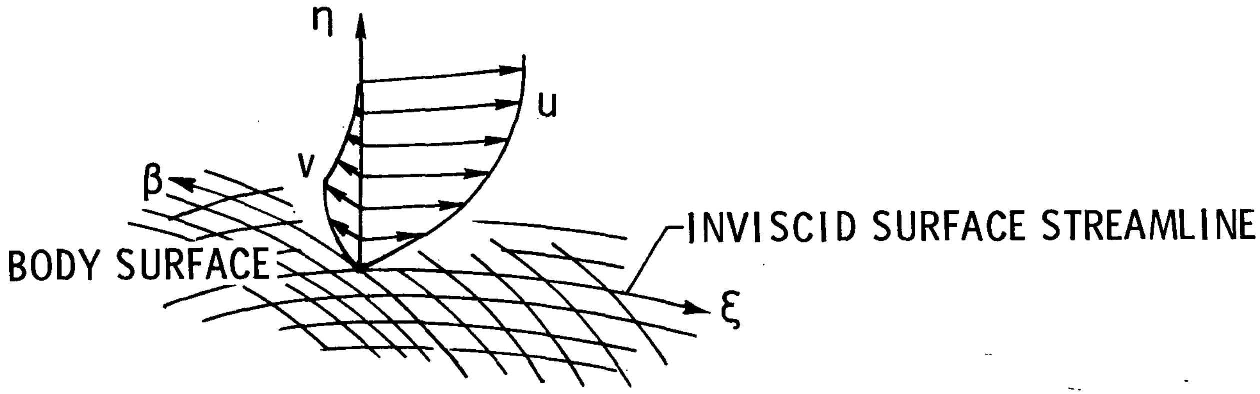
BOUNDARY-LAYER SOLUTION

(Figure 1)

If the boundary-layer equations are written in a surface-oriented, streamline coordinate system where the ξ-coordinate is in the direction of an inviscid surface streamline, the typical velocity profile in the boundary layer will be as depicted in this figure. If it is assumed that the crossflow in the boundary layer (i.e., flow in the β-direction) is small and can be neglected, the three-dimensional (3-D) boundary-layer equations reduce to an equivalent form for axisymmetric flow about a body at zero incidence (see refs. 2 and 3). The distance along an inviscid surface streamline is interpreted as the distance along an equivalent axisymmetric body, and the scale factor for the β-coordinate (which is a measure of the streamline divergence) is interpreted as the radius of an equivalent axisymmetric body. The small crossflow approximation has been shown to be valid when the ratio of wall to stagnation enthalpy is small (ref. 4) as is the case in most space-shuttle applications.

This approximation makes a significant simplification to the boundary-layer problem and allows computations to proceed along inviscid surface streamlines using any boundary-layer solution available for axisymmetric flow. To be applicable to space shuttle the boundary-layer solution must be capable of handling laminar, transitional, and turbulent flow. Techniques that involve numerical solution of the nonsimilar boundary-layer equations (e.g., ref. 5) could be used. However, since this would destroy some of the simplicity desired in the present method, the local similarity method of Beckwith and Cohen (ref. 6) is used to predict laminar heating rates and a modification of the integral method of Reshotko and Tucker (ref. 7) is used to predict the turbulent heating rates. In the transitional region a weighted average of laminar and turbulent values is used. The present analysis includes both ideal-gas and equilibrium-air thermodynamic properties. The results that will be presented in this paper are for laminar flow of an ideal gas.

BOUNDARY-LAYER SOLUTION



1. ASSUME SMALL CROSSFLOW IN BOUNDARY LAYER

2. REDUCE 3-D BOUNDARY-LAYER EQUATIONS TO EQUIVALENT FORM FOR AXISYMMETRIC FLOW AT $\alpha = 0°$

3. APPLY COMPUTATIONS ALONG INVISCID SURFACE STREAMLINES USING ANY METHOD APPLICABLE TO AXISYMMETRIC FLOW

4. INCLUDE LAMINAR, TRANSITIONAL, AND TURBULENT FLOW

5. INCLUDE IDEAL-GAS AND EQUILIBRIUM-AIR THERMODYNAMIC PROPERTIES

Figure 1

INVISCID-SURFACE-STREAMLINE SOLUTION

(Figure 2)

If the entropy and pressure distribution on the surface are known, ordinary differential equations can be obtained for the streamline path and for the scale factor H from Euler's equations and the equations of the surface geometry. In Phase I of the present development, the flow in the vicinity of the surface is assumed to have passed through a normal shock (typical blunt-body assumption). This is not a valid approach for space-shuttle applications at high flight velocities; thus the method is being extended in Phase II to account for variable entropy at the boundary-layer edge. The results that will be presented in this paper are for a Phase I approach.

Thus, starting at the stagnation point, the streamline path, the scale factor H, and the heat-transfer rate are computed along a selected streamline independent of other streamlines. Solutions are then computed along other streamlines until an adequate surface heating distribution is obtained.

The surface pressure distribution must be known to start the calculation and must be obtained independently. Experimental pressures can be used, if they are available in sufficient detail. However, they must be very accurate since second derivatives of the pressure are required. Approximate methods such as Newtonian theory appear to be the most promising source for surface pressure distributions at this time, but as more exact methods become available they can be used.

Another critical problem area is the description of the surface geometry. Two approaches have been used. First, a two-dimensional (2-D) cubic spline function has been used to "surface fit" body coordinates. The application of this method is easy and it has proven useful in describing certain simple geometric shapes, but it has not yielded the mathematical consistency necessary for describing complex configurations. The second method used to describe the surface geometry is analytic equations.

INVISCID-SURFACE-STREAMLINE SOLUTION

1. ASSUME ENTROPY AND PRESSURE DISTRIBUTION ON SURFACE
2. OBTAIN ORDINARY DIFFERENTIAL EQS. FOR STREAMLINE PATH AND SCALE FACTOR (H) FROM EQS. OF MOTION AND GEOMETRY
3. STARTING AT STAGNATION POINT, CALCULATE STREAMLINE PATH, SCALE FACTOR (H), AND BOUNDARY-LAYER SOLUTION FOR A SELECTED STREAMLINE
4. OBTAIN SURFACE PRESSURE DISTRIBUTION FROM
   A. EXPERIMENTAL DATA
   B. APPROXIMATE METHOD
5. DESCRIBE SURFACE GEOMETRY
   A. 2-D CUBIC SPLINE
   B. ANALYTICAL EQS.

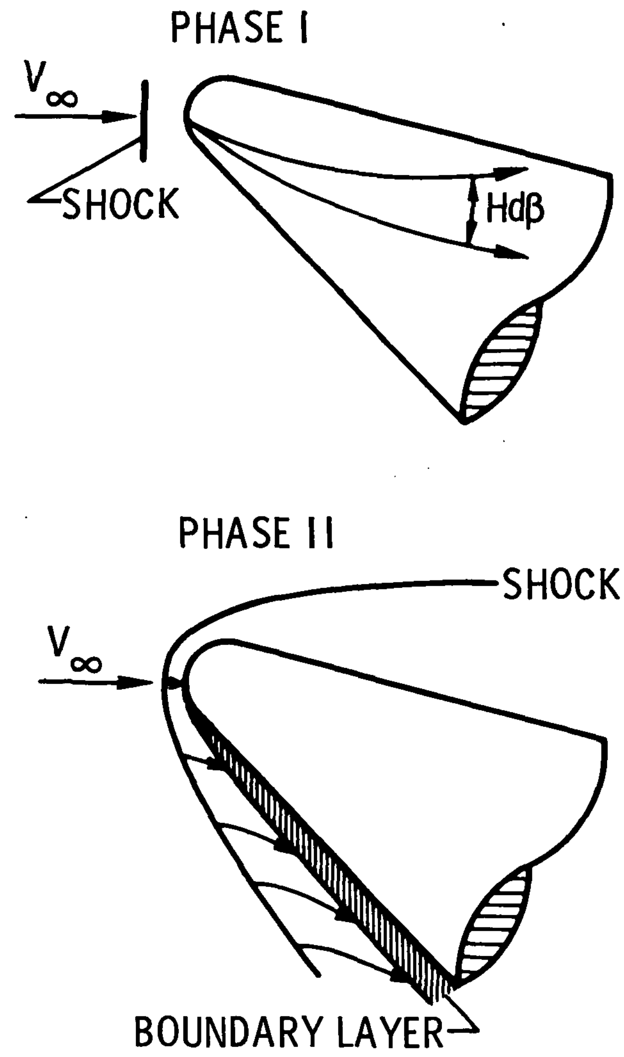


Figure 2

RESULTS FOR BLUNT 15° HALF-ANGLE CONE
(Figure 3)

This figure shows heating rates for a blunt 15° half-angle cone at $\alpha = 20^\circ$ and $M_\infty = 10.6$. The data, taken from reference 8, are presented as a ratio of local heating rate to that at the stagnation point $q_w/q_{w,s}$. The left-hand side of this figure shows axial distributions of $q_w/q_{w,s}$ for two rays on the cone, the most windward ray ($\varphi = 0^\circ$) and the side ray ($\varphi = 90^\circ$). In both cases, the agreement between the heating rates computed by the present theory and the experimental data is excellent.

The right-hand side of this figure shows a circumferential distribution of heating at $x/r_N = 26.5$. Again, the agreement between theory and experiment is excellent.

In computing the heating rates for this case, Newtonian theory was used to calculate the pressure distribution and a two-dimensional cubic spline function was used to describe the surface geometry.

Although other approximate methods have been developed that are applicable to simple axisymmetric bodies such as blunt cones (e.g., ref. 9), they cannot be applied to general three-dimensional bodies. The present method is not restricted to simple body shapes.

RESULTS FOR BLUNT 15° HALF-ANGLE CONE

$\alpha = 20°$

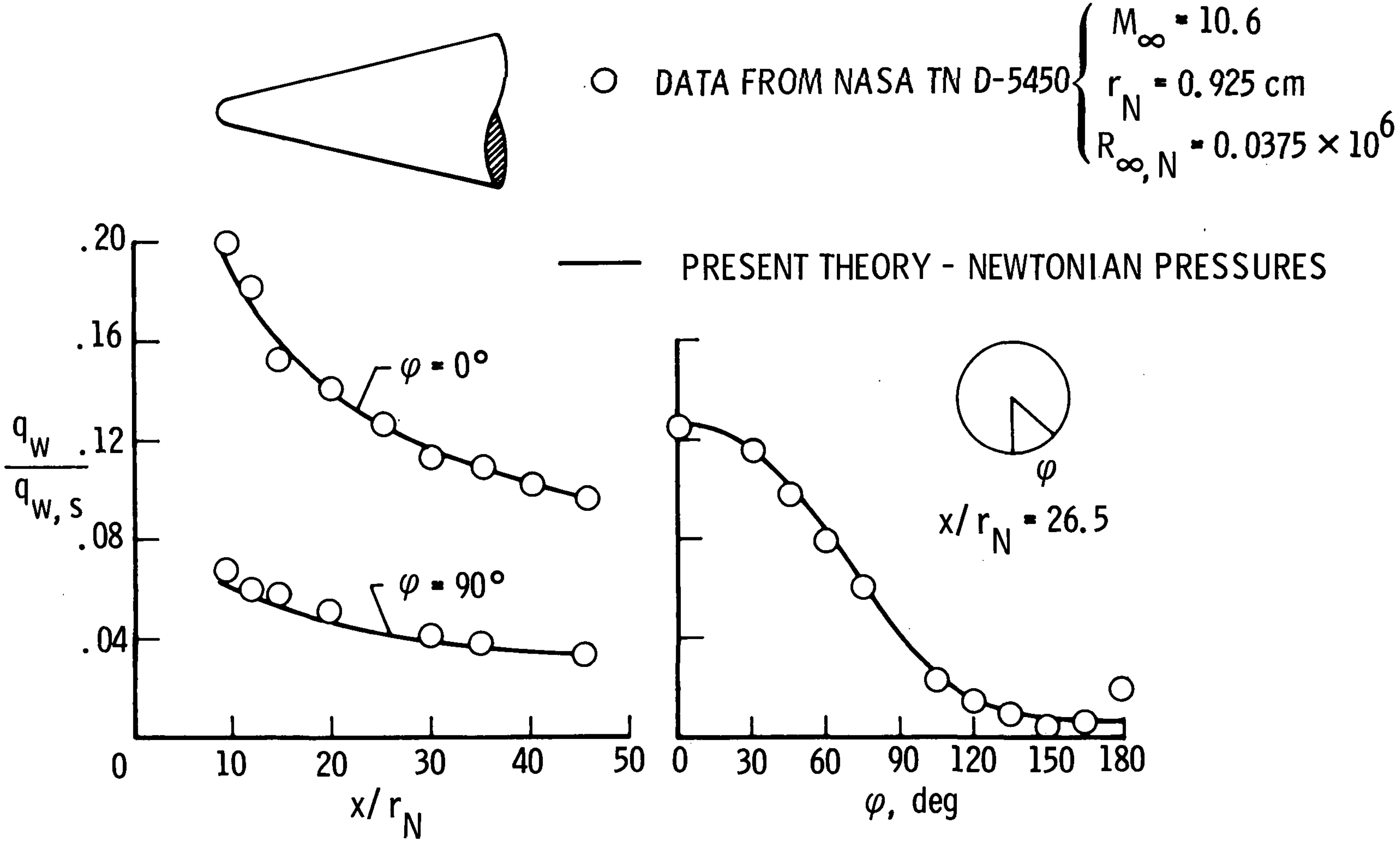


Figure 3

NAR 134B DELTA-WING ORBITER
(Figure 4)

This figure shows the NAR 134B delta-wing orbiter on which computations have been performed. This configuration was selected because of the availability of thermocouple heat-transfer data that were obtained at Ames Research Center (ARC) at $M_\infty = 7.4$ (ref. 10). The dimensions shown on the figure are for the ARC thermocouple test model. The surface geometry was described by analytical equations, with the use of a method suggested by J. V. Rakich of ARC and discussed in paper no. 5 by P. Kutler, J. V. Rakich, and G. G. Mateer. Basically, the method consisted of fitting the planform and plane-of-symmetry profile with polynomial functions of x and then using different elliptical segments to fit the upper- and lower-half cross sections.

NAR 134B DELTA-WING ORBITER

ARC THERMOCOUPLE TEST MODEL

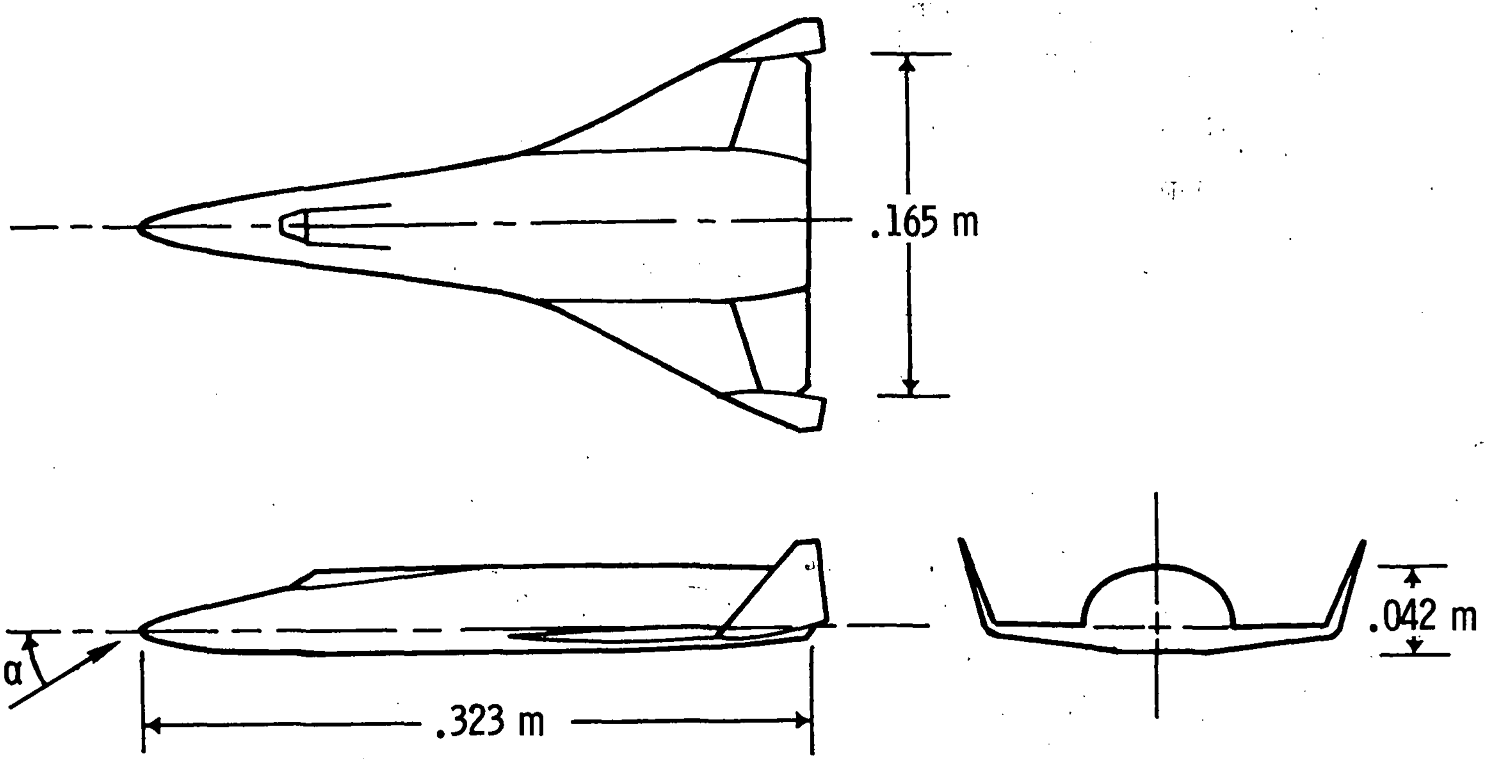


Figure 4

RESULTS FOR NAR 134B DELTA-WING ORBITER

(Figure 5)

This figure shows a comparison of heating rates computed by the present theory, using a Newtonian pressure distribution, with experimental data at $\alpha = 30^{\circ}$ for the NAR 134B delta-wing orbiter shown in figure 4. The heat-transfer data are presented as a ratio of local heating rate to a reference value q_w/q_{REF}, where the reference value is at the stagnation point of a scaled 0.3048-meter-radius sphere. Axial distributions of q_w/q_{REF} are presented in the upper part of the figure for the windward plane of symmetry ($\varphi = 0^{\circ}$). The theory and data are in good agreement over the forward portion of the model (i.e., $x/L < 0.5$), but the theory falls below the data over the aft portion (i.e., $x/L > 0.5$). Newtonian theory predicts a maximum pressure occurring on the windward plane of symmetry for $x/L \lesssim 0.4$; thus $(\partial^2 p/\partial\varphi^2)_{\varphi=0} < 0$ in this region and the surface streamlines tend to diverge. (Note that $(\partial p/\partial\varphi)_{\varphi=0} = (\partial^2 p/\partial x\,\partial\varphi)_{\varphi=0} = 0$ due to symmetry.) For $x/L \gtrsim 0.4$, Newtonian theory predicts a maximum pressure occurring off the windward plane of symmetry; thus $(\partial^2 p/\partial\varphi^2)_{\varphi=0} > 0$ in this region, the surface streamlines tend to converge, and the heating rates are reduced. Examining unpublished experimental pressure data obtained on this same configuration at ARC, one finds that the data (although sparse) tend to indicate that as far back as $x/L = 0.6$, $(\partial^2 p/\partial\varphi^2)_{\varphi=0} \leqq 0$. Thus, the previous calculation was repeated with the condition $(\partial^2 p/\partial\varphi^2)_{\varphi=0} = 0$ for $x/L > 0.4$ and resulted in the heat-transfer rates shown by the dashed line. This result is in better agreement with the experimental data and suggests that the previous computation (solid line) underpredicted the data over the rearward portion of the model because of the unrealistic lateral pressure distribution obtained from Newtonian theory.

The circumferential distribution of heating is shown in the lower left-hand part of the figure. The thermocouple data were supplemented by paint-test data obtained at Langley Research Center (LaRC) at $M_\infty = 8$. The theory and data are in reasonably good agreement. In the lower right-hand part of the figure, the computed inviscid surface streamlines are shown over the forward portion of the lower surface. The streamline divergence increases as the leading edge is approached. This fact accounts for the increase in heating in the vicinity of the leading edge.

RESULTS FOR NAR 134B DELTA-WING ORBITER

$\alpha = 30°$

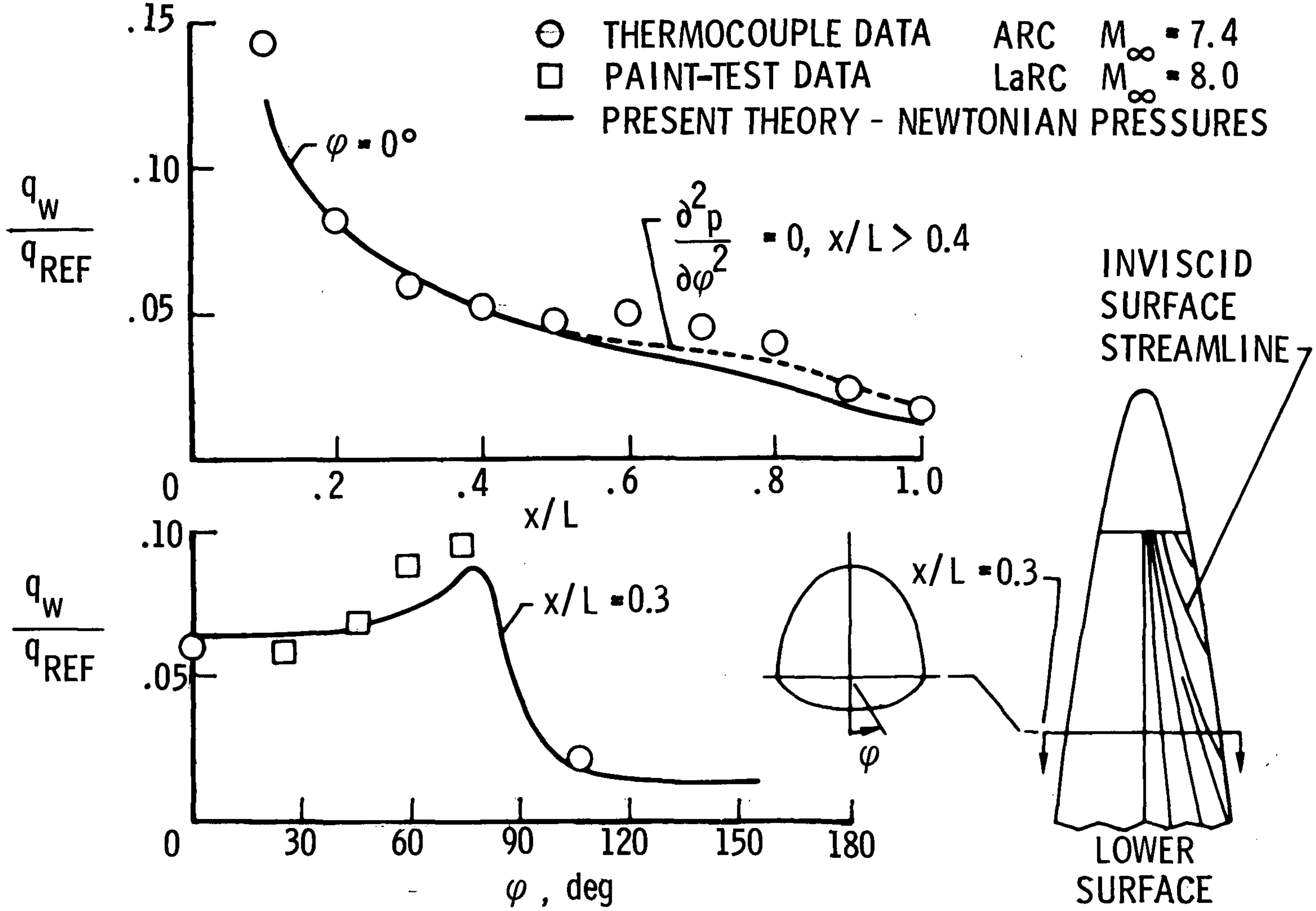


Figure 5

SUMMARY REMARKS
(Figure 6)

A simple method has been developed for computing the three-dimensional heating on shuttle-type configurations. The method is very fast; for example, typical results presented in this paper for a single streamline required only a few seconds of computing time on the CDC 6600 computer. In general, it requires that the surface pressure distribution be obtained independently, although Newtonian theory is a self-contained option in the basic computer program. For cases where the surface pressure distribution can be approximated with reasonable accuracy, the heating rates computed by the present method have been shown to compare favorably with experimental data. As more exact methods become available for computing the surface pressure distribution, these methods can be used to obtain the surface pressure distributions needed in the present theory.

The basic computer program for Phase I (normal-shock entropy) with a cubic-spline geometry routine is available. Further work is in progress to include variable boundary-layer-edge entropy in the program and to improve the mathematical representation of complex geometries.

SUMMARY REMARKS

1. A SIMPLE METHOD HAS BEEN DEVELOPED FOR COMPUTING 3-D HEATING ON SHUTTLE-TYPE CONFIGURATIONS

2. HEAT TRANSFER RATES COMPUTED BY THIS METHOD HAVE BEEN SHOWN TO COMPARE FAVORABLY WITH EXPERIMENTAL DATA

3. THE BASIC COMPUTER PROGRAM FOR PHASE I (NORMAL-SHOCK ENTROPY) WITH A CUBIC-SPLINE GEOMETRY ROUTINE IS AVAILABLE

4. WORK IS IN PROGRESS TO:

   A. INCLUDE VARIABLE BOUNDARY-LAYER-EDGE ENTROPY IN THE PROGRAM

   B. IMPROVE THE MATHEMATICAL REPRESENTATION OF COMPLEX GEOMETRIES

Figure 6

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