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13. ABSTRACT *(Maximum 200 words)*

Two separate areas of investigation are explored of two-dimensional flow fields computed from the Burnett and Navier-Stokes equations: (1) evaluation of various forms of Burnett equations from computations of 1-D hypersonic shock structure and 2-D flow over a flat plate at zero incidence; and (2) investigation of the interaction at high altitudes of a hypersonic oblique shock impinging on a cowl lip.

Among five different formulations of Burnett equations, two were found to exibit in shock structure a small region of flow wherein the heat flux is physically unreal. Preliminary computations with the three other formulations are made for flow over a flat plate.

It is found that the well-known severe overheating, due to oblique shock impingment on a leading edge, decreases significantly as altitude increases, disappearing at Knudsen numbers above about 0.1.

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INVESTIGATION OF BURNETT EQUATIONS FOR TWO-DIMENSIONAL HYPERSONIC FLOW

AFOSR Contract 92J0012

Report on Research to November 1, 1993

The subject research comprises two separate areas of investigation. Each has a common objective of exploring physical results from numerical computations of two-dimensional flow fields using the Burnett equations and, by way of comparison, also the Navier-Stokes equations. Unlike the latter set of motion equations, which have remained the same for a century and a half since the time of Stokes, there have been a number of different forms of Burnett equations advanced subsequent to the original form derived by D. Burnett in 1935. One essential portion of our research program, therefore, has included an evaluation of each of these differing forms.

Results through October 31, 1993 from the two separate areas of investigation are outlined in the pages which follow. The presentation is of 'executive-summary' type inasmuch as detailed technical accounts of each area up to July 1993, have been published in the following AIAA papers:

(I) Welder, W. T., Chapman, D. R., and MacCormack, R. W. "Evaluation of Various Forms of the Burnett Equations," *AIAA paper 93-3094*, 24th Fluid Dynamics Conference, July 6–9, 1993, Orlando, FL.

(II) Comeaux, K. A., Chapman, D. R., and MacCormack, R. W. "Viscous Hypersonic Shock-Shock Interaction on a Blunt Body at High Altitude," *AIAA paper 93-2722*, 28th Thermophysics Conference, July 6–9, 1993, Orlando, FL.

It is noted that many of the results of publication (I) were also presented at the May 17–19, 1993 Hypersonics Symposium held at Wright-Patterson Air Force Base, Ohio.

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Evaluation of Various Forms of Burnett Equations

The different formulations of Burnett-order equations for gas motion that we have investigated are:

(i) "Augmented Conventional Burnett" equations, which utilize an Euler based approximation for the material derivative D/Dt appearing in viscous shear stress and heat flux, and add several select higher order terms necessary for stability at high Knudsen numbers.

(ii) "Original Burnett" equations, which make no approximation for D/Dt.

(iii) "Woods" formulation of Burnett equations, which contain different physical terms than either (i) or (ii), and make no approximation for D/Dt.

(iv) "Burnett: Modified Navier-Stokes Approximation for D/Dt," which is less approximate than (i) but more approximate than (ii).

(v) "Woods: Modified Navier-Stokes Approximation for D/Dt," which is the same as (iii) except that an approximation is made for D/Dt.

Historically, the original Burnett equations of 1935 contained D/Dt terms explicitly without approximation, but no flow field computations using these equations were attempted until the present research. In 1939 Chapman and Cowling introduced an Euler-based approximation for D/Dt, which is a valid mathematical approximation consistent with Burnett order terms. This yields the conventional Burnett equations generally used until recently when it was discovered that these equations, unfortunately, are unstable at high Knudsen numbers. Hence the augmented formulation (i) of X. Zhong, one of our previous Ph.D. students, was constructed to provide necessary stability.

Our comparative evaluation of all these different forms has been carried out first for the one-dimensional-flow within shock structures. The most surprising result obtained is that explicit retention of the D/Dt terms, as in formulations (ii) and (iii), leads to an incompatibility with the second law of thermodynamics. Specifically, a region of flow in the upstream portion of a hypersonic shock wave exists wherein the heat flux dq/dx and temperature gradient dT/dx are of the *same* algebraic sign. This same sign corresponds to heat energy going from cold to hot regions. This physically unacceptable result was not previously discovered, apparently because flow-field computations with Burnett formulations that explicitly retain D/Dt without approximation have not been attempted heretofore. In view of this surprising discovery, our comparison of results from different Burnett equations is limited to formulations (i), (iv), and (v) above, which either do not show this incompatibility, or show it only to a very minor degree. It is most curious that the somewhat arbitrary process of making an approximation to D/Dt greatly reduces, or essentially eliminates, a conflict with the second law of thermodynamics. Why this happens is not as yet understood.

Comparative results for shock structure computed from equation (i) set, the augmented conventional Burnett equations, equation (iv) set, the Burnett equations with modified Navier-Stokes approximation for D/Dt, and equation (v) set, the Woods equations with modified Navier-Stokes approximation for D/Dt, have been presented in ppaer (I) cited above. The main results found are that shock-wave density profiles computed from (v) agree very closely with experiment (Figure 1), while from (iv) and (i) the agreement is not quite as good, the computed thicknesses being about ten percent thinner than experimental values (Figure 2). On the other hand, the temperature-density separation distance between these profiles computed from (v) does not agree quite as well with Direct Simulation Monte Carlo (DSMC) computations as does the temperature-density separation distance computed from (i) (Figure 3). The DSMC results are regarded essentially as accurate as good experimental data would be if such data were available for shock temperature profiles. In all cases, the various Burnett formulations yield results in much better agreement with experiment/DSMC than the simpler Navier-Stokes equations.

The results outlined above, with exception of those pertaining to the temperature—density separation in shock structure, were presented in paper (I) of the July 1993 AIAA conference publication. During the period from July through October 1993, attention was shifted from shock structure to the two-dimensional hypersonic flow over a flat plate at zero angle of incidence. Most of the effort during this four month period focused on coding and debuging the 2-D Burnett equations corresponding to the three different formulations (i), (iv), and (v) that did not exhibit serious incompatibility with the second law. By October 31, the coding/debugging was largely complete and a few computational results were obtained.

Results obtained from two cases of our initial 2-D computations of the hypersonic flow over a flat plate are shown in Figures 4 and 5 for argon gas, and in Figures 6 and 7 for nitrogen. The case of argon gas was computed with the augmented conventional Burnett equations to check on consistency with earlier results by Zhong. Close agreement was obtained between the results from the two different codes. The case of nitrogen is one for which some experimental data and DSMC computations of drag are available for comparison. These comparisons, however, were not completed by October 31, 1993.

It is noted from Figure 4 that the thermodynamic pressure (ρRT) computed from the Burnett equations can be considerably different from the normal stress at the surface of the plate. It is the latter, of course, that should correspond to a physical measurement of pressure from a surface orifice.

Oblique Shock-on Cowl Lip Interaction at High Altitude

The primary conclusion obtained from research in this area prior to July 1993, is that the well-known overheating created by a shock on shock interaction becomes progressively smaller as altitude is increased. At low altitude where shock thickness is negligible relative to cowl lip radius, the overheating due to shock-shock interaction, as is well known, can amount to more than an order of magnitude; but at high altitudes (Knudsen numbers greater than about 0.1) where shock thickness is sizeable relative to cowl lip radius, we have found that the overheating due to shock-shock interaction vanishes. This was not anticipated. At such altitudes the only overheating is due to the physical positioning of a cowl lip downstream of a hypersonic oblique (bow/ramp) shock across which the density increase outweighs the velocity decrease, thereby producing an overheat ratio of about a factor of two. This conclusion was based on Navier-Stokes computations for a perfect gas, and was described in paper (II) of the July 1993 AIAA conference publication cited above.

During the period from July through October 1993, the following improvements/refinements were made to the computational code:

a) An adaptive grid procedure was incorporated to make the most effective use of a given number of grid points by automatically concentrating them in zones of the flow field wherein gradients are greatest.

b) A new computational algorithm—embodying a TVD scheme—was incorporated to improve resolution in certain critical portions of the flow field.

c) The number of grid points was quadrupled from a 160×80 mesh to 320×160.

d) The effects of thermodynamic nonequilibrium were added to the code to account for the physical effects of rotational and vibrational energy relaxation.

Prior to October 31, 1993 some results were obtained with improvements (a), (b), and (c) incorporated in the code. These refinements were found to affect the computational results on overheating ratio at low altitudes, but not at high altitudes. This was expected, since many very complex and small-scale details in the flow produced by shock-shock interaction are present at low—but not at high—altitudes; and these fine-structure details need careful resolution. A plot of the overheating is shown in Figure 8 as a function of Knudsen number, as computed with incorporation of two of the refinements of the code, namely the TVD scheme and the adaptive grid. At the lowest altitude ($Kn = .0018$) the overheating ratio of 14 is somewhat higher than the value of about 13 reported in July 1993 AIAA paper; but when the increased grid of 320×160 was used the value for overheating ratio increased to 17 (not shown on Figure 8). Thus grid refinement appears to be required for adequately resolving the fine-structure flow details near the cowl lip leading edge.

An illustration of these details is shown in Figure 9 which is a zoom-type display of the adapted grid, and the Mach and temperature contours in this critical region where overheating is maximum. A curious unexpected detail is the small separation bubble that can be seen situated near the 0.0 number in the central portion of the Mach contours display.

This corresponds to a very low heating rate, whereas location of the impinging jet in the lower portion of the Mach and temperature contour displays corresponds to the maximum heating rate.

These results were obtained using the Navier-Stokes equations. At the time of contract expiration date, coding of the Burnett equations had not yet begun for the oblique shock on cowl lip interactions.

Comparison Of Shock Reciprocal Thickness For Argon Using Woods Equations With Modified NS Approximation For D/Dt

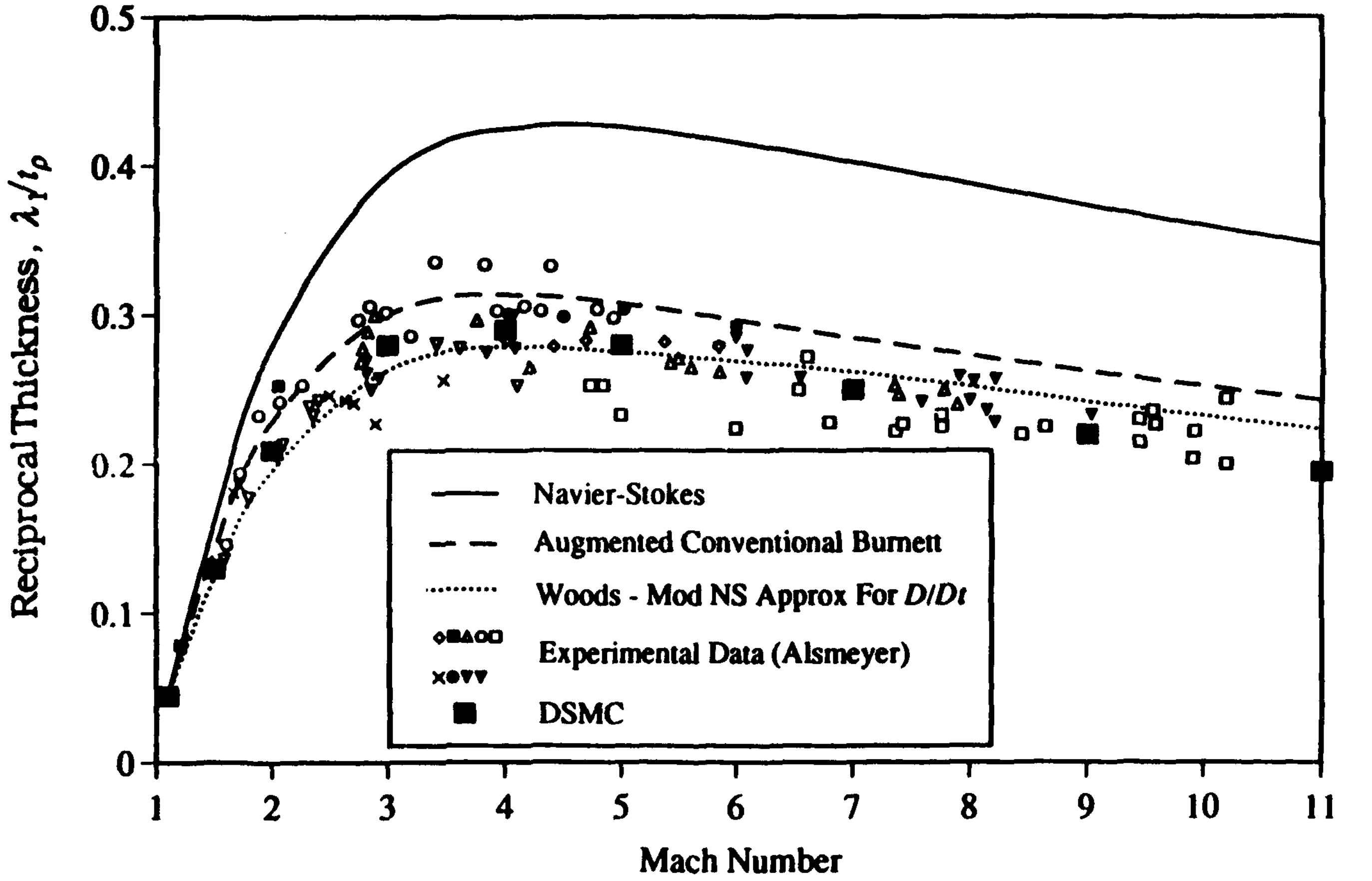


Figure 1.

Comparison Of Shock Reciprocal Thickness For Argon Using Burnett Equations With Modified NS Approximation For D/Dt

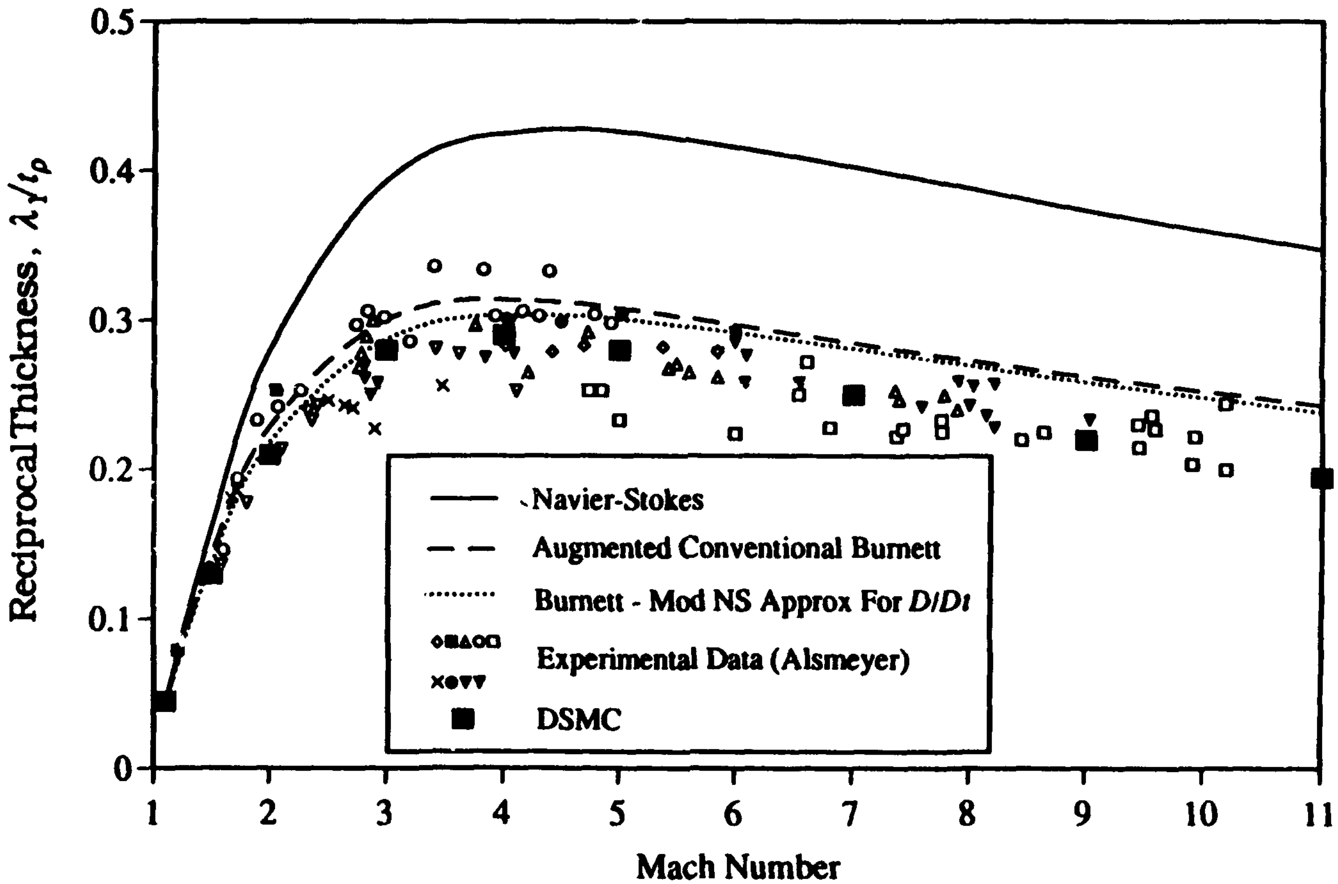


Figure 2.

Comparison Of Shock Temperature Separation For Argon Using Woods Equations With Modified NS Approximation For D/Dt

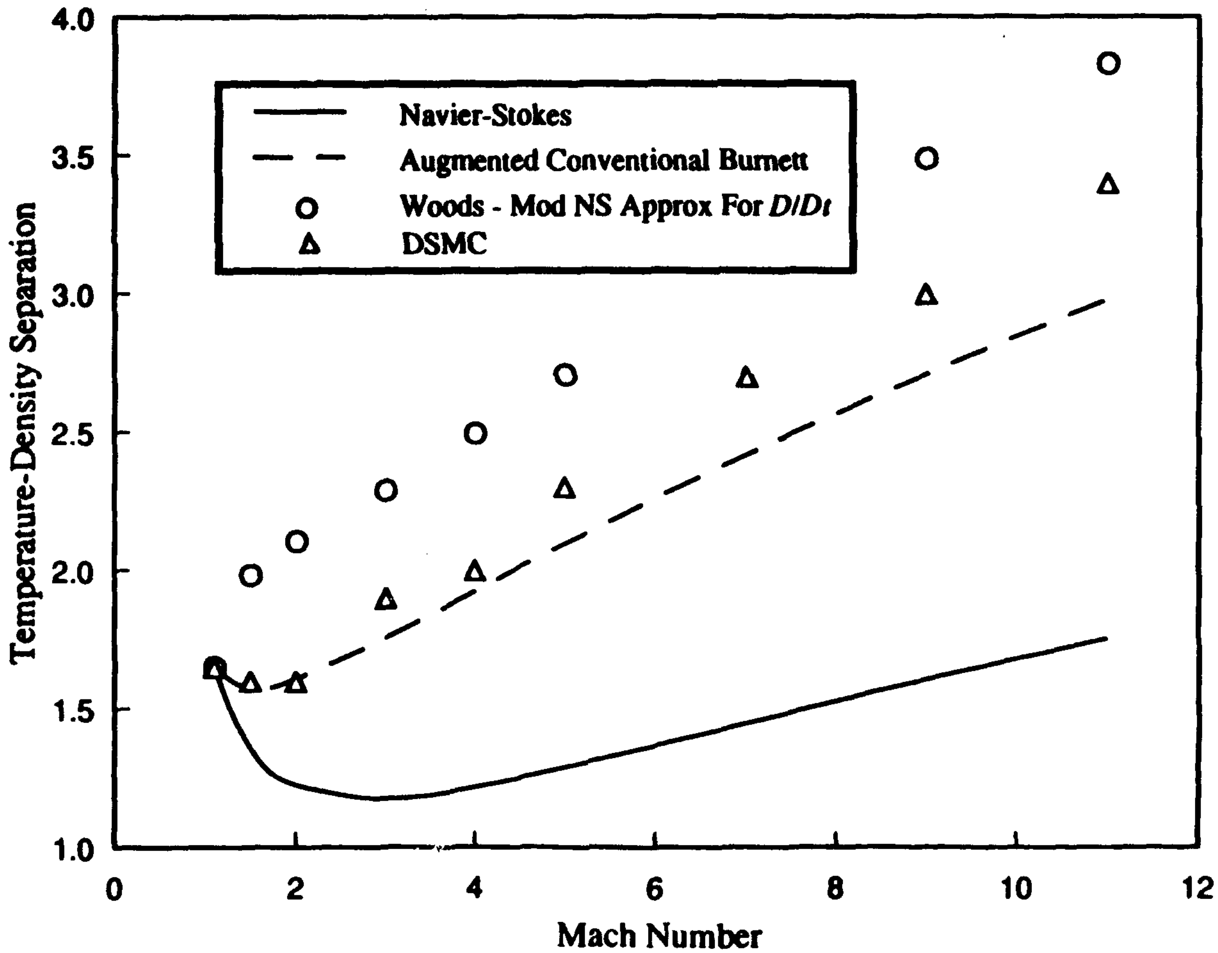
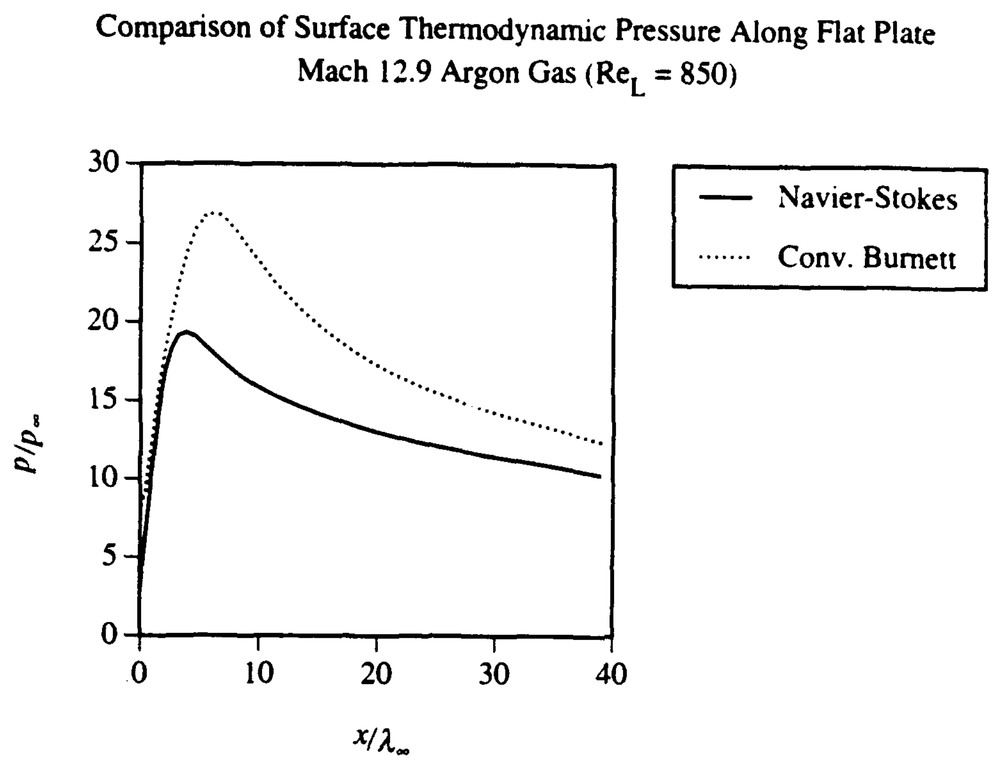


Figure 3.


Comparison of Surface Thermodynamic Pressure Along Flat Plate
Mach 12.9 Argon Gas (Re_L = 850)
30
25
20
15
10
5
0
0
10
20
30
40
p/p_∞
x/λ_∞
Navier-Stokes
Conv. Burnett

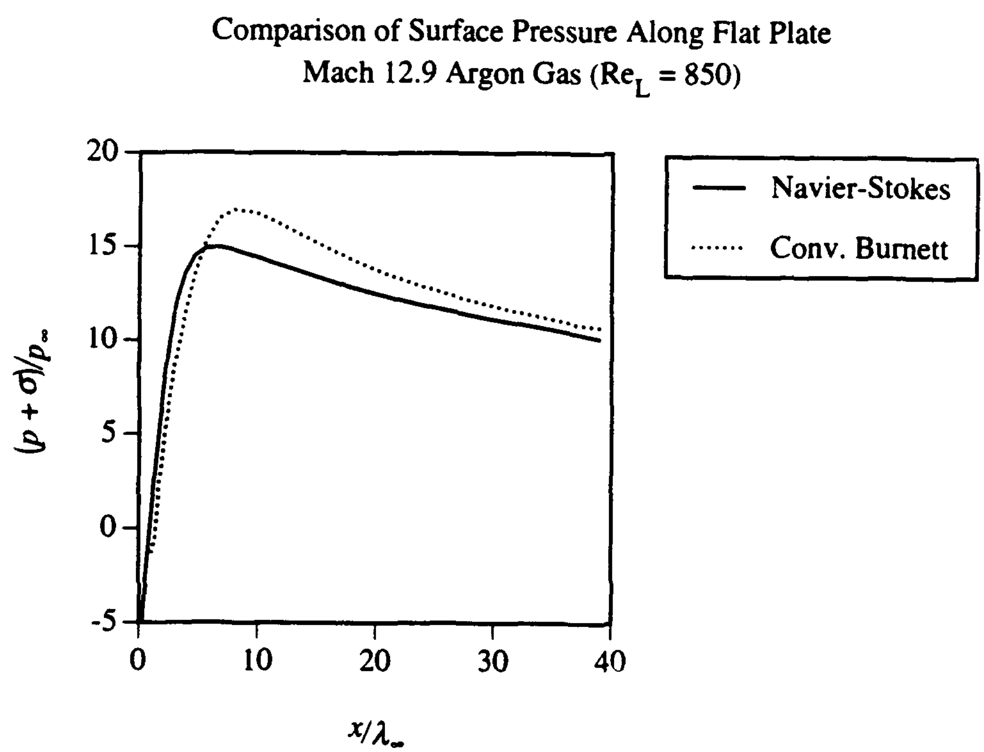
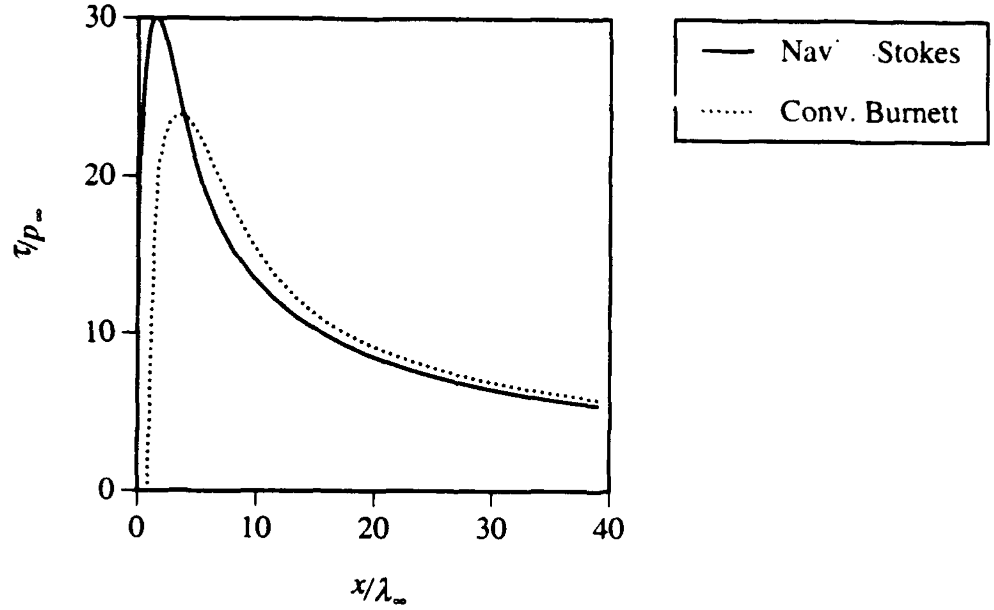

Comparison of Surface Pressure Along Flat Plate
Mach 12.9 Argon Gas (Re_L = 850)
20
15
10
5
0
-5
0
10
20
30
40
$(p+\sigma)/p_\infty$
x/λ_∞
Navier-Stokes
Conv. Burnett

Figure 4.

Comparison of Surface Shear Stress Along Flat Plate
Mach 12.9 Argon Gas (Re_L = 850)



Comparison of Surface Temperature Along Flat Plate
Mach 12.9 Argon Gas (Re_L = 850)

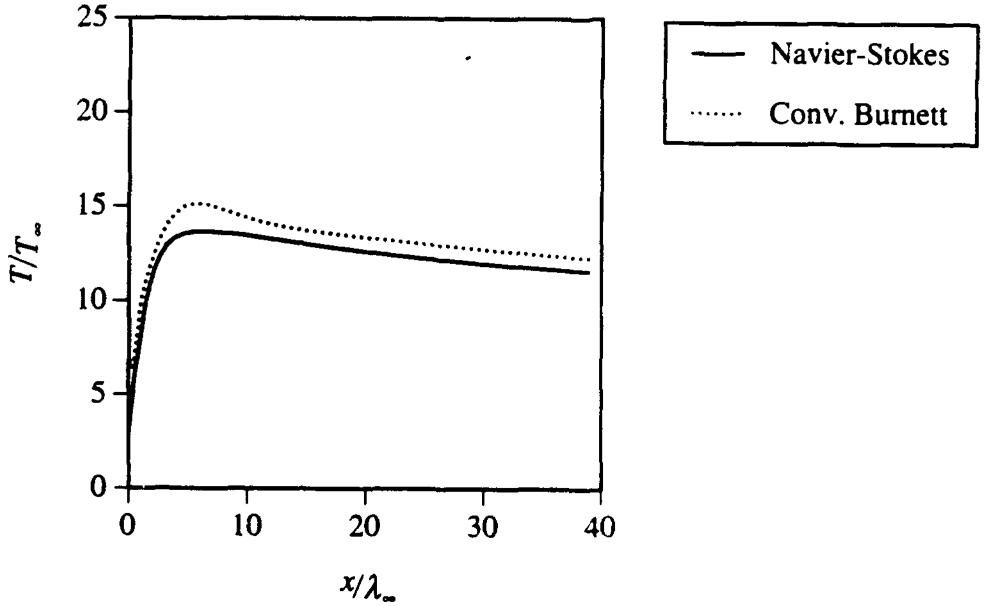
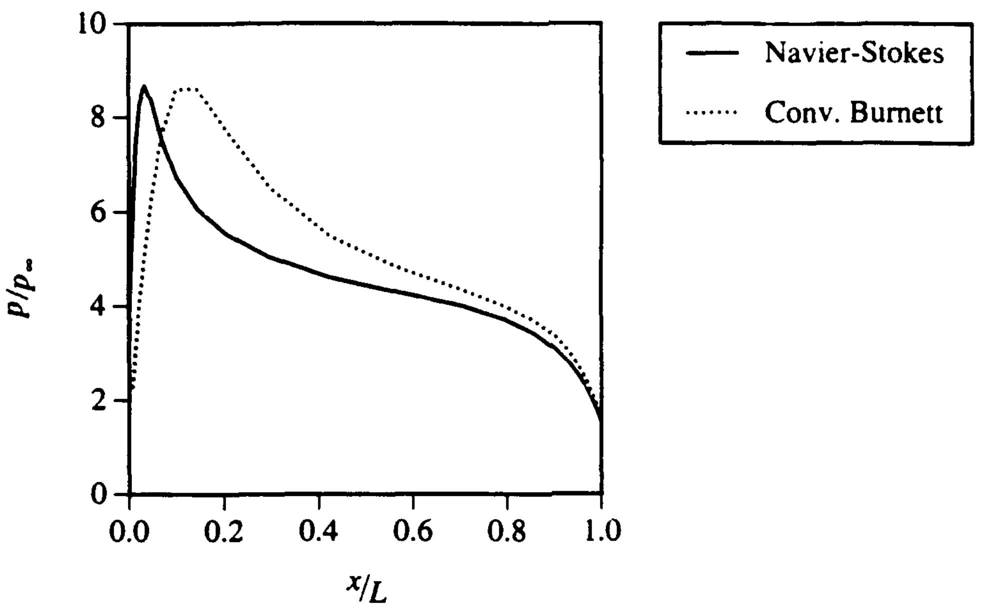


Figure 5.

Comparison of Surface Thermodynamic Pressure Along Flat Plate
Mach 7 Nitrogen Gas (Re_L = 1000)



Comparison of Surface Pressure Along Flat Plate
Mach 7 Nitrogen Gas (Re_L = 1000)

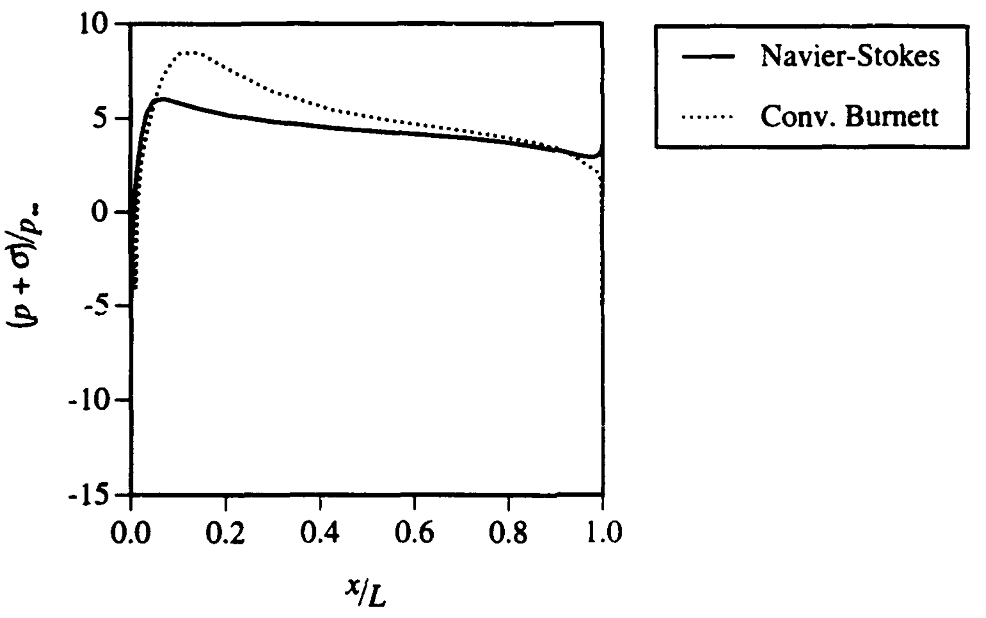
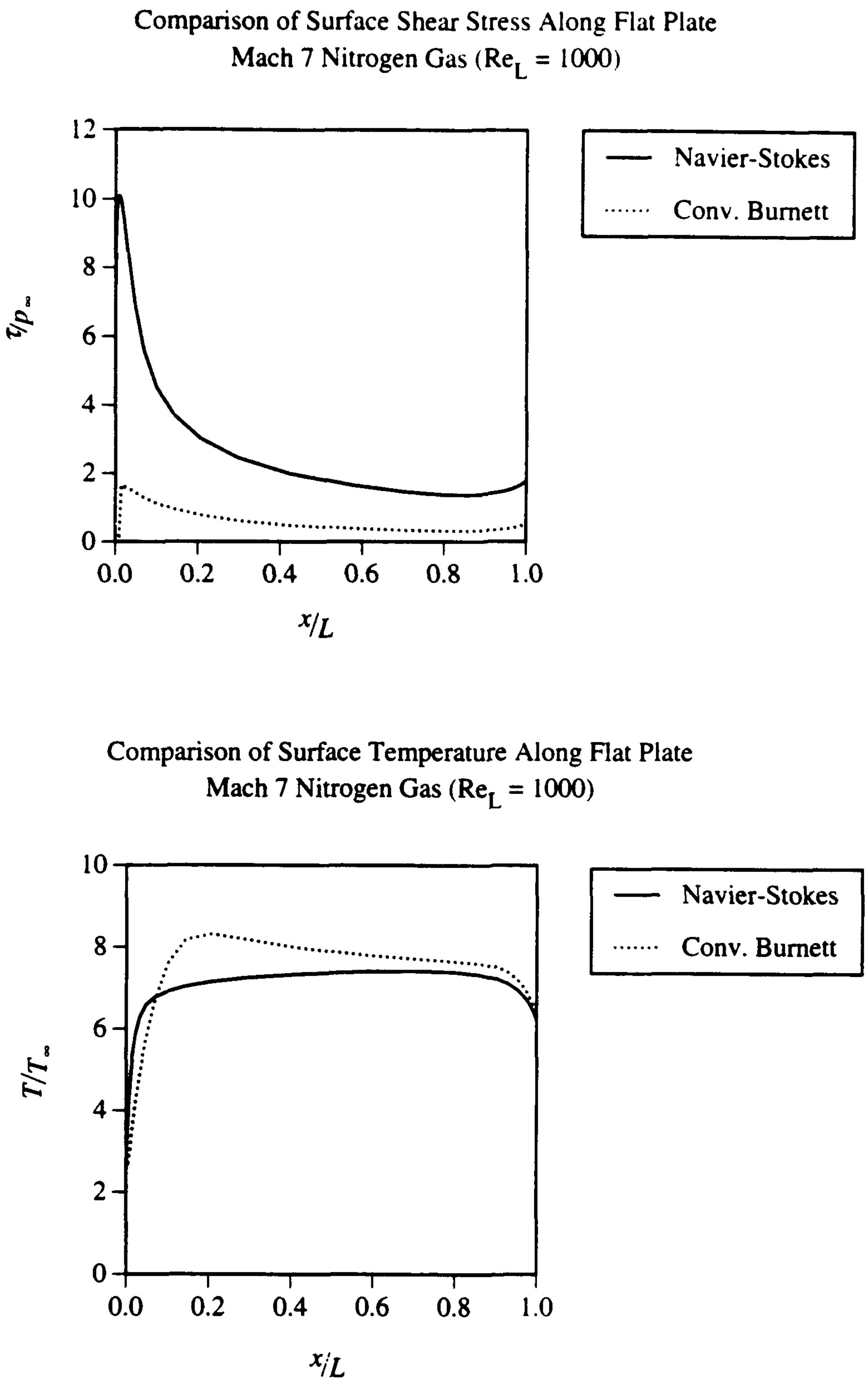


Figure 6.



Comparison of Surface Shear Stress Along Flat Plate
Mach 7 Nitrogen Gas (Re_L = 1000)
Navier-Stokes
Conv. Burnett
τ/p_∞
0
2
4
6
8
10
12
0.0
0.2
0.4
0.6
0.8
1.0
x/L
Comparison of Surface Temperature Along Flat Plate
Mach 7 Nitrogen Gas (Re_L = 1000)
Navier-Stokes
Conv. Burnett
T/T_∞
0
2
4
6
8
10
0.0
0.2
0.4
0.6
0.8
1.0
x/L

Figure 7.

Stagnation Point Heat Flux Ratios For Mach 15 Shock Interactions

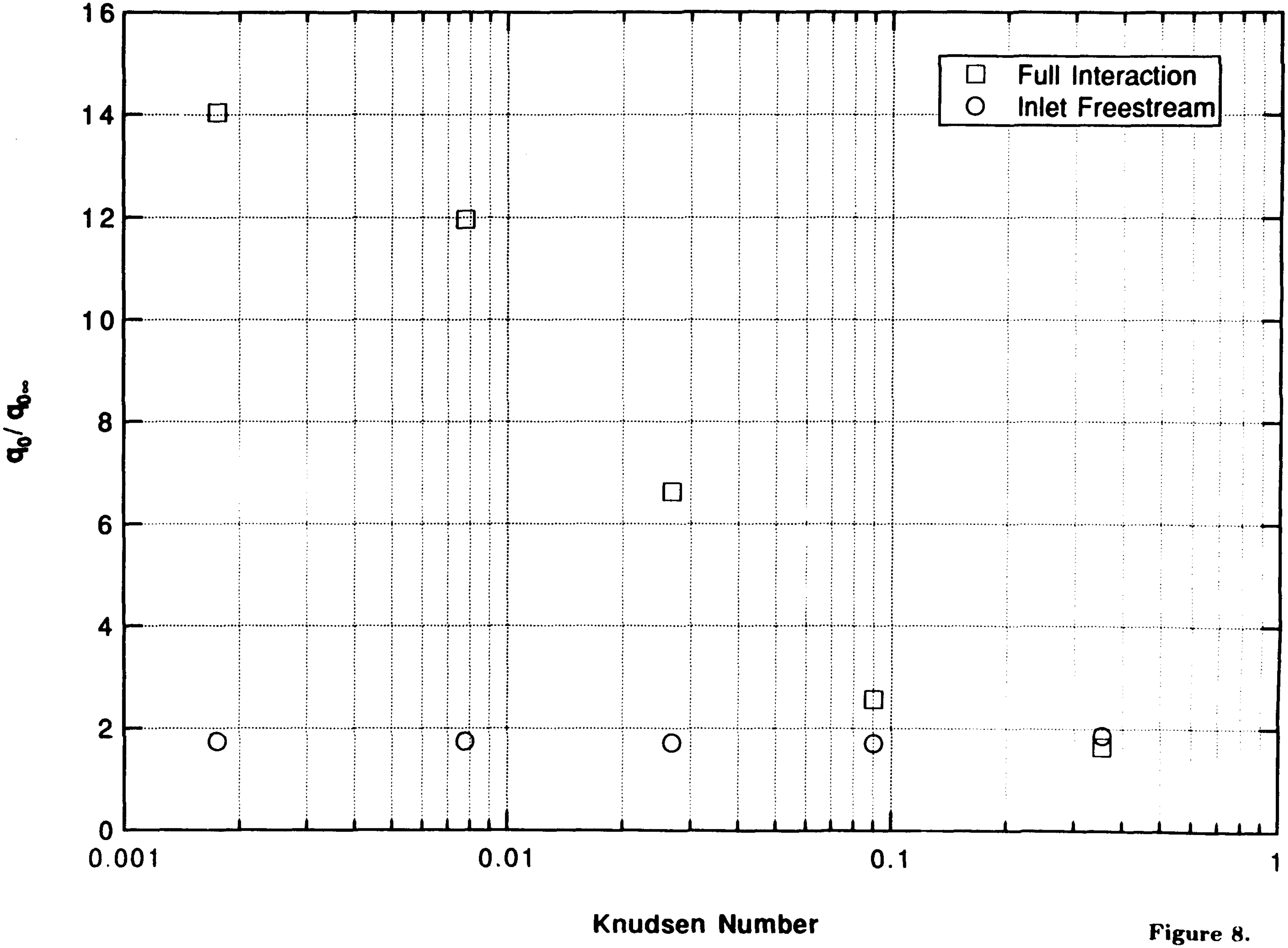


Figure 8.

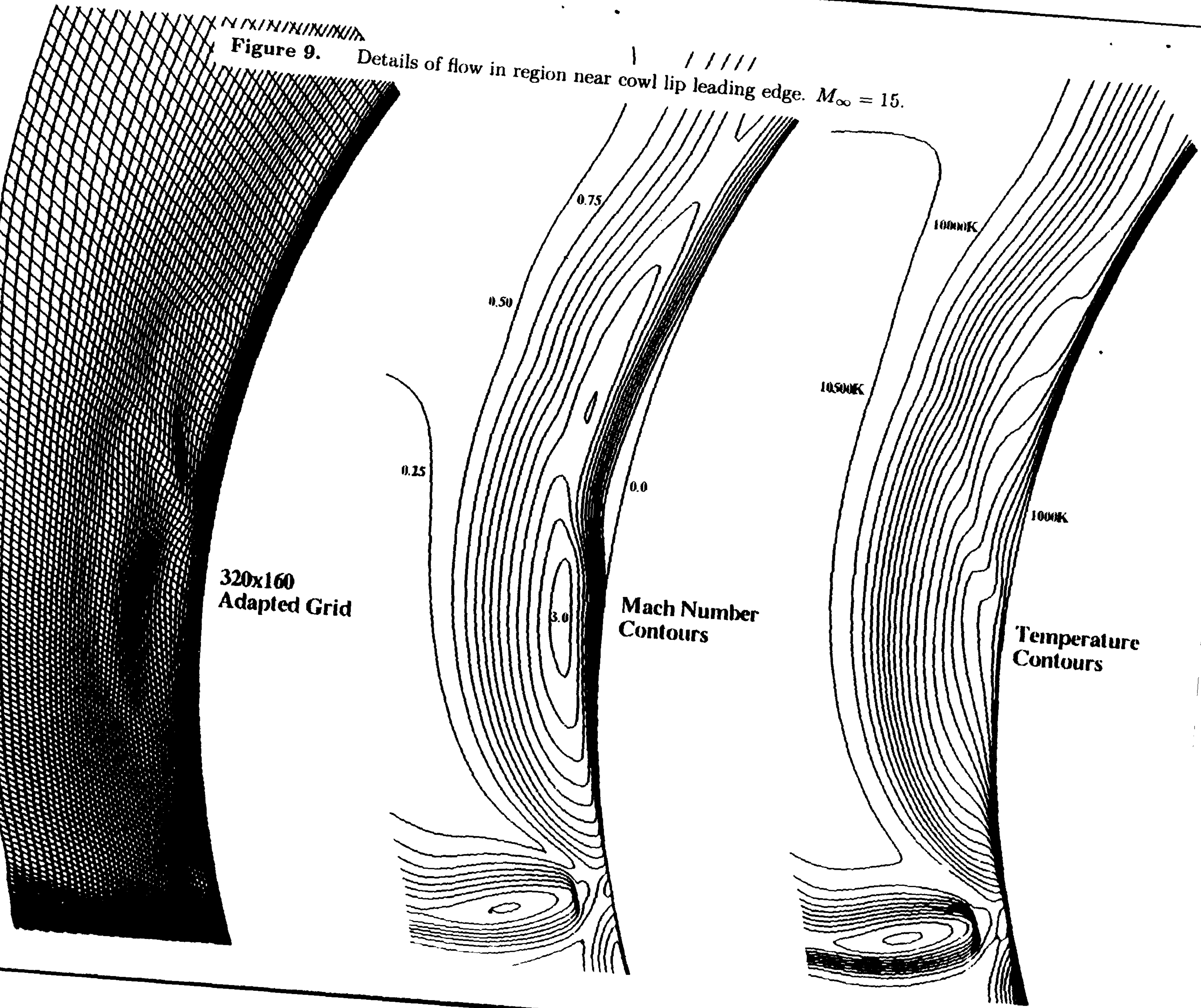


Figure 9. Details of flow in region near cowl lip leading edge. $M_\infty = 15$.