Flowfield and Vehicle Parameter Influence on Results of Engineering Aerothermal Methods

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Flight- and ground-test heat-transfer data, detailed predictions, and engineering solutions have been compared. The impact of several parameters on heat transfer and the capability of three engineering codes to predict these results have been demonstrated. Results have shown that fairly good agreement with data and detailed solutions can be obtained, but good engineering judgment is required in choosing the options in the codes. In particular, comparison of the results of the engineering codes, AEROHEAT, INCHES, and MINIVER, with Reentry F flight data and ground-test heat-transfer data for a range of cone angles, and with the predictions obtained using the detailed VSL3D code, has shown very good agreement in the regions of applicability of the engineering codes. The impact of several flowfield and vehicle parameters, including entropy, pressure gradient, nose bluntness, gas chemistry, and angle of attack on heating levels has been shown to be important. Particular care must be exercised when using engineering codes since comparisons have demonstrated that the parameters of this study can significantly influence the actual heating levels and the prediction capability of a code. The engineering codes provide the user with relatively simple techniques to define the aerothermal environment for parametric or preliminary design studies.

Nomenclature

L = total body length
M_∞ = freestream Mach number
M_e = local Mach number
$\dot{q}_{\text{ref}}$ = reference heating rate
$\dot{q}_w$ = surface heating rate
R_N = body nose radius
Re_θ = momentum thickness Reynolds number
R_∞ = freestream Reynolds number
S = wetted surface distance
T_w = wall temperature
x = body axial length
α = angle of attack
γ = ratio of specific heats
ϕ = circumferential angle
θ_c = cone half-angle

Introduction

ENGINEERING codes have been demonstrated over the last decade to be of practical importance in supporting aerothermal studies of outer planetary and Earth entry missions, e.g., Ref. 1–10. These methods were used not only in parametric studies but also in the design phase of entry vehicles. From the 1960s to mid 1970s, these so-called approximate techniques were the primary source for predicting the aerothermal environment about entry vehicles.

However, with advances in computational capabilities, computer codes that include the solution of the full governing equations for a reacting gas with application to complex geometries are now available. These benchmark codes, like the approximate codes, need to be verified for application to specific vehicle studies. The detailed codes can be verified by comparison with other benchmark code results and with ground- and flight-test data. With the increasing interest in hypersonic applications, particularly the transatmospheric vehicles (TAV), the detailed codes should be instrumental in final design decisions. The focus of a recent investigation was to verify the applicability of a detailed code and also to provide insight to the effects of nose blunting and angle of attack on the transition location and resulting heating levels and drag coefficients. Unfortunately, these detailed or benchmark codes not only have very large computer storage and run time requirements, but also the size and complexity of these codes require a user to devote a large amount of time to understanding and manipulating the code. Based on the status of benchmark codes, engineering codes should also continue to contribute to the mission study process. These approximate methods may need to be modified, if possible, to include important flowfield aspects. Obviously, code reliability is of primary importance, but the flexibility to treat important technical areas is also critical. The effect of pressure and entropy gradients and/or of angle of attack may significantly impact the heat-transfer level.

Therefore, the emphasis of this study is to demonstrate the reliability as well as flexibility of several engineering codes that are used in the aerospace industry. The idiosyncrasy of engineering codes in contrast with detailed codes is that the approximate codes often force the user to choose from several options the method by which the flowfield should be computed. These options, which a user should clearly understand, are exercised in this study in order to demonstrate the relative heating levels that may result from a particular set of selections. First, the applicability of several engineering heat-transfer codes is demonstrated by comparison with benchmark code predictions and also with ground- and flight-test data. Then, the importance of several flowfield and vehicle parameters, such as local entropy values, pressure gradient, body bluntness, and cone angle on the local heat-transfer rates is illustrated, and the capability of the codes to account for these effects is demonstrated. The influence of angle of attack and gas chemistry on the heating levels is also shown.

Analysis

For the purposes of this paper, a description of the detailed and engineering codes used in this study is given. An even more detailed discussion of the codes is presented in Ref. 11.

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Viscous-Shock-Layer Code

The three-dimensional viscous-shock-layer (VSL) method is based on the solution of a subset of the Navier-Stokes equations in which parabolic approximations are made in both the streamwise and crossflow directions. In the VSL method, the entire shock layer is modeled with a single set of equations that are valid throughout the inviscid and viscous regions, which thereby eliminating inherent difficulties encountered in matching boundary layer and inviscid solutions, e.g., accounting for entropy effects. Davis[12] developed the application of the VSL equations for two-dimensional flows over axisymmetric configurations. Murray and Lewis[13] extended the method to three dimensions and applied the code (VSL3D) to spherically blunted conical configurations. The VSL3D code was then modified[14] to include transition, turbulent flow, and chemical equilibrium. A further extension[15] of the code was made to treat chemical nonequilibrium in the shock layer. The version of the VSL3D code which is presented in Ref. 14 with some modifications is used in this paper.

MINIVER Code

The MINIVER program[16] is a simple engineering code that provides the user a menu for selecting methods to compute postshock and local flow properties as well as heating-rate values. The calculations can be based on perfect gas or equilibrium air chemistry. Angle-of-attack (AOA) effects are simulated either through use of an equivalent tangent-cone or an approximate crossflow option. The flow can be computed for two- or three-dimensional surfaces. However, the three-dimensional effects are available only through use of the Mangler transformation (laminar or turbulent) for flat plate-to-sharp cone conditions and do not allow the user to study the downstream effects of nose blunting.

AEROHEAT Code

Another approximate technique, developed by DeJarnette,[17] uses the axisymmetric analog concept[18] which has been applied extensively[19,20] to heating-rate calculations over three-dimensional bodies. This method is widely used in the aerospace industry and is referred to as NHEAT or AEROHEAT. For application of the axisymmetric analog concept, the three-dimensional boundary-layer equations are written in the streamline coordinate system, and the crossflow velocity (tangent to the surface and normal to the streamline direction) is assumed to be zero. The resulting equations are identical to the axisymmetric 0-deg AOA forms if the distance along the streamline is considered the surface distance and the metric (a scale factor in the crossflow direction) is equated to the axisymmetric body radius. Several techniques[17,21] have been employed by DeJarnette and associates for computing the inviscid surface streamline paths and the metric coefficients associated with the spreading of streamlines. The basic Maslen[22] method is used to compute the shock shape corresponding to each inviscid surface streamline, and mass balancing is employed to account for local entropy effects on the surface heating. Approximate heating methods are used, and local pressures are either computed analytically or can be input. The required pressure option does not represent one of the strong points in the AEROHEAT code. The user needs to know if the available options adequately model the surface pressures for the configuration under investigation.

INCHES Code

The INCHES code[23] is an approximate inviscid boundary-layer method that was initially developed for engineering calculations of inviscid radiative and convective heating rates for planetary missions. The code uses a modified Maslen technique[24] and computes the axisymmetric 0-deg AOA flowfield over paraboloids, ellipsoids, hyperboloids, and sphere cones. Since the code computes the flowfield over the desired body rather than applying the inverse method suggested by Maslen, a better definition of inviscid properties is obtained. Variable-entropy effects on the heat transfer can be included by using local inviscid properties located a boundary-layer thickness away from the body surface. The study of Ref. 23 included AOA effects (crossflow) in the heating calculations over the windward and leeward symmetry planes of sphere cones through use of DeJarnette and Davis[21] method. However, the inviscid shock shape and flowfield at angle of attack are computed based on an equivalent cone.

Results and Discussion

In this section, results generated using the engineering and VSL codes are first compared with existing flight- and ground-test data. The data consist of laminar and turbulent heating measurements over blunt and slender cones at equilibrium and perfect-gas chemistry conditions. Second, the inluence of flowfield (entropy and gas chemistry) and vehicle (bluntness and angle of attack) parameters on the heating levels is illustrated. The existing capabilities of the engineering codes to accurately predict these effects are demonstrated. For the comparisons with the flight- and ground-test data, the measured wall temperatures are employed in the calculations. The other comparisons are based on a constant wall temperature as noted in the appropriate figures. Since the parameter $\dot{q}_{ref}$ is used in this investigation only to nondimensionalize the local heating, the value is arbitrarily selected for each condition. The focus of this study is to assess the capability of the engineering codes to predict the level and trend of the experimental data and the benchmark predictions. Thus, the absolute value of the heating rate for a particular condition is not pertinent for this study.

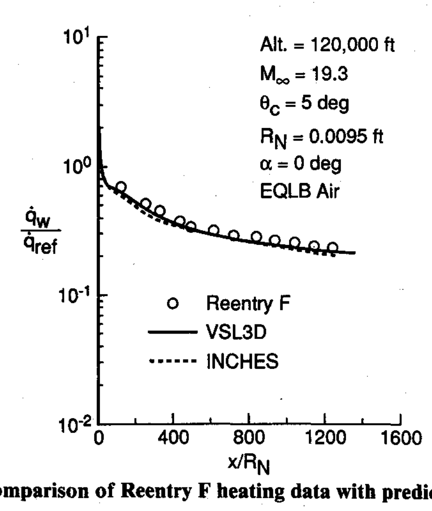

Fig. 1 Comparison of Reentry F heating data with predicted results.

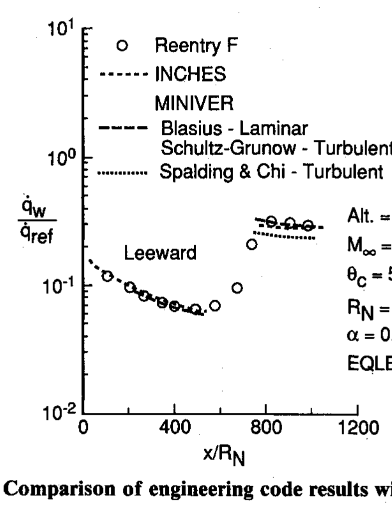

Fig. 2 Comparison of engineering code results with Reentry F heating data.

Flight Data

In Figs. 1–3, the approximate code results are compared with heat-transfer data from a flight experiment and also with results from the detailed VSL3D code. The flight experiment, known as Reentry F, was performed in 1968 to provide accurate measurement of turbulent heating rates on a nearly sharp conical vehicle in regions where freestream Mach number and Reynolds number, total enthalpy, and ratios of wall-to-total temperature could not be obtained by ground-based experiments. The Reentry F vehicle was a 5-deg sphere cone, 13 ft in length, with an initial nose radius of 0.1 in. A graphite nosetip extended for the first 7.69 in. followed by a conical beryllium frustum. Temperature measurements were obtained for the prime data period at altitudes between 120,000 and 60,000 ft at freestream Mach numbers near 20. These temperature data were reduced to heating rates[25] and compared[26] with results of prediction techniques existing at that time.

Figure 1 represents Reentry F data at an altitude of 120,000 ft with a freestream Mach number of 19.3. The flow in this case was laminar over the entire vehicle, and the angle of attack was approximately zero. The comparison between experiment and predictions with the INCHES code shows agreement within 10% in this case. A heating distribution computed using the VSL3D code is in similar agreement with the data and the INCHES results. Equilibrium air chemistry was used in all of the Reentry F calculations. Figures 2 and 3 show the experimental laminar and turbulent data for a Reentry F trajectory point at 80,000 ft, and the data are compared with the engineering and VSL3D code predictions, respectively. The Mach number remained near 20 for this case, but a small angle of attack (0.14 deg) existed. The data and predictions are shown for the most leeward plane (the primary thermocouple ray). The data show that boundary-layer transition occurred about halfway down the vehicle on the leeward side. For the calculations, transition was assumed at the reported location. In Fig. 2, laminar and turbulent heating-rate predictions using the INCHES and MINIVER codes are compared with the data. Both engineering codes assume instantaneous transition for this comparison. As shown, the INCHES prediction is in good agreement (within 10%) with both the laminar and fully turbulent data. The laminar heating method in MINIVER also yields results in good agreement with the data. After transition, the results of both turbulent heating methods used in MINIVER are compared with the data. The results of the heating method that is based on the Schultz-Grunow[27] skin-friction relation are in very good agreement with the data. Conversely, the heating technique that uses the Spalding and Chi[28] skin-friction relation produces turbulent heating rates 15 to 20% lower than the data. Similar results have been noted previously.[29] In Fig. 3, the agreement between the experimental data and the detailed predicted results is excellent.

Ground-Test Data

Figure 4 presents experimental laminar heating rates measured[30] over a blunted 15-deg cone at a 0-deg angle of attack and a freestream Mach number of 10.6. Corresponding predictions based on both the INCHES and the AEROHEAT codes are shown to be in very good agreement with the experimental data. The AEROHEAT code has recently been modified[31] to include a pressure correlation option for slender cones and a new procedure for computing the metric. The AEROHEAT results that are shown in the figure are based on the new pressure correlation. The MINIVER results overpredict the data on the forward portion of the vehicle but approach the level of the data farther downstream. This result is as expected since the MINIVER prediction is based on a simple sharp cone that does not address bluntness and associated variable-entropy effects. Far downstream, where these effects dissipate, good agreement is generally noted.

A comparison of predicted and ground-test laminar and turbulent heating rates is presented in Figs. 5a and 5b, respectively. Zero-deg AOA data were measured[32] over a blunted 7-deg cone at a freestream Mach number of approximately 8.0. Predicted laminar heating rates using the INCHES and AEROHEAT codes are shown to yield comparisons within 10% of the data. The corresponding results for MINIVER show agreement to within 15% of the data. These differences in the comparisons of the MINIVER code results can be attributed mainly to bluntness effects. The comparisons of the turbulent data with the results of the INCHES code are noted in Fig. 5b to be within 10–20% with comparisons generally in the 15–20% range over most of the cone frustum. In addition, the results of an axisymmetric VSL code[33] show a similar type of comparison with the data. The reason for these larger discrepancies is not presently known. The AEROHEAT prediction using the Spalding and Chi skin-friction relation is seen to underpredict the data by approximately 25%. The MINIVER turbulent results are observed to again overpredict the data over the most forward portion of the vehicle but to approach the data farther downstream.

Ground-test turbulent heat-transfer rates measured[34] over a blunted 8-deg cone at a freestream Mach number of 5 and a 0-deg angle of attack are compared with predicted values in Fig. 6. Natural transition occurred on the hemispherical nosecap. A comparison of predicted heating rates based on the VSL3D and INCHES codes with the experimental data is very good for this blunt-body dominated flow region. As might be expected, the MINIVER sharp-cone solution overpredicts the data by 30%. The solution identified as a MINIVER blunt-cone solution employs constant normal-shock entropy and Newtonian pressures coupled with blunt-cone running lengths. However, the flat-plate to sharp-cone Mangler transformation is used. Slightly better agreement than that obtained using

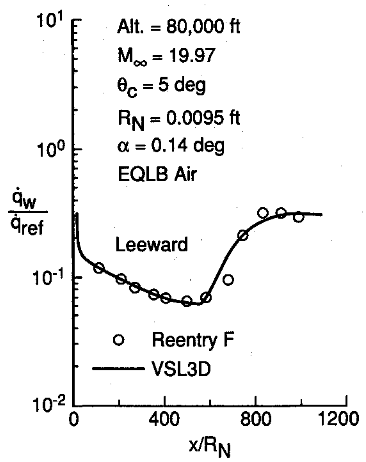

Fig. 3 Comparison of detailed code results with Reentry F heating data.

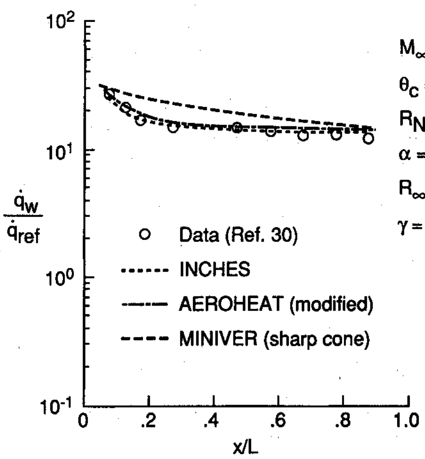

Fig. 4 Comparison of experimental laminar heating rates with predicted results.

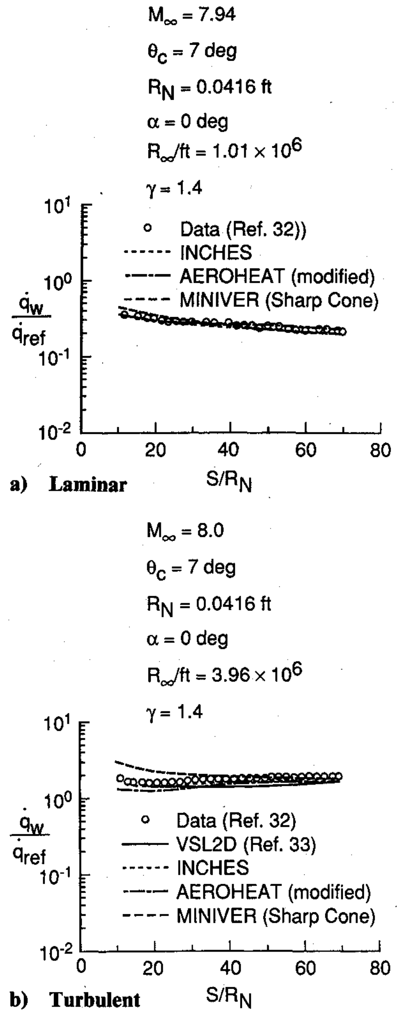

Fig. 5 Comparison of engineering code results with experimental heating data.

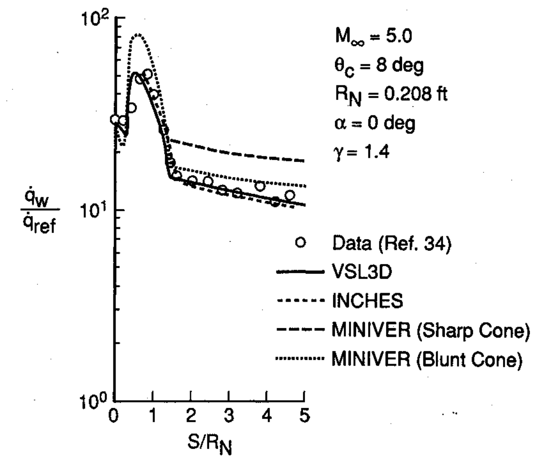

Fig. 6 Comparison of detailed and engineering code results with blunt-body turbulent heating data.

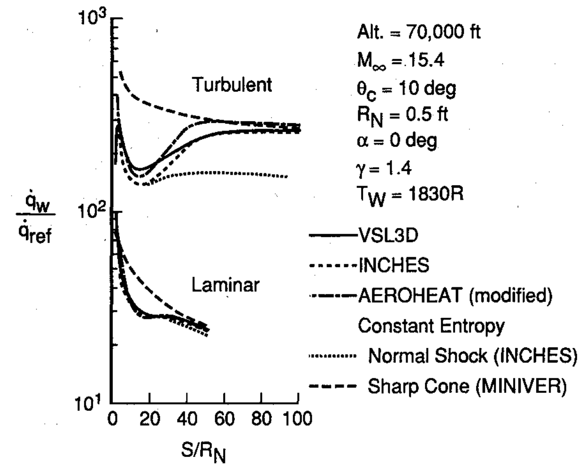

Fig. 7 Effect of entropy on engineering code heating predictions.

sharp-cone properties is noted in this region dominated by bluntness effects.

Effects of Flowfield and Vehicle Parameters

Entropy

A comparison of predicted heating rates over a blunted 10-deg cone at a freestream Mach number of approximately 15 is presented in Fig. 7. The comparison is presented in order to illustrate the effect of local entropy values on the approximate code calculations. The agreement between the VSL3D, AEROHEAT, and the INCHES results is excellent for laminar flow conditions over the body including the region affected by variable entropy and pressure overexpansion/recompression. The computed turbulent results of the VSL3D and INCHES codes are in generally good agreement except near the body location of $S/R_N \approx 15$, where discrepancies of about 20% are noted. The turbulent AEROHEAT results using the skin-friction relation that was developed for the INCHES code is also shown to be in good agreement to an $S/R_N \approx 15$. Downstream of this location, the turbulent heating values are shown to increase rapidly and approach a sharp-cone value. This result may be due to improperly accounting for the entropy variation. Such results are typical of those presented[35] for methods using mass balancing and not including proper edge boundary conditions. Calculated results based on the INCHES and MINIVER codes for normal-shock and sharp-cone entropy conditions, respectively, are compared with the previous results. These constant-entropy calculations illustrate the importance of variable-entropy conditions on the local heating rates. For normal-shock entropy conditions, the calculated laminar heating values from INCHES are 10% lower than VSL3D heating rates in the recompression region. However, the corresponding turbulent results based on normal-shock entropy conditions are 60% of the computed VSL3D rates. The MINIVER results, based on sharp-cone entropy conditions, are shown to yield poor comparison in bluntness dominated regions as would be expected.

Gas Chemistry

Computed results based on the VSL3D code are shown in Fig. 8 for blunted 5- and 15-deg cone angles at 0-deg angle of attack and a 5-deg cone at 10-deg angle of attack. The calculations are for laminar and turbulent conditions at perfect gas and equilibrium chemistry states. Boundary-layer transition was assumed at a ratio of Re_θ/M_e equal to 150. Equilibrium air chemistry has a greater impact on turbulent heating than on corresponding laminar levels for either cone angle. Also, for turbulent heating conditions, equilibrium air is shown to have a greater effect on the 15-deg cone results than the 5-deg cone heating values relative to perfect gas calculations. For the sake of clarity, turbulent heating results computed with the INCHES code are not shown in the figure. However, excellent agreement with both the perfect gas and equilibrium VSL3D values was obtained. Based on the assumed transition criterion, transition was computed at a more forward body location (approximately 10%) for equilibrium-air chemistry. Note that the computed perfect gas laminar heating for a 5-deg cone at 10-deg angle of attack is about 60% greater than the heating rates computed for a 15-deg cone at 0-deg angle of attack.

However, the corresponding turbulent heating rates for these two cases are shown to be nearly the same. In Ref. 36, the reason for computing smaller three-dimensional effects for turbulent flow conditions than for comparable laminar conditions was attributed to the large turbulent shear stresses. In addition, while the results for both the cone at angle of attack and the equivalent cone (15-deg) indicate a forward movement of transition relative to the 5-deg cone at a 0-deg angle of attack, the use of an equivalent cone in transition studies is shown to produce a very conservative estimate.

Bluntness

Laminar heating rates computed over a blunted 5-deg cone at 150,000 ft altitude and a freestream Mach number of 15 are presented in Fig. 9 for two nose radii—0.125 and 0.75 ft. As expected, the effect of increasing nose bluntness is noted to significantly reduce the heating over the surface. The comparison of the VSL3D, INCHES, and AEROHEAT calculated results are very good and illustrate the capability of these engineering codes to account for pressure gradient and variable-entropy conditions on the laminar heating rates. A significant improvement is observed in the present AEROHEAT results using the new pressure correlation[31] compared with the results presented in Ref. 11, where a modified Newtonian pressure distribution was used for the AEROHEAT heating calculations. The computed VSL3D pressure distributions shown in Fig. 9 of Ref. 11 demonstrate that the flow over the larger nose radius body is completely bluntness dominated, whereas the bluntness affects only about the first 20% of the smaller radius body. As a result of these pressure differences, the associated calculated total drag based on laminar flow conditions did not increase for the range of nose radii considered in Ref. 11.

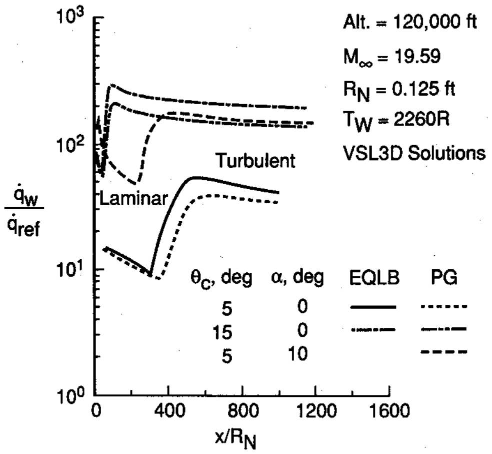

Fig. 8 Effect of gas chemistry on laminar and turbulent heating levels.

Angle of Attack

In Figs. 10 and 11, the effect of angle of attack on engineering code predictions is demonstrated by comparison with ground-test data and predicted results of the detailed VSL3D code. The laminar heat-transfer data presented in Fig. 10 were measured[30] over a blunt 15-deg cone at a freestream Mach number of 10.6. The data are shown for 0-, 5-, and 20-deg angles of attack. At the AOA conditions, the data are presented along the 180-deg meridian (windward ray) for the 5- and 20-deg AOA cases and along the 90-deg meridian for the 20-deg AOA condition. Results of the VSL3D code are shown to be in good agreement with the 20-deg AOA heating data for the 180- and 90-deg rays. The INCHES code results are demonstrated to be in good agreement with both the 5- and 20-deg AOA data. The VSL3D code results are 5–10% higher than the windward symmetry plane heating data at a 20-deg angle of attack, and the INCHES results are approximately the same percentage lower than the data. The results of the AEROHEAT code are, likewise, shown to be in good agreement with the predicted results and data at the 20-deg AOA condition. Also for the same condition, the MINIVER code results, which are based on an approximate crossflow option to account for angle of attack, are generally in good agreement. Note that the data for 0-deg angle of attack and for 20-deg angle of attack along the 90-deg ray are in good agreement. This result was noted in Ref. 23 to have been observed in several experimental studies.

Figure 11 presents comparisons at two angles of attack of predicted heat-transfer results based on engineering and detailed codes. The calculations are based on a blunted 5-deg cone at an altitude of 150,000 ft and a freestream Mach number of 15. The calculations are for 3- and 20-deg AOA conditions and are shown in Figs. 11a and 11b, respectively. For the smaller angle of attack, the VSL3D results are shown to be approximately 40% greater than the engineering code predictions except for the modified AEROHEAT code.[31] Discrepancies greater than 25% are noted for the 20-deg AOA condition but are observed to persist over a smaller region of the body. At surface distances greater than 4 ft, the heating results based on the INCHES code for the 20-deg AOA condition are within 15% of the VSL3D values. This difference is approximately the same discrepancy noted in results of the two methods for comparison with the data in Fig. 10. The inability, in general, of the engineering codes to predict the heating peak at angle of attack and subsequent higher heating levels especially at the lower angle of attack for the slender cone (5 deg) was determined to be due to the procedure for computing the metric. The metric in AEROHEAT and INCHES

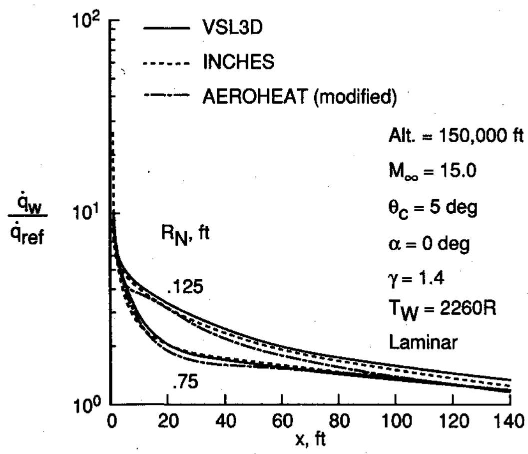

Fig. 9 Effect of nose blunting on heat-transfer predictions.

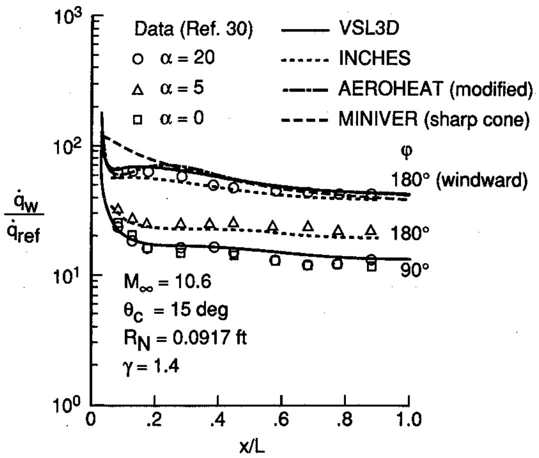

Fig. 10 Effect of angle of attack on experimental data and heating predictions.

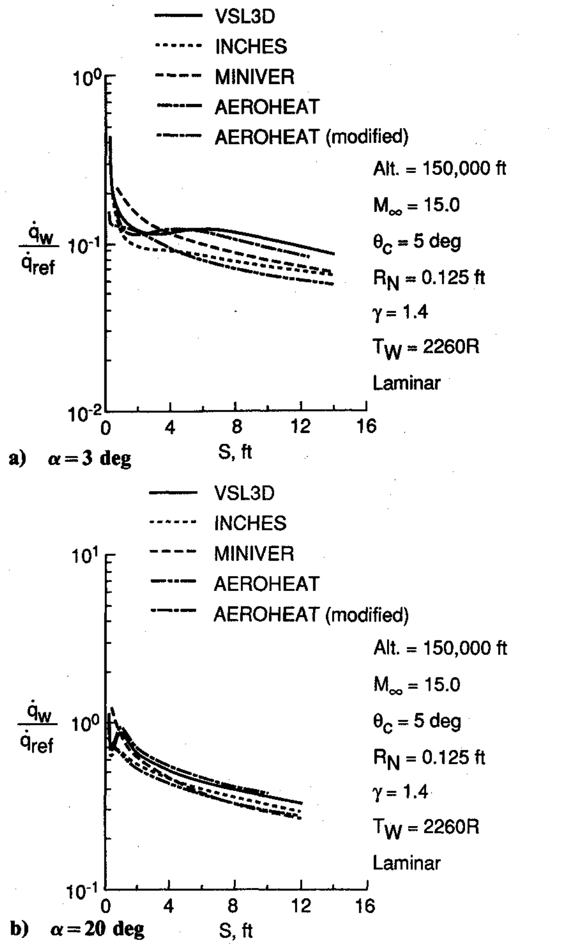

Fig. 11 Comparison of predicted heat transfer at angle of attack.

is computed from the surface geometry. An option has been included in the AEROHEAT code so that the metric can be computed also from the pressure distributions. The resulting modified AEROHEAT heat-transfer calculations are shown for both the 3- and 20-deg AOA conditions, and the improvement in the agreement with the VSL3D results is quite significant. Currently, the flexibility to account for AOA effects in this manner has not been incorporated in the INCHES code.

Concluding Remarks

Flight- and ground-test heat-transfer data, detailed predictions, and engineering solutions have been compared. The impact of several parameters on the heat transfer and the capability of three engineering codes to predict these results have been demonstrated. Results have shown that fairly good agreement with data and detailed solutions can be obtained, but good engineering judgement is required in choosing the options in the codes. In particular, comparison of the results of the engineering codes, AEROHEAT, INCHES, and MINIVER, with Reentry F flight data and ground-test heat-transfer data for a range of cone angles and with the predictions obtained using the detailed VSL3D code has shown very good agreement in the regions of applicability of the codes. The MINIVER code employs only a Mangler flat-plate to sharp-cone transformation to account for three-dimensional effects. As a result, the code does not include any procedure to account for variable-entropy effects. A pressure correlation has recently been incorporated in the AEROHEAT code that has significantly enhanced the capability of that code to predict reliable heating rates for axisymmetric bodies. The INCHES code is an axisymmetric method with some engineering angle-of-attack capability whose range of application at angle of attack has been demonstrated to be limited. The influence of several flowfield and vehicle parameters, including entropy, pressure gradient, nose bluntness, gas chemistry, and angle of attack, on heating levels has been illustrated. Particular care must be exercised when engineering codes are used since comparisons have demonstrated that the parameters of this study can significantly influence the actual heating levels and the prediction capability of a code. The engineering codes provide the user with relatively simple techniques to define the aerothermal environment for parametric or preliminary design studies. However, the applicability of the available options to the actual flowfield physics and the accuracy of those options must be understood whenever engineering codes are used.

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