Analysis of STS-2 Experimental Heating Rates and Transition Data

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Experimental laminar and "fully" turbulent windward-ray heating rates obtained from the second Space Shuttle flight are compared with predicted rates based on equilibrium-air approximate and detailed analyses. A comparison of the results of the prediction techniques yields discrepancies of approximately 10%. The experimental laminar heating rates for altitudes greater than 67 km are as much as 35% lower than the results of the approximate code over the first 40% of the Shuttle length. The approximate equilibrium predictions are in good agreement with these laminar data beyond the 40% station and over the entire Shuttle at altitudes lower than 67 km. However, recent results of a detailed viscous-shock-layer nonequilibrium code indicate significant departures, especially at high altitudes, from the equilibrium state. Factors which may affect the comparisons of data and the nonequilibrium predictions are considered. The turbulent heating comparisons are good and boundary-layer transition data are compared with a current boundary-layer transition criterion.

Nomenclature

L	= vehicle length to hinge line
M_∞	= freestream Mach number
M_e	= local Mach number
$\dot{q}_c$	= convective heating rate
$\dot{q}_r$	= surface reradiative heating rate
R_θ	= momentum thickness Reynolds number based on local conditions
U_∞	= freestream velocity
X	= axial measurement of vehicle
X_{TR}	= axial transition location
α	= angle of attack
ρ_∞	= freestream density

Introduction

AERODYNAMIC and aerothermodynamic data measured during re-entry of the Space Shuttle Orbiter provide an invaluable free-flight experimental data base for a winged lifting vehicle at Earth entry conditions. The analyses of these data base and computational techniques are intended to aid in the design of future advanced transportation systems and to provide possible improvements to the present Shuttle. The data, which are recorded by an onboard instrumentation system or telemetered after blackout to ground-track stations, included over 200 temperature measurements. An inverse one-dimensional transient heat-transfer analysis,[1] which models the heat conduction within the thermal protection system (TPS), and the surface radiation, is used to compute the convective rates. On the first flight of the Space Shuttle, the flight recorder malfunctioned and only flight data telemetered after blackout were available. For the second flight of the Space Shuttle, hereafter referred to as STS-2, the flight data are available through the entire re-entry period.

For the present investigation, the experimental laminar and turbulent rates measured along the windward-symmetry plane of STS-2 are compared with approximate[2] and detailed[3] equilibrium-air calculations. Typical results of a nonequilibrium viscous-shock-layer (VSL) method[4,5] are also included. The calculation methods are restricted to the windward-symmetry plane of Shuttle-like bodies at angles of attack from 25 to 45 deg. The experimental and predicted heating rates are compared over a freestream Mach number range from approximately 27.0 to 7.0. In addition, design criteria, which are used for transition to turbulent flow and were determined from ground-test information, are compared to computed values based on experimentally determined free-flight transition locations. Comparisons of STS-2 to STS-1 heating rate and transition data are also included.

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Analysis

In this section, the analyses used in the heat-transfer data reduction procedure and the prediction techniques are discussed briefly. Also the procedures used to determine the freestream parameters (pressure, temperature, and density) and trajectory (velocity, angles of attack, and sideslip) are outlined.

Trajectory

The trajectory reconstruction process[6] utilizes the ground-tracking data and onboard measurements of Orbiter inertial attitude, linear accelerations, and angular rates to determine the inertial position, velocity, and attitude of the vehicle from near-orbital altitude to landing. Onboard measurements of linear accelerations and angular rates are integrated from 183 km to touchdown to obtain a trajectory which is constrained in a weighted least-squares sense to fit ground base tracking data. Ground base tracking data provide measurements of range, azimuth, elevation, and Doppler range rate relative to the tracking station. The result is a statistically best estimate of the vehicle entry trajectory (position, velocity, and attitude) in an inertial reference space. Consideration of the rotation and oblate shape of the Earth allows the trajectory information to be transformed into an Earth/atmosphere referenced system. The product of the trajectory reconstruction process is then a Best Estimated Trajectory (BET) of Orbiter entry.

Freestream Parameters

Definition of the state of the atmosphere through which the Orbiter has flown is accomplished by a process[7] which combines atmospheric modeling with the direct measurement of atmospheric profiles of pressure, temperature, density, and winds. The atmospheric data which result from balloon and sounding rocket launches are measured from the ground to an altitude of approximately 90 km. These soundings, however, are made at only a few locations, the locations may not be along the Orbiter entry ground track, and the time of day of the soundings may not correspond with that of Orbiter entry. Atmospheric data above 90 km are estimated using upper atmospheric models.

The measured and estimated data are then used to define the freestream pressure, density, temperature, and winds along the Orbiter entry corridor. The BET determined by trajectory reconstruction defines the time of day and corresponding latitude, longitude, and altitude of Orbiter entry. Atmospheric modeling defines the time-of-day and latitude variations in atmospheric properties. The atmospheric data are extrapolated to the Orbiter entry corridor in a manner which accounts for the time-of-day and latitude differences between the Orbiter entry and the atmospheric soundings.

Heat-Transfer Data Reduction

The Orbiter development flight instrumentation (DFI) includes thermocouples mounted within the TPS, in thermal contact with the surface coating, at over 200 vehicle surface locations. The measurements provide time histories of TPS surface temperature throughout the entry and are the basis for the determination of convective heating rates. The measured temperature-time histories are smoothed and subjected to an interactive review process to assure that the smoothed data provide an accurate representation of the raw temperature data. An inverse, one-dimensional, transient heat-transfer analysis[1] is used to determine the convective heating rate to the TPS surface.

The importance of using the transient analysis[1] to compute the convective heating rate rather than assuming a radiation equilibrium condition is demonstrated in Fig. 1. At times when the heating level is low, e.g., times less than 330 s, the reradiation term is shown to be 20-90% of the actual convective flux. An opposite trend is noted late in the trajectory when the convective flux is less than the surface reradiative cooling term. For this period of time, the reradiative term is approximately 10% greater than the convective term. In addition to the low heating level condition, the radiative equilibrium assumption is not adequate for conditions when some transient phenomenon such as boundary-layer transition is influencing the vehicle aerothermodynamics. For the results shown in Fig. 1, boundary-layer transition and "fully" turbulent flow occur approximately at 1270 and 1320 s, respectively. Thus a radiative equilibrium calculation for the experimental turbulent heating rate at a time of approximately 1320 s would yield a heating rate 20% lower than the rate computed by the transient analysis.[1] However, it is recognized that for an investigation based on computed and measured temperatures, the 20% heating discrepancies result in only 5% temperature differences.

In a recent analysis[8] of STS-1 heating rates, the experimental data were reduced based on two emissivity data sets.[1] There are discrepancies in the two data sets, especially at high temperatures. For example, at 1110 K, the data sets yield emissivity values of 0.90 and 0.76 and such discrepancies produced proportional differences in the heating rates. There did not appear to be obvious deficiencies of technique in either data set to warrant rejection. However, for the simplicity of presenting the STS-2 results, the experimental heating rates have been reduced using only the higher emissivity data set.

The impact on the computed experimental heating rates due to uncertainties in parameters, such as the thermal properties of the TPS, the surface emittance, temperature measurements, and the thermocouple depth location, has been investigated.[9] For the STS-1 conditions, such uncertainties are reported[1] to contribute a ±10% error in the measured heating rates. This error analysis included a 6% contribution due to emissivity uncertainties and not the large values previously noted.

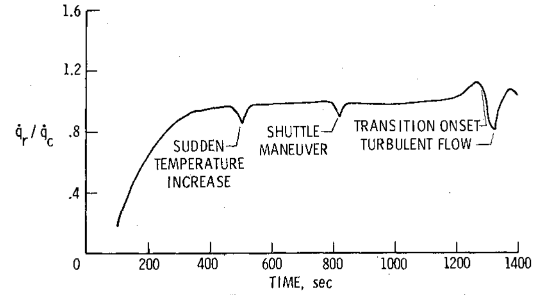

Fig. 1 Comparison of transient heating and radiative equilibrium approximation at $X/L = 0.2$.

Prediction Methods

Detailed

The axisymmetric viscous-shock-layer (VLS) analyses of Moss include a detailed description of the equilibrium[3] and nonequilibrium[4] chemistry and transport properties. The equilibrium analysis provides for ablation injection at the surface, and the flow may be either laminar or turbulent. Currently the nonequilibrium analysis is based only on laminar flow conditions. The set of VSL equations is obtained from the steady-state Navier-Stokes equations by retaining terms up to second order in the inverse square root of the Reynolds number. The set of governing equations is then solved as a parabolic set of equations using an implicit finite-difference numerical procedure. The nonequilibrium code has been modified[5] recently to include finite-rate wall reactions.[10]

Approximate

The approximate heating method[11] uses a rapid inviscid flowfield procedure,[12] laminar and turbulent heating equations which can be computed for constant- or variable-entropy edge conditions, and equilibrium-air correlations.[13] Variable-entropy edge conditions are computed at any point along the body by moving out into the inviscid flowfield a distance equal to the boundary-layer thickness which is computed also by correlation techniques. Laminar and turbulent heating calculations based on the approximate method have been demonstrated[11] to be in good agreement (within approximately 15%) with corresponding VSL results[3] at Earth, Venusian, and outer-planet entry conditions. The approximate results are shown[11] also to agree well with a range of ground-test heat-transfer data. Hence the code has been demonstrated to yield reliable and rapid heating predictions which could be used for parametric or preliminary design studies.

Shuttle Application

The flow environment along the windward ray of the Shuttle is approximated by using the approximate and VSL methods with an equivalent axisymmetric body. The equivalent axisymmetric body is used[2] to model the coordinates of the Shuttle windward-symmetry plane at angles of attack from 25 to 45 deg. For a given angle of attack, a hyperbola with a computed nose radius and body half-angle is used. Resulting heating-rate calculations have been validated for both laminar and turbulent flow conditions by comparison with Shuttle experimental ground-test heat-transfer data and results of existing predictions[14,15] at Shuttle flight design conditions. In a recent analysis,[8] the results of the approximate method have been compared to the STS-1 heating data. These comparisons[2,8] yield discrepancies of approximately 10-15% and validate the concept of using an equivalent axisymmetric body to model the Shuttle windward symmetry plane flowfield.

The possible reason that use of the analytic body in the heating method yields good comparisons with the Shuttle windward-ray heat transfer is that the vehicle has a rather flat bottom surface with a smoothly decreasing slope. Naturally, an analytic body will not provide a good description of a body shape with a discontinuous slope. Such a region is encountered on the Shuttle at the start of the body ramp located approximately at $X/L=0.8$. Computed heating rates using the approximate flowfield calculations and a Prandtl-Meyer expansion starting at $X/L=0.8$ have been shown[2] to be within 15% of the experimental data.

Results and Discussion

In this section of the paper, the experimental heating rates reduced[1] from the thermocouple measurements located along the STS-2 windward-symmetry plane are compared with corresponding results of equilibrium-air approximate and detailed prediction methods. At several of the selected freestream conditions, results of a finite-rate VSL code,[4] recently modified[5] to include finite catalytic wall (FCW) recombination rates,[10] are presented. In addition, a transition criterion computed at experimentally determined free-flight transition locations is compared to similar results for STS-1[8] and ground-test conditions.

Heating Rates

Experimental heating-rate distributions reduced from the STS-2 windward-ray thermocouple measurements, are presented in Figs. 2a-j. These experimental results are reduced using the high emissivity data set and represent laminar, transitional, and turbulent heating data over a range of freestream Mach numbers from approximately 27.0 to 7.0 and of altitudes from 86.0 to 43.0 km. The time noted on the figures represents time from entry interface, when the Orbiter reached an altitude of 121.9 km (400,000 ft). The ±10% error band is not shown on the experimental data presented herein for clarity of illustrating the current results.

At each freestream condition in Fig. 2, the results of the approximate code[2] are compared with the experimental laminar and "fully" turbulent data. Also, at selected conditions, results of an equilibrium[3] and finite-reacting[5] VSL code and a recently developed equilibrium method referred to as a "local swept cylinder" technique[16] are compared with the approximate code results and experimental data.

Laminar

The results of the approximate method are in good agreement (within 10%) with the laminar data beyond $X/L=0.40$ for altitudes above 67 km (Figs. 2a-d) and over the entire Shuttle for altitudes from 67-48 km (Figs. 2e-h). At altitudes lower than 46 km (typical results in Figs. 2i-j) the laminar data at $X/L<0.20$ are approximately 20% greater than the predicted results. Note that STS-1 laminar data at $X/L<0.15$ and obtained at essentially the same STS-2 conditions as shown in Fig. 2j are lower than the STS-2 data and in much better agreement with the predicted results. For the range of conditions shown in Fig. 2, the results of the equilibrium VSL[3] and swept cylinder[16] methods are within 10% of the approximate method. Typical comparisons are shown at selected conditions in Fig. 2.

The researcher is prone to assume that when the equilibrium predictions are in such good agreement with the experimental data, the flow is in an equilibrium state. However, it is recognized first that results of preflight calculations[10] indicate that the Shuttle flowfield is in nonequilibrium. Second, the TPS on the Orbiter windward surface consists of a coated high-temperature reusable surface insulation (HRSI). This coating contains silica which is basically noncatalytic with respect to atomic nitrogen and oxygen recombination. For tests in nonequilibrium flow with the Shuttle TPS, past experience[10,17] has shown that the measured or computed heating rate to the HRSI is lower than that obtained for a highly catalytic or computed equilibrium value. Recent nonequilibrium results[5] for STS-2 also indicate significant departures from the equilibrium state. The equilibrium and nonequilibrium predicted heating rates are essentially equal only at freestream velocities less than approximately 2.96 km/s. However, this limited range of agreement would appear to at least eliminate the influence of gas chemistry as a reason for the poor comparison previously noted in Figs. 2i and 2j. For the range of conditions shown in Fig. 2, the nonequilibrium heating rates[5] using published finite-rate surface recombination rates[10] are lower (as much as 45%) than the equilibrium predictions, but in only fair agreement with the data. Also, as noted, the data are in good agreement with the equilibrium predictions at freestream conditions for which nonequilibrium flow is predicted. Typical comparisons are shown in Fig. 2. Fortunately there are other measurements on STS-2 that support the hypothesis that nonequilibrium flow effects persist to low altitudes and velocities. However, these data constitute the catalytic-tile experiment,[17] which will be analyzed independently by the investigators.

The problem then arises as to why the predicted nonequilibrium rates are not in better agreement with the experimental values. Such factors as the accuracy of the present species rate constants for the flowfield calculations or surface recombination rates, possible flowfield or surface contamination and the TPS emissivity value may contribute to the poor comparisons. For example, the possibility of flowfield or, more likely, surface contamination is raised since two acoustic sensors located at X/L stations of approximately 0.1 and 0.2 melted during entry. The estimated melt time was 480 s. The temperature histories of thermocouples located from X/L of 0.2-0.5 indicate an abrupt rise at approximately this time. As a point of illustration, the temperature trace at an X/L of 0.2 is shown in Fig. 3. Actually postflight inspection of the Orbiter also showed contamination of the TPS, and that contamination was limited primarily to a narrow region along the centerline. Thus, there appears to be the possibility that the surface catalysis of the instrumented tiles was increased (characterized by the temperature jump). A more detailed investigation of these factors, especially the surface recombination rates, and other factors is presented in Refs. 5 and 18. Currently, it is not obvious which, if any, of these factors are affecting the comparisons of the nonequilibrium predictions and experimental data. However, for this paper, the numerous unresolved questions preclude an initial objective which was to obtain an engineering correlation of the nonequilibrium predictions for use in the approximate code. Such a task does not seem appropriate at this time.

For future Shuttle flights and corresponding data analyses, there are several tasks, such as resolving the emissivity question, removing or relocating the acoustic sensors, and extending the catalytic-tile experiment[17] beyond the 40% station, which may impact the questions raised in this investigation. The implication of locating a catalytic tile at a location of about $X/L=0.7$ would demonstrate the extent of catalytic effects along the Shuttle surface.

Turbulent

The Shuttle flowfield, based on recent nonequilibrium calculations,[5] is at an equilibrium state prior to the onset of boundary-layer transition. For the purpose of investigating both the boundary-layer transition movement and associated turbulent heating levels, laminar and "fully" turbulent results predicted by the approximate code were compared with the experimental data at numerous freestream conditions from the time corresponding to the onset of the transition front. While this complete set of results is not presented in the paper, the turbulent comparisons presented in Figs. 2i and 2j are typical. Turbulent data from STS-1 are presented also in Fig. 2j and are shown to be about 10% lower than the STS-2 data. Discrepancies of less than 10% are obtained when the predicted results are compared with data for either flight.

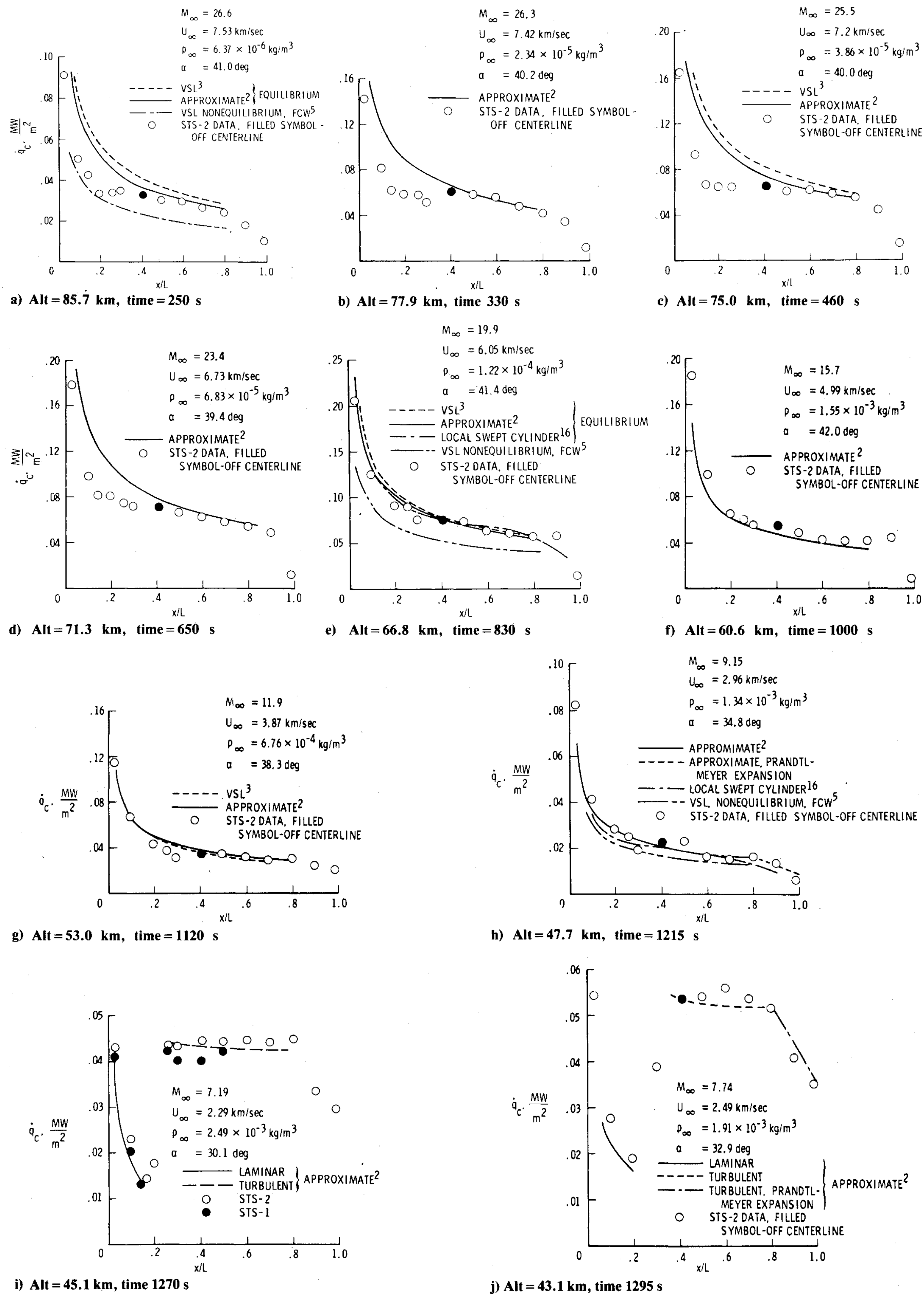

Fig. 2 Comparison of measured and predicted heating rates for STS-2:

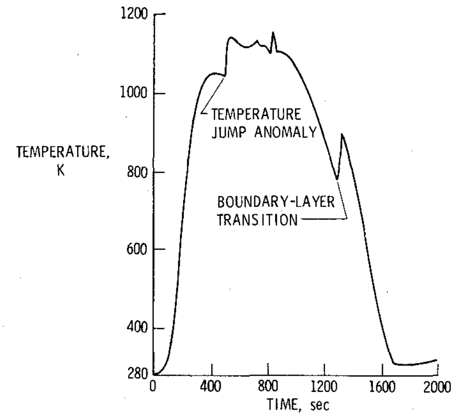

Fig. 3 Temperature-time history at $X/L = 0.2$.

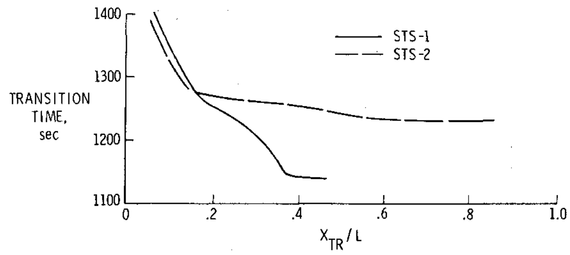

Fig. 4 Boundary-layer transition movement.

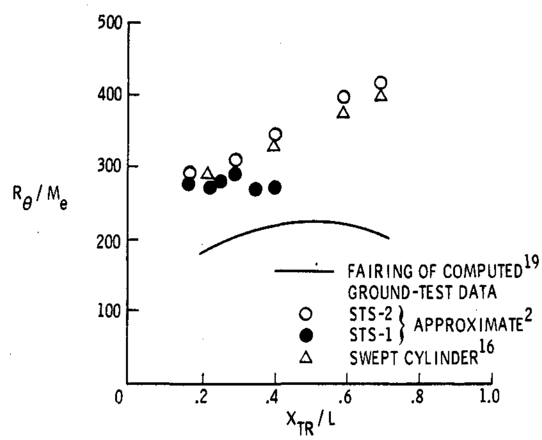

Fig. 5 Comparison of transition criterion at Shuttle flight and ground-test conditions.

Also note that for this set of calculations to investigate the progress of the transition front and turbulent heating, the predicted laminar rates were in good agreement (within 10%) with the STS-2 laminar data along the windward symmetry plane until the boundary-layer transition front progressed forward of $X/L = 0.2$. At these conditions, discrepancies which have been mentioned previously of approximately 20% are obtained (see Figs. 2i and 2 j). The cause of such behavior is not understood currently.

Boundary-Layer Transition

The location of transition to turbulent flow (used herein) can be defined as the region on the vehicle surface where the experimental heating rates show a distinct rise from the laminar trend. Other procedures which can be used to determine transition are to take the sharp upward break in the heating rate or temperature-time histories.

The use of any of these techniques showed transition onset on the STS-2 Orbiter to occur (time = 1225 s) at a freestream Mach number and Reynolds number of 8.9 and 8.3×10^6, respectively. The time for transition onset corresponds to a trajectory time later than determined for STS-1. This result and the fact that a boundary-layer transition front moved rapidly along the STS-2 windward surface are shown in Fig. 4. These results appear to be much different than the trends noted for the STS-1 flight. The reason for the different trends is not known at this time.

A transition criterion (R_θ / M_e) computed at the experimentally determined STS-2 transition locations is shown as a function of the respective normalized axial transition lengths in Fig. 5. The limited STS-1 results[8] are included also. Over the first 30% of the Shuttle, the STS-1 and STS-2 results are in good agreement and a transition criterion value of approximately 290 would be representative. The transition criterion for STS-2 conditions has been computed by both the approximate[2] and local swept-cylinder[16] techniques and the results are in generally good agreement over the Shuttle length. At STS-2 transition-onset, the computed local wetted length Reynolds number, Mach number, and momentum thickness Reynolds number were approximately 5.0×10^6, 2.2, and 900, respectively.

Ground-test transition results computed in the same parametric form by Goodrich[19] are represented also in Fig. 5. The ground-test data yield a peak value in R_θ / M_e of about 225. Note that while the present techniques[2,16] were not used to recompute the ground-test results, flight transition Reynolds numbers tend to be greater than ground-test results on similar bodies.[20-22]

Concluding Remarks

The instrumentation on the Space Shuttle includes thermocouples at over 200 surface locations. The resulting temperature-time histories, which are available for the entire STS-2 entry, have been reduced to heating rates using a transient one-dimensional heat-transfer analysis. An error band of ±10% has been computed for the experimental heating rates due to uncertainties in temperature-dependent thermal properties, the surface emittance, the temperature measurement, and thermocouple depth location.

The STS-2 experimental heating rates represent laminar, transitional, and turbulent free-flight heating data and are presented over a range of freestream Mach numbers and altitudes from approximately 27.0 to 7.0 and 86.0 to 43.0 km, respectively. The windward symmetry-plane laminar and "fully" turbulent data are compared with results of equilibrium-air approximate and detailed codes. These methods, which are restricted to the windward-ray and to angles of attack from 25-45 deg have been demonstrated previously to yield good comparisons (within 10-15%) with ground-test Shuttle heat-transfer data, results of existing techniques at Shuttle design trajectory conditions and the limited STS-1 results.

A comparison of the results predicted by the equilibrium codes yields discrepancies of approximately 10%. The laminar heating rates predicted with the approximate code are in good agreement (within 10%) with the STS-2 data beyond an $X/L = 0.4$ for altitudes above 67 km and generally with all the data at altitudes below 67 km. In spite of this agreement with the equilibrium predicted results, recent results of a nonequilibrium code indicate significant departure from the equilibrium level, especially at high altitudes. In fact, the nonequilibrium and equilibrium rates are approximately equal at only altitudes below 48 km. However, the nonequilibrium results did not yield generally good agreement with the laminar data. Factors such as flowfield or surface contamination may impact the predicted or experimental heating levels.

Turbulent heating occurred on the Shuttle at the lower altitudes when the Shuttle flowfield was in an equilibrium state. Discrepancies of less than 10% are noted for comparisons of results of the approximate code and STS-1 and STS-2 turbulent data.

The onset of transition on STS-2 occurred at a much later trajectory time compared to the STS-1 result. Also, the transition front moves rapidly to the forward region of the vehicle. For each experimentally determined transition location, local flow properties are computed and presented in the form of a boundary-layer transition parameter. This parameter, the local momentum thickness Reynolds number divided by the local Mach number, was used in preliminary Shuttle design studies. The comparison of STS-2 and the limited amount of STS-1 data is good over the first 30% of the vehicle. A value of approximately 290 would be an average representation of the results. Downstream of $X/L = 0.3$, the STS-2 results increase to a value of about 400, which corresponds to the transition onset value. These free-flight results are higher than the ground-test data with a peak value of 225 for the transition parameter.

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