gines, but this would not be excessive with expander-cycle engines and would provide good engine-out capability.

Results with the new stage I are shown in Fig. 4 overlayed on Fig. 2. A significantly increased capability is provided at all payloads. Figure 4 also shows the requirements for the LEO and GEO missions. The payload to GEO is about 5.4 Mg, and the payload to LEO is over 31.7 Mg. Propellant handling problems would be reduced because the storables would be eliminated.

New Stage II as an Orbit Transfer Vehicle

Figure 5 shows the capability of the new stage II alone. This allows consideration of the stage as an orbital transfer vehicle, assuming it has been placed in a low-altitude easterly orbit by another launch vehicle, such as the Advanced Launch System (ALS). The stage has the capability to place about 18.1 Mg of payload in GEO. This would require 70 Mg to be placed in LEO by the launch vehicle, which is in the range being considered by the ALS studies.

Concluding Remarks

Significant improvements to the standard Titan/Centaur capability can be achieved by developing one or two new hydrogen stages requiring engines with a thrust level of about 667 kN or less. The new stage II might also be useful as an orbital transfer vehicle.

Reference

[1]Valesco, T. E., Huang, R. S., and Edwards, R. G., "Characteristics of Launch Vehicles Selected for High Speed Reentry Testing Studies," LTV Aerospace Corp., NASA CR-66248, April 1967.

Hypersonic Nonequilibrium Viscous Solutions over Slender Bodies

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Introduction

THE low-altitude ascent phase of a transatmospheric vehicle[1] should provide conditions that define the major thermal protection requirements of the vehicle. The higher altitude phase and entry conditions are probably characterized by nonequilibrium heating conditions. For these conditions, the designer must determine if an active cooling method is required, in particular, for leading edges, and the resulting weight increase. The leading edges (nose, tail, wings) and adjacent downstream surfaces represent a large surface region for these vehicles, and the additional coolant weight requirements may be important to vehicle performance.

Although the importance of nonequilibrium flow has been known for some time, its benefits to flight applications for a low catalytic surface were first illustrated by the heating rates measured during the initial flights of the Space Shuttle. As a result of the data from those early Shuttle flights, the effect of nonequilibrium chemistry on the Shuttle thermal environment is well documented.[2,3] However, the altitude-velocity range and vehicle attitude and bluntness ranges, for which nonequilibrium chemistry impacts laminar heat transfer over long slender bodies, are not well established by experimental or computational results.

A recent parametric study[4] was conducted to increase the computational data base on the nonequilibrium aerothermal environment for slender vehicles at hypersonic speeds. The study included the variation in altitude-velocity conditions, blunted cone half-angles, and nose bluntness. The effects of vehicle attitude and surface temperature were also considered. The laminar heat transfer calculations were presented as a ratio of the noncatalytic to fully catalytic heating rates to illustrate the maximum potential for a heating reduction in dissociated nonequilibrium flow. A smaller value of the ratio implies a larger potential for a heating reduction in nonequilibrium flow. The heating rate for a finite-catalytic wall would be greater than the value computed for a noncatalytic wall, and, thus, the actual heat reduction would be less than the values presented in Ref. 4. As the flow chemistry tends toward a frozen or equilibrium state, the ratio approaches one, and benefits of a finite-catalytic surface would not be realized.

The purpose of this technical Note is to provide an extension of the Ref. 4 investigation. Smaller nose radii are included for the cone half-angle range; individual nonequilibrium stagnation heating rates are presented at an ascent condition as a function of nose radius and also for an entry trajectory to demonstrate actual heating reductions; and the corresponding equilibrium heating predictions are presented to indicate the degree of conservatism present for such an assumption.

Analysis

For a complete detailed analysis, a Navier-Stokes (NS) method may be desirable, but the NS solution procedures require prohibitive computer run times and storage requirements for a parametric study over long bodies. The viscous shock-layer (VSL) equations, a subset of the NS equations, are obtained by retaining terms up to second-order in the inverse square root of the Reynolds number. The VSL method has been used extensively to study the effect of various physical phenomena (such as coupled radiation and ablation, turbulence, and nonequilibrium chemistry) on flowfield computations. The flow governing equations, boundary conditions, chemical kinetics thermodynamic and transport properties, and solution techniques for the VSL method of this study are presented in detail in Ref. 5.

Results and Discussion

The parametric study[4] included cone half-angles of 6, 10, and 20 deg with corresponding nose radius range of 0.125, 0.5, and 0.75 ft. For this Note, the heating-reduction ratio is presented as a function of wetted distance over a 6 deg cone for a nose radii range from 0.05 to 0.75 ft. The computed ratio is also presented for a 0.25 ft radius to provide a better understanding of the heating trend with nose radius. The calculations were obtained at an altitude of 175,000 ft for a freestream Mach number of 25 and a 2260 R wall temperature. A value of the heat-reduction ratio of less than 50% is obtained at running lengths equal to at least 14 ft for the larger nose

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radii. However, a negligible reduction in the ratio value at distances less than a foot from the stagnation point is noted for the 0.05 ft radius. The trend with increasing nose radius is explained in Ref. 4; the results presented in Fig. 1 are qualitatively representative of the calculations over the cone-angle range. Note that very small nose radii appear to be more characteristic of leading-edge bluntnesses for proposed transatmospheric vehicles.

For an extensive range of nose radii, the stagnation-point heating rates are presented in Fig. 2 for an altitude of 175,000 ft and a freestream Mach number of 25 (typical of an ascent trajectory condition), with a 2260 R wall temperature. The heating calculations are based on equilibrium and nonequilibrium chemistry conditions. An equilibrium prediction is presented to indicate conservatism in this assumption at these conditions and to demonstrate that, for increasing nose radii, the nonequilibrium results do approach an equilibrium level. The nonequilibrium predictions as a function of nose blunting were shown in Ref. 4, in terms of the heating ratio. The curve was shown to decrease to a minimum value (maximum nonequilibrium condition), and then increase. This trend with increasing radius is due to the flowfield changing from a frozen state and approaching an equilibrium state, i.e., the flow distances become large relative to the relaxation distance required for the chemical reactions. Although the ratio was used to demonstrate the potential for a heating reduction in nonequilibrium

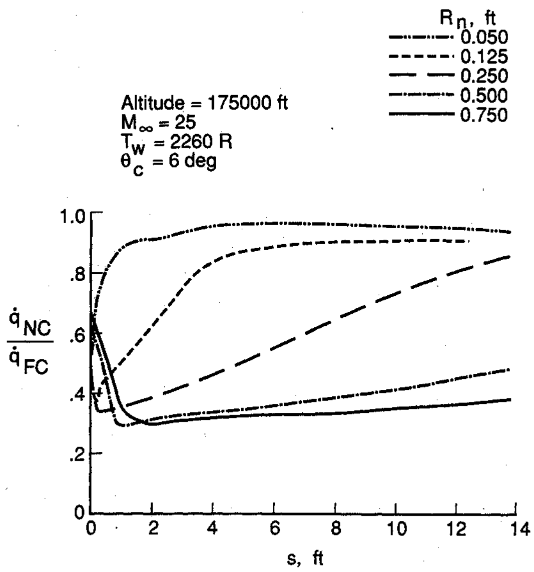

Fig. 1 Nose radius effect on nonequilibrium heating ratio.

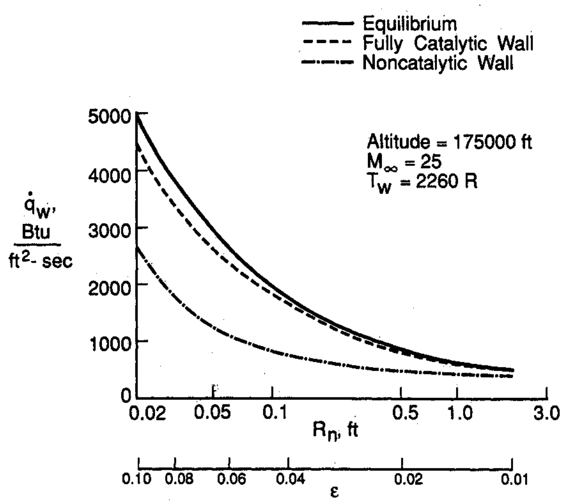

Fig. 2 Nose radius effect on stagnation-point heating rates.

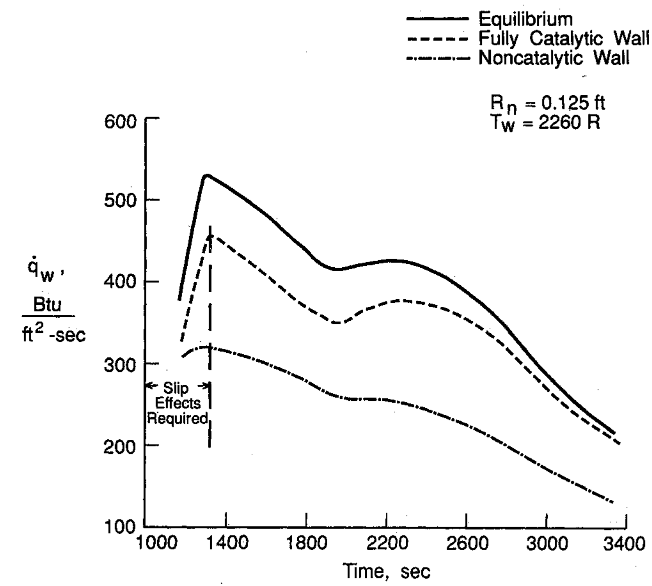

Fig. 3 Stagnation-point heating-rate time histories.

flow, the results shown in Fig. 2 demonstrate that the actual heating reduction cannot be inferred from a relative comparison of the ratios. For example, at nose radii of 0.02 and 0.5 ft, a ratio of 0.6 was shown in Fig. 9 of Ref. 4. However, a comparison of the individual rates in Fig. 2 shows that the heating reduction for the smaller nose radius is, at least, six times larger.

The Ref. 4 study was based completely on a parametric investigation. The influence of nonequilibrium flow on the heating for an assumed entry trajectory has not been a topic of discussion. For an assumed entry trajectory, similar to that presented in Ref. 1, the stagnation-point heating-rate histories are presented in Fig. 3 for both equilibrium and nonequilibrium conditions. The calculations are based on a nose radius of 0.125 ft and a 2260 R wall temperature. Prior to a time of 1300 s (altitudes greater than 260,000 ft) the calculations indicated that a slip-modified analysis is required for these conditions. For a smaller nose radius, slip-modified calculations would thus be required at a latter time (lower altitude). Although a slip analysis is not provided herein, it should be recognized that the nonequilibrium slip heating rates will be lower than the rates shown in Fig. 3. The results of Ref. 5 indicate that slip effects should be included for a Knudsen number greater than 0.1. Since the calculations show that nonequilibrium effects are dominant even at the lower altitudes, the equilibrium results are again provided to indicate an upper limit on the heating values and the conservatism that would be present in such an assumption.

Concluding Remarks

The investigation represented an extension of a numerical study to improve the understanding of nonequilibrium flow effects on the heating over slender bodies. The nose bluntness range of the parametric study was extended to include smaller nose radii, and, as might be expected, the downstream influence of nonequilibrium flow was found to be much smaller than for the larger nose radii. Although a ratio of nonequilibrium noncatalytic to fully catalytic heating rates was used to characterize the maximum potential for a heating reduction over the range of conditions, a comparison of individual stagnation nonequilibrium heating rates demonstrated that a relative comparison of the ratios was not indicative of the actual heating reduction. Finally, the corresponding equilibrium heating rates illustrated the conservatism in such an assumption. This conservatism would probably result in excessive coolant weight requirements.

References

[1]Williams, R. M., "National Aerospace Plane: Technology for America's Future," *Aerospace America*, Vol. 24, No. 11, Nov. 1986, pp. 18–22.

[2]Rakich, J. V., Stewart, D. A., and Lanfranco, M. J., "Results of a Flight Experiment on the Catalytic Efficiency of the Space Shuttle Heat Shield," *Progress in Astronautics and Aeronautics: Entry Vehicle Heating and Thermal Protection Systems; Space Shuttle, Solar Starprobe, Jupiter Galileo Probe*, Vol. 85, edited by P. E. Bauer and H. E. Collicott, AIAA, New York, 1983, pp. 97–123.

[3]Thompson, R. A., "Comparisons of Nonequilibrium Viscous-Shock-Layer Solutions with Shuttle Heating Measurements," *Journal of Thermophysics and Heat Transfer*, Vol. 4, No. 2, 1990, pp. 112–169.

[4]Zoby, E. V., Lee, K. P., Gupta, R. N., Thompson, R. A., and Simmonds, A. L., "Viscous Shock-Layer Solutions with Nonequilibrium Chemistry for Hypersonic Flows Past Slender Bodies," *Journal of Spacecraft and Rockets*, Vol. 26, No. 4, 1989, pp. 221–228.

[5]Lee, K. P., "Viscous Shock Layer Analysis of Hypersonic Flows Over Slender Vehicles," Ph.D. Thesis, Old Dominion Univ., Norfolk, VA, Aug. 1988.

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