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Nonequilibrium Viscous-Layer Computations of Space Shuttle TPS Requirements

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The thermal protection system requirements on the windward pitchplane of a typical shuttle orbiter are evaluated using a recently developed computational procedure. This procedure treats chemically nonequilibrium inviscid and viscous flows for surfaces of arbitrary catalycity. Surface catalycities for typical shuttle materials were evaluated from arc plasma generator data. Computations for the shuttle orbiter demonstrated the significance of entropy swallowing on heat transfer and show that for representative catalycity values, nonequilibrium effects are small though not insignificant. It is shown that the reduced heat transfer rates, caused by surface effects, observed in arc plasma facilities, should be reviewed carefully since these reduced rates will not be as significant for the larger orbiter dimensions.

Nomenclature

H_T = total enthalpy
$k_w(\mathrm{O})$ = surface catalycity for O recombination
$k_w(\mathrm{N})$ = surface catalycity for N recombination
M_e = boundary-layer edge Mach number
M_∞ = freestream or flight Mach number
P = pressure
P_{t_2} = total pressure behind a normal shock wave
q = heat flux
q_{cat} = heat flux to catalytic surface
Re_θ = Reynolds number based on momentum thickness
s = surface or streamwise coordinate
t = time
U_∞ = freestream or vehicle velocity
α = vehicle angle of attack

I. Introduction

THE design of a space shuttle vehicle with a thermal protection system (TPS) which can survive a large number of atmospheric entry flights requires an accurate assessment of thermal, structural, and chemical erosion effects. To aid in making these assessments, a computational procedure was developed to treat homogeneous and heterogeneous kinetically controlled chemistry in laminar or turbulent nonsimilar viscous flows. Because the shuttle TPS system will have more than one kind of exposed surface, a requirement was established that the computational procedure must treat arbitrary distributions of surface materials and boundary-layer edge states. In particular, the shuttle orbiter reusable baseline TPS consists of: 1) Reusable carbon-carbon (RCC) on the wing leading edges and forward nose region where surface temperatures exceed 2760°R; 2) A gray coated silica high-temperature reusable surface insulation (HRSI) over the vehicle where surface temperatures are below 2760°R but above 1660°R. The HRSI is the dominant (by surface area) TPS material on the windward side of the vehicle; 3) White-coated reusable surface insulation (LRSI) on the areas where maximum surface temperatures do not exceed 1660°R. The LRSI is the dominant TPS material on the lee side of the vehicle.

Extensive testing of coated RSI and RCC materials has shown that surface temperatures, at any given heating rate, are lower than would be expected for equilibrium conditions or for catalytic surfaces in nonequilibrium conditions. Calculations indicate that these lower temperatures cannot be rationalized by heat leakage to the sample holder, endothermic chemical reactions, sample heat sink effects, or an exceptionally high surface emittance. The most likely rationale is that the coatings on these materials are not catalytic for dissociated air. Since the shuttle trajectory has a long residence time at high altitudes, nonequilibrium chemistry effects should be properly assessed for an efficient TPS design.

The importance of catalytic wall behavior is understood in the interpretation of arc plasma test results, but has yet to be determined and applied in the design weight of the shuttle TPS. The effect of material catalycity on the shuttle leading-edge temperature and downstream materials can only be assessed by calculating the chemical state of the flowfield and the subsequent heating for the entry trajectory being flown. The discussion to follow will describe the experimental determination of surface catalycity of typical shuttle materials and the application of a computational procedure for predicting finite catalycity heating for typical shuttle entry conditions.

II. Surface Kinetics

With regards to surface kinetics, there are two classes of reactions which are of interest. First, there is the surface catalyzed recombination of dissociated air and second, there is the thermochemical erosion of the surface by the hot

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boundary-layer gases. The first effect will have a large contribution to surface heating rates whereas the second, except in extreme cases, would have a small, if not negligible, effect on heat transfer. However, the second effect may be directly more important since the destruction of oxidation inhibition coatings will require a refurbishment of the TPS.

There are reasonably accurate means of measuring the recombination rates of binary gases (i.e., O-O_2 or N-N_2 mixtures) at low pressures (~ 1 torr); however, a great deal of controversy can be raised with regards to multi-component gas mixtures. In this case, the apparent recombination rates may be substantially different from the real rates due to the competition for surface active sites. In addition, for air reactions which involve rapid shuffle reactions, the apparent rates can be further altered because the catalytic recombination of 0 to form 0_2, if substantial N is still present, will react in the region adjacent to the surface to deplete N in favor of O as shown in the following reactions

$$O_2 + N \rightarrow NO + O; \quad NO + N \rightarrow N_2 + O$$

Since it is not possible to analytically treat the effects of preferential surface adsorption, the accurate measurements of binary gas catalytic rates would be of limited value. Instead, until substantial improvements in the state-of-the-art are achieved, the apparent reaction rates should be measured under conditions similar to the entry environment, thereby keeping extrapolation errors to a minimum.

An arc plasma generator is one of the few hyperthermal facilities that can simulate typical shuttle environments for an extended period of time. Some recent data suitable for determining catalycities were reported[1] for candidate shuttle materials, namely, oxidation inhibited carbon/carbon composites (LTV), coated silica refractory insulation (LI-900), and coated columbium. The surface coating on the carbon/carbon is believed to be primarily silicon carbide. Compositions of the other coatings are given in Table 1. All coatings have a significant amount of silica which at high temperatures is expected to form a glassy surface with a low to moderate catalycity. The referenced data were obtained for dissociated air over a range of enthalpies between 3000 and 20,000 Btu/1bm and at a pressure of about 0.01 atm with flat faced cylinder models. At low-enthalpy conditions, only oxygen would be dissociated for equilibrium chemistry, whereas at higher enthalpies, both oxygen and nitrogen would be dissociated. The maximum enthalpy of 20,000 Btu/1bm is significantly greater than would be experienced by an Earth orbit re-entry vehicle and would result in some ionization effects which are not considered in the current analysis. Unfortunately, the data was not obtained with the intent of calculating catalytic efficiencies so that there are no data for any one of the materials which span the whole enthalpy range. However, since all coatings contain silica and have glassy properties, it would not be, for first approximations, very unrealistic to assume that the catalycities were similar for all of these materials. The distribution of data lends a small degree of support for this assumption. With heat transfer data that spans the enthalpy range of interest at a representative pressure level, it is then possible to "back-out" effective surface catalycities for O and N recombination using a nonequilibrium boundary-layer code.[2]. This kind of iterative data analysis was performed for a representative sample of data[1] and the results are shown in Fig. 1. Heat transfer rates to these typical shuttle materials were as low as 40% of the catalytic values as determined by a metallic calorimeter. In this data analysis it was assumed that nitric oxide concentrations were unaffected by wall collisions and that the catalycity of O recombinations, as determined at low enthalpies, remained constant at higher enthalpies where significant N atoms were present. Based on these assumptions the catalycities which best matched the data are:

$$k_w(O) \simeq 34.1 \text{ fps} \quad O \rightarrow 1/2\, O_2$$

$$k_w(N) \simeq 10.2 \text{ fps} \quad N \rightarrow 1/2\, N_2$$

Thus, in mixtures of dissociated oxygen and nitrogen, the surface is approximately three times more catalytic for oxygen recombination than for nitrogen recombination.

The previous results must, however, be treated with some reservation since the data was not obtained in a parametric manner specifically for catalycity evaluation. Moreover, two very important considerations have not been addressed, namely: 1) in dissociated multicomponent mixtures the competition for surface active sites may result in a composition dependent catalycity; and 2) direct surface recombination of O and N to form NO was not considered. The primary reason for attaching credibility to the above catalycity values is that they were obtained under representative environments so that there is no need for extensive extrapolation of the results.

Table 1 Elemental composition of coatings, percent by weight

	R5 12E coated columbium 752	VH 109 coated columbium	LTV coated carbon/ carbon	LI-900
Si	38	70		
Nb	57			
W	4			
Fe	0.2	5		
Cr	0.1	5		
Hf		20	[a]	[b]

[a] Proprietary but believed to be mostly SiC. [b] Silicon carbide, borosilicate glass.[3]

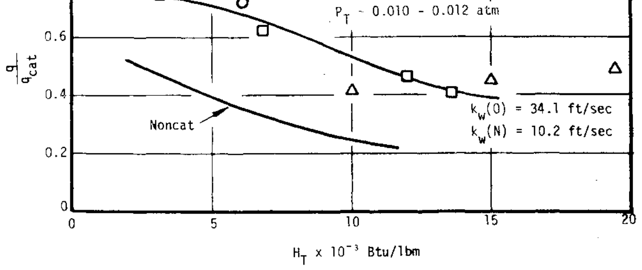

Fig. 1 Catalycity evaluation from arc plasma data.

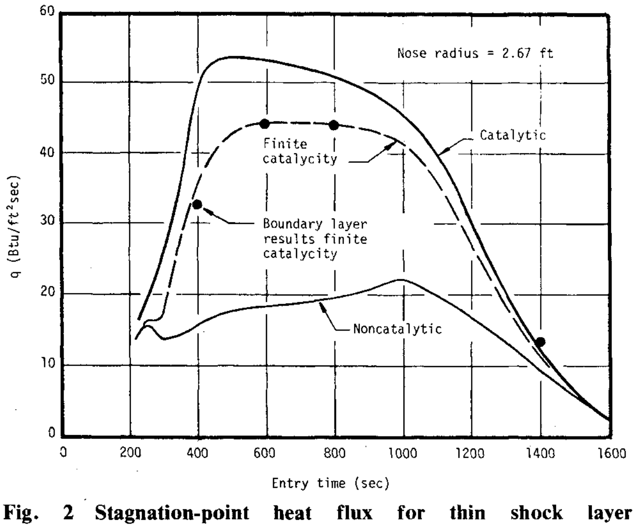

Fig. 2 Stagnation-point heat flux for thin shock layer, nonequilibrium flow.

III. Stagnation Point Results for Typical Shuttle Vehicle

Stagnation-point heating rates were calculated for a nose radius of 2.67 ft, which is representative of a typical shuttle vehicle. The calculations were performed using thin shock-layer assumptions with a frozen shock wave. Homogeneous kinetics were represented by 12 chemical reactions and heterogeneous reactions were assumed to be fully catalytic, noncatalytic, or partially catalytic using the previous catalycity values. The results are shown in Fig. 2 as a function of entry time (time from an altitude of 400,000 ft for a typical trajectory). It can be seen from this figure that a noncatalytic surface represents a significant reduction in heat flux (compared to a catalytic surface) over the period between 300 and 1200 sec; however, a finite catalycity surface yields only about 5-15% reductions over this same range. This rather small reduction can be compared with the arc jet results of Fig. 1, the difference being an effect of the larger nose radius and hence thicker shock and boundary layers. Note that all three curves come together for $t < 200$ and $t > 1600$ sec. The former is a consequence of the low dissociation rates at high altitudes and the latter is a consequence of equilibrium flow conditions in the boundary layer. Also shown in Fig. 2 are finite catalycity results based on boundary-layer assumptions with equilibrium conditions at the outer edge. The differences between boundary-layer and shock-layer results are seen to be minimal for these conditions. Whether or not similar results would hold in downstream regions must be determined by a detailed flowfield analysis.

IV. Shuttle Pitch-Plane Heating

To assess the effects of the above catalycities on regions other than the stagnation point, nonequilibrium predictions were made for an earlier Rockwell International orbiter shown in outline in Fig. 3. The total vehicle length is about 120 ft. Three sets of environmental conditions were taken from the baseline trajectory and are shown in Table 2. In this calculation, nonequilibrium effects in both the shock layer and the boundary layer were considered.

Five basic steps are used in the computational procedure: 1) the streamline pressure history in the inviscid region is approximated from ideal or real gas calculations; 2) the thermochemical history along inviscid streamlines is calculated; 3) Nonequilibrium viscous shock layer solutions are calculated for the nose region; 4) the intercept of the inviscid streamlines with the "edge" of the boundary layer must be specified and be consistent with the shock layer solutions; and 5) with Steps 1-4 defining the edge state, nonequilibrium boundary-layer solutions must be calculated for prescribed surface conditions. As with the stagnation region solutions, these calculations were performed using the code described in Ref. 2. Some details of Steps 1-4, leading to the specification of nonequilibrium edge states have already been presented[2,4]; however, the following comment will be included for completeness.

The vehicle surface pressure distribution on the windward pitch plane was specified by a combination of Newtonian flow at the nose and tangent cone conditions downstream. These distributions, shown in Fig. 4, are supported by representative wind tunnel data.[5] Based on these pressure distributions and correlations of shock shape from wind tunnel shadowgraphs, streamline pressure distributions were calculated by assuming that the windward pitchplane profile of the shuttle at angle of attack was the generator of an axisymmetric body. Since pressure distributions are relatively insensitive to chemistry, nonequilibrium states along these prescribed-pressure streamlines were then calculated by chemical relaxation from a frozen shock wave. The state of each streamline at its entry into the "boundary layer" then defined the boundary-layer edge states for the Step 5 calculations. Edge states for the three entry conditions shown in Table 2 are shown in Figs. 5-8. Also shown in Fig. 5-7 are the edge states based on an equilibrium isentropic expansion from the stagnation point. The large difference between the nonequilibrium and equilibrium states is obvious from these figures and is because of the difference in entropy across an oblique shock vs a normal shock.

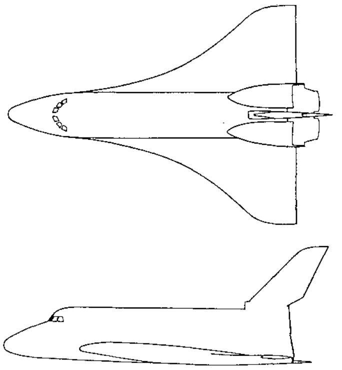

Fig. 3 Shuttle geometry.

Table 2 Baseline trajectory

t (sec)	U_∞ (kfps)	Alt (kft)	M_∞ (-)	α (deg)
400	25.4	250	28	34
800	21.8	224	22	32.3
1400	10.4	164	9.61	30

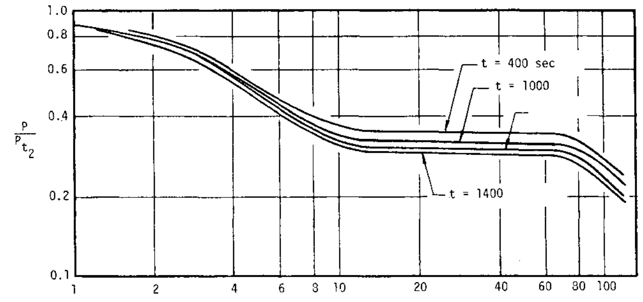

Fig. 4 Surface pressure distribution, windward centerline.

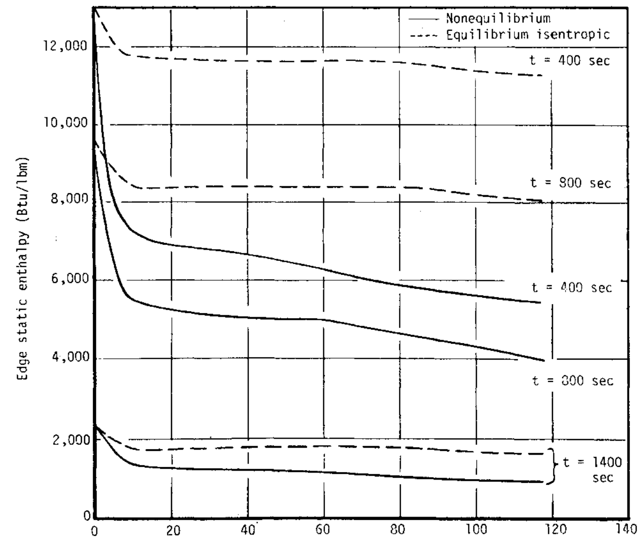

Fig. 5 Edge enthalpy.

Because of the large differences in dissociation levels at the boundary-layer edge of isentropic vs nonequilibrium specification, one would expect that there would be a substantial influence in surface heating, especially for low-catalycity surfaces. In an attempt to demonstrate this, heat transfer rates on the shuttle vehicle were calculated for equilibrium and nonequilibrium conditions and the results are shown in Fig. 9. Catalycity values are those shown in Fig. 1. As expected, stagnation region heat transfer is lower for nonequilibrium conditions; however, only a very short distance downstream the nonequilibrium heating exceeds the equilibrium values. In retrospect, this effect is more directly related to entropy layer swallowing than to nonequilibrium chemistry. That this is so is shown in Fig. 10, where for the $t = 800$ sec case, equilibrium boundary-layer calculations with the nonequilibrium entropy distribution are compared with the two $t = 800$ sec curves from Fig. 9. Now for most of the shuttle vehicle, nonequilibrium heating is less than the corresponding equilibrium heating.

The entropy swallowing also has an effect on transitional and turbulent flow heating. In the $t = 1400$ sec case, transition was assumed to begin at $Re_\theta / M_e = 150$. For equilibrium boundary-layer flows transition occurred at $s \sim 12$ ft; however, for nonequilibrium flows that was delayed to 17 ft because of a larger value of M_e. Somewhat more significant is the difference in heat transfer after turbulent flow is established. This again is an entropy effect and is supported by the studies reported by Bartlett, et al.[6]

One final comparison is shown in Fig. 10 by including the heat transfer distribution for a noncatalytic surface. As

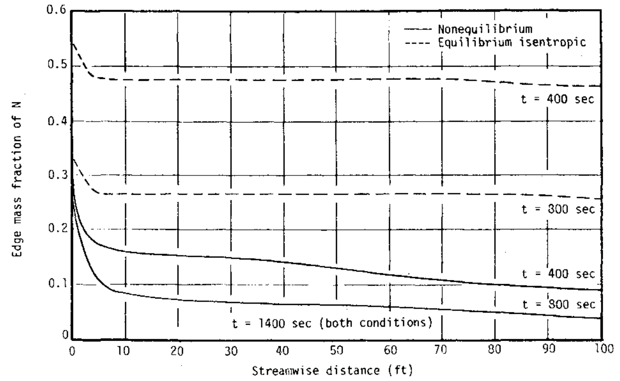

Fig. 6 Edge N mass fraction.

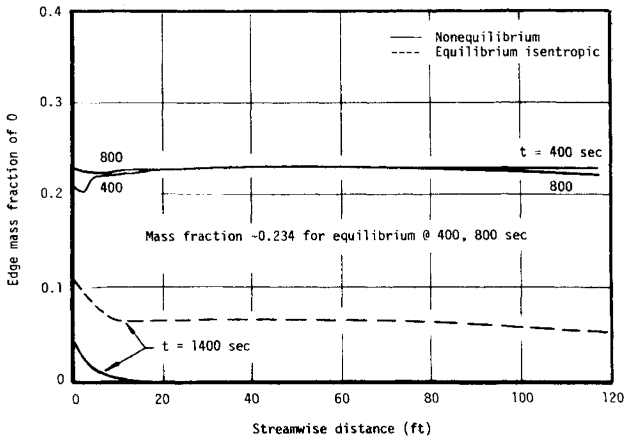

Fig. 7 Edge O mass fraction.

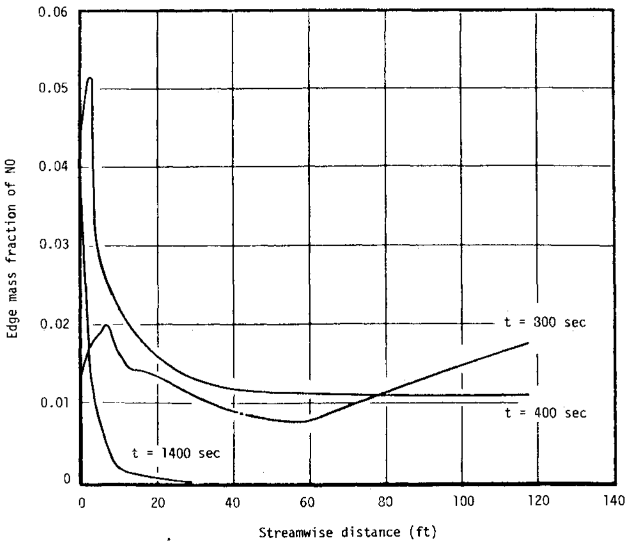

Fig. 8 Edge NO mass fraction.

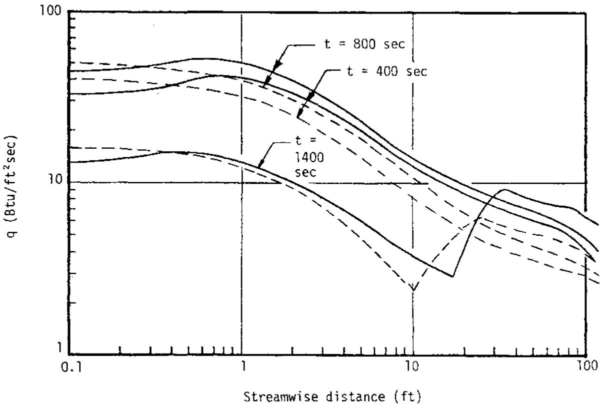

Fig. 9 Shuttle heating rates; —— nonequilibrium, entropy layer, semi-catalytic wall; --- equilibrium, isentropic edge, expansion.

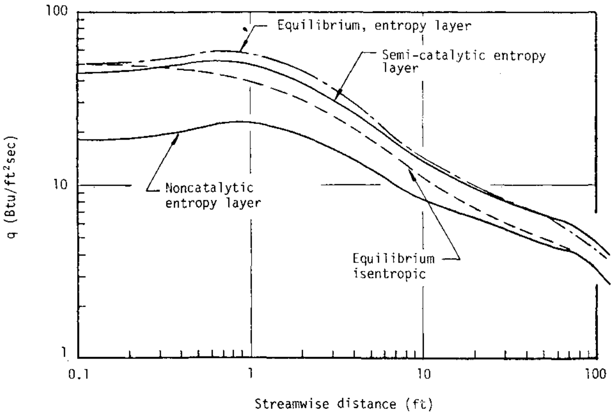

Fig. 10 Comparison of $t = 800$ sec heating rate predictions.

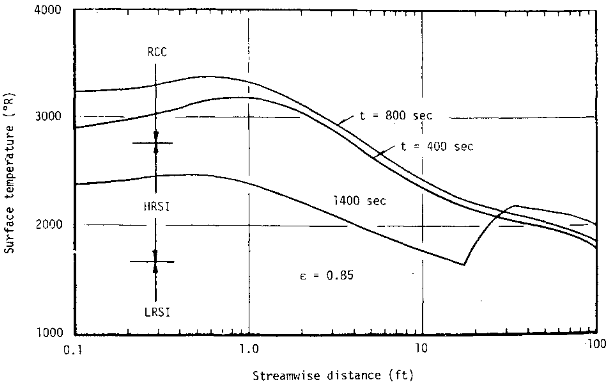

Fig. 11 Radiation equilibrium surface temperature.

predicted by many independent investigations, the reductions in heating are substantial but difficult to realize because of the very thick boundary layers. The low noncatalytic heating rates do, however, show that the boundary layer is nearly frozen for at least this entry condition.

Finally, the predicted surface temperatures for steady-state radiation into free space for an emissivity of 0.85 are shown in Fig. 11. Based on these calculations, RCC is required at the nose of the shuttle to a distance approximately 4.5 ft downstream of the stagnation point. Referenced to the zero angle of attack stagnation point this means that RCC is required to a distance of about 6 ft since the assumed nose radius was 2.67 ft.

V. Conclusions

Several important conclusions can be drawn from this investigation. 1) With a carefully prepared and executed arc jet test program, it is possible to determine the individual catalytic efficiencies for both O and N recombinations in dissociated air. 2) Nonequilibrium boundary-layer flows over a shuttle vehicle with arbitrary catalycity can be computed provided that boundary-layer edge conditions can be specified. Laminar, transitional, and turbulent flow effects are also included. 3) Entropy swallowing effects have a pronounced effect upon surface heating rates on a shuttle vehicle. For moderate catalycities, these effects can be greater than nonequilibrium effects. 4) Care must be exercised in predicting the response of flight vehicles based on ground facility experimental data since the change in model size has a significant effect on the surface chemical state. 5) The viscous layer code used in this investigation is universal in the sense that it is equally suitable for predicting complex flight environments with finite surface kinetics as well as for predicting and evaluating ground facility material performance. Thus it is possible to treat many of the complex interacting phenomena associated with shuttle entry heating.

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