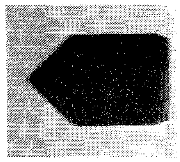

Fig. 3 Schlieren photograph of shock wave about cone-cylinder in chlorine at Mach number of 2.25 and ambient pressure of 5.9 mm Hg.

shock-wave angle as the flow changes from equilibrium to frozen flow. Although the leading-edge shock inclination is near the frozen value for $p = 29.5$ mm Hg and $M > 2.5$, the experimental data do not show the sudden detachment predicted for Mach numbers under 2.4 in frozen flow. This difference in behavior is attributed to subsonic flow in the shock layer which permits the expansion at the shoulder to affect the flow over the entire forebody of the cone-cylinder.

The schlieren photograph in Fig. 2 shows the slightly curved but attached shock, which is attributed to a subsonic shock layer rather than vibrational nonequilibrium. At the lower ambient pressures, nonequilibrium effects and the effect of a subsonic shock layer appear to act simultaneously.

The effect of vibrational nonequilibrium on flow detachment may be seen by comparing the schlieren photographs in Figs. 2 and 3. At essentially the same Mach number, the flow is attached for an ambient pressure of 202 mm Hg but is detached at 5.9 mm Hg. This same effect was shown in numerous schlieren photographs obtained in these experiments.

An analysis by D. R. Chapman presented in Ref. 2 permits interpretation of the present shock-shape measurements in terms of the vibrational relaxation characteristics of chlorine. An asymptotic expansion of Eq. (15) of Ref. 2

$$y = x \tan\omega_e + 2\tau u_0(\omega_f - \omega_e) \sec\omega_e + \ldots \qquad (1)$$

is particularly useful for comparison with the experimental results. The distances x and y are measured along and normal, respectively, to the cone's surface. In applying Eq. (1), relaxation time τ and shock-layer velocity u_0 from Ref. 3 were used to give a value of $\tau u_0/d$ equal to $4.6/p$ (mm Hg) which should apply over the narrow Mach number range of the present experiments. The infinite-cone predictions given in Fig. 1 were used to estimate the parameter $(\omega_f - \omega_e)$ required in Eq. (1).

Direct measurements from schlieren photographs of shock-layer thickness at the shoulder are presented in Fig. 4 for ambient pressures of 29.5 and 203 mm Hg. For the Mach numbers for which a cone-cylinder behaves like an infinite cone, Eq. (1) provides a good prediction of shock-layer thickness for varying degrees of vibrational nonequilibrium. At lower Mach numbers near shock detachment, however, this prediction method is inapplicable because of the effect of the cylindrical portion of the model on the flow about the conical nose.

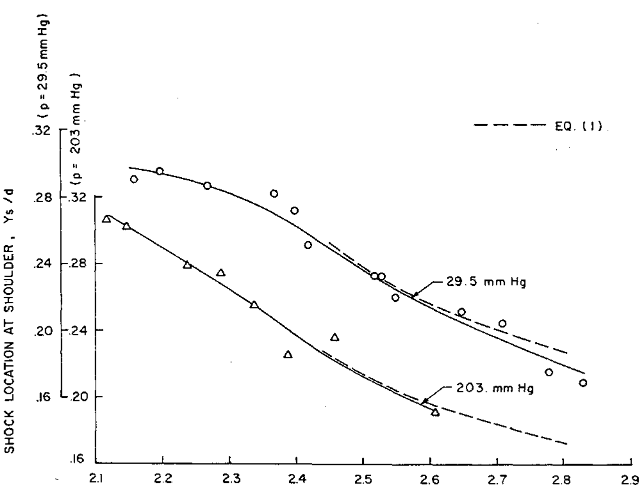

Fig. 4 Comparison of theory and experiment for shock-wave location at shoulder of cone-cylinder in chlorine.

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Surface Recession of Phenolic Nylon in Low-Density Arc-Heated Air

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BECAUSE the analysis of the charring-ablative thermal protection systems used on high-speed vehicles involves understanding a complex process involving many interacting phenomena, numerous experimental programs have been conducted to evaluate the performance of ablative materials. Analysis of the weight loss histories and surface temperatures[1,2] indicates the importance of the oxygen concentration, i.e., gas composition, on the performance of phenolic nylon. Lundell et al.[3,4] studied high-density phenolic nylon over a wide range of test conditions and low-density phenolic nylon at stagnation pressures in excess of 0.1 atm.

The current study considers the mechanisms of surface recession for low-density phenolic nylon. Char removal at the surface is accomplished by thermal and shearing stresses and by chemical reactions with the boundary-layer species and the pyrolysis gases. The results reported herein, which were obtained using stagnation-point (i.e., flat-faced cylindrical) models, reflect the importance of reactions between the pyrolysis gases and the char at relatively low stagnation pressures. Since the models were in a stagnation-point environment, char removal by shear stresses was not considered.

Equipment and Models

The experimental program was conducted in the Hyperthermal Tunnel of the University of Texas at Austin. The facility is an 80-kw d.c., continuous-flow, arc tunnel, which can provide either a 1.5 or 3.0 in. stream of a two-component gas at a nominal Mach number of 3. The operating characteristics include a maximum centerline stagnation enthalpy of 15,000 Btu/lb and a maximum model stagnation pressure of 0.07 atm. (A detailed description of the equipment may be found in Ref. 5.)

The models used in the current program were machined from low-density (approximately 35 lb/ft^3) phenolic nylon. The model design was similar to that described in Ref. 6. Measurements to define the material performance were made

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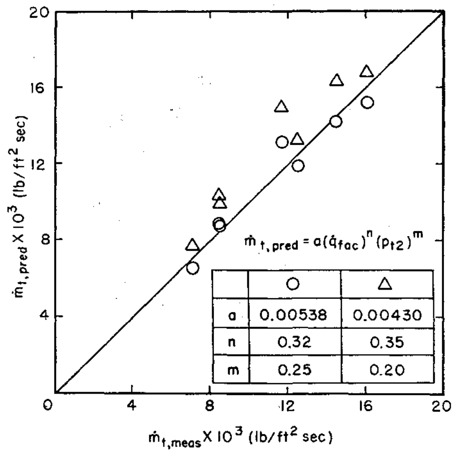

Fig. 1 Total mass-loss rate correlation.

on the 0.50-in. diam core that was inserted in a concentric shroud whose outer diameter was 1.00 in. The model axis was parallel to the flow, so the core experienced essentially uniform, stagnation-point heating on the single, exposed surface. The facility calorimeter, which is a water-cooled, asymptotic type, is also a flat-faced cylinder, 1 in. in diameter. Therefore, it was not necessary to introduce factors accounting for geometric differences to relate the calorimeter value of heat transfer to the model configuration.

To define the time dependence of the degradation process, four to six models were exposed to the test stream for 20 to 120 sec at each test point. The range of flow conditions were: facility calorimeter convective heating rate, $\dot{q}_{fac} = 80$ to 400 Btu/ft^2 sec; model stagnation pressure, $P_{t2} = 0.006$ to 0.05 atm; centerline stagnation enthalpy, $H_{CL} = 3500$ to 11,500 Btu/lb.

Results and Discussion

Two marked differences were noted between the model behavior observed during the current program and the results reported in the literature. Lundell et al.[3] were unable to use cored models of low-density phenolic nylon due to severe gouging at the interface between the core and the shroud, which was observed while testing at stagnation pressures between 0.1 and 2.8 atmospheres. This difficulty was not encountered during the present tests which were conducted at lower stagnation pressures. The problem was not mentioned in Ref. 7, which reported measurements over a wide range of stagnation pressures.

The postrun condition of the model core clearly indicated the presence of three distinct zones: a char zone, a thin pyrolysis zone, and the virgin material. At higher stagnation pressures, Lundell et al.[3] found the pyrolysis layer was so thin for low-density phenolic nylon that the ablated models could be considered to consist of just two layers, i.e., char and virgin plastic. Although the models were exposed for as much as 120 sec, the ablative process was "quasi-steady state," i.e., the interface velocities were constant but unequal.

As illustrated in Fig. 1, the total mass-loss rates measured in the current program are in good agreement with the values predicted using the correlations presented in Ref. 7 for low-density phenolic nylon. In the referenced study two low-density phenolic nylon materials (one supplied by Langley, the other supplied by Hughes) were subjected to numerous arc-heated environments. The resultant total mass-loss-rate measurements were correlated using the relation

$$\dot{m}_{t,\text{pred}} = a(\dot{q}_{\text{fac}})^n(P_{t2})^m \tag{1}$$

where $a = 0.00538$, $n = 0.32$, $m = 0.25$ for the Langley material and $a = 0.00430$, $n = 0.35$, $m = 0.20$ for the Hughes material. For the heat-transfer rates and the Pitot-probe pressure measurements from the current program predicted values of the total mass-loss rate, $\dot{m}_{t,\text{pred}}$, were computed for both sets of empirical constants using Eq. (1). The measured mass-loss rates were obtained from the current data using a least-squares curve fit of polynomial one, i.e., a straight line.

To evaluate the surface recession measurements, it is necessary to define the mechanisms of char removal at the stagnation point. Surface recession of the phenolic nylon char may be attributed to: 1) reactions with gases present in the boundary layer, 2) reactions with gases generated within the degrading specimen and percolated to the surface, and 3) shrinkage of the material during degradation. The last two factors would explain surface recession observed when a model is exposed to purely radiative heating or to an inert test stream.[4] Due to the relatively low pressures of the current program, these two factors represented a larger fraction of the measured surface recession than would be the case for tests at higher pressures (see, for example, Ref. 3).

Since the phenolic nylon char is principally carbon,[8] an approximation to the surface oxidation by gases present in the boundary layer can be made by utilizing the results for a graphite surface found by Scala and Gilbert.[9] As indicated there, for the present test conditions, i.e., stagnation pressures between 0.006 to 0.05 atm and surface temperatures from 2850° to 4000°F, the oxidation of graphite is diffusion-limited. Using a theoretical analysis of diffusion-limited oxidation of a graphite surface in an air environment, Scala and Gilbert determined a relation for the graphite mass loss rate $\dot{m}_G$,

$$\dot{m}_G = 0.00635(P_{t2}/R_{\text{eff}})^{0.5} \tag{2}$$

If one assumes that the char-removal rate at the surface of the ablative material can be approximated by this Eq. (2), then the surface-recession velocity V_s may be calculated using the expression

$$V_s = \frac{0.00635}{\bar{\rho}_c}\left(\frac{P_{t2}}{R_{\text{eff}}}\right)^{0.5} = 0.000415\left(\frac{P_{t2}}{R_{\text{eff}}}\right)^{0.5} \tag{3}$$

The average char density $\bar{\rho}_c$ and the effective radius of curvature R_{eff} were assumed to be constants. The average density of the phenolic nylon char was found to be 15.3 lb/ft^3. The effective radius for the flat-faced cylindrical models was assumed to be $R_{\text{eff}} = 2.9\ R_b$ (Ref. 10), where R_b is the cylindrical radius.

Experimental values of the surface-recession velocity were computed using a least-squares curve fit of the measured surface-recession histories. The measured values of the surface-recession velocity are compared in Fig. 2 with the data of Lundell, et al.[3] and the values calculated using Eq. (3). The surface-recession velocity for a char-forming ablator model

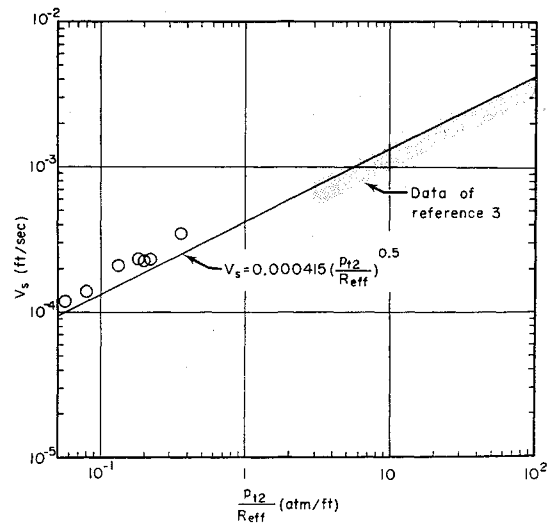

Fig. 2 Surface-recession velocity correlation.

would be expected to be less than for a graphite model since the pyrolysis vapors block a portion of the incident convective heating and since the combustion reaction of the vapors with the air in the boundary layer utilizes oxygen that would otherwise diffuse to the surface. Adjusting the surface-recession velocity to account for the "inert environment" contribution (i.e., subtracting the amounts due to shrinkage and due to oxidation by pyrolysis gases as determined from the surface-recession velocity measured in an inert environment), the velocities are below the level predicted for graphite using Eq. (3).[11]

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Nozzle Boundary-Layer Displacement Thickness at Mach Numbers 30 to 70

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Nomenclature

$(A/A^*)_{eff}$ = ratio of effective nozzle-to-throat cross-sectional area (mass flow considerations)
$(A/A^*)_{geo}$ = ratio of geometric nozzle-to-throat cross-sectional area
d^* = nozzle throat diameter
M_∞ = freestream Mach number
$p_{t,1}$ = reservoir pressure
p_∞ = freestream static pressure
$R_{\infty,x}$ = freestream Reynolds number based on axial distance from nozzle cone apex
$T_{t,1}$ = reservoir temperature
T_∞ = freestream static temperature
x = axial distance from nozzle cone apex
δ^* = boundary-layer displacement thickness
γ_∞ = freestream ratio of specific heats
θ = nozzle-divergence half-angle

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Introduction

OVER the past decade, the empirical relations of Refs. 1 and 2 for predicting hypersonic nozzle boundary-layer displacement thickness in air have received considerable usage. More recently, a similar study in nitrogen (Ref. 3) showed that extrapolation of the empirical relations of Refs. 1 and 2 to Mach numbers greater than those from which they were obtained resulted in overestimation of the nozzle displacement thickness. An empirical relation employing the same parameters used in Refs. 1 and 2 was derived by Whitfield and presented by Edenfield in Ref. 3. This relation was obtained from higher Mach number data so as to more accurately predict hypersonic nozzle displacement thickness for Mach numbers to approximately 20. The present study provides preliminary nozzle displacement thickness results in helium at Mach numbers much greater than those of the aforementioned hypersonic studies. These results, obtained in the Langley hotshot tunnel, include the effects of wide ranges of reservoir pressure, reservoir temperature, and geometric area ratio. An empirical relation for predicting nozzle displacement thickness over the present range of Mach numbers (30 to 70) is presented.

Apparatus and Tests

A description of the Langley hotshot tunnel is presented in Ref. 4. As mentioned in Ref. 4, this facility employs a 10° total-divergence angle conical nozzle. The present helium results, which represent part of a recent calibration study, were obtained for a reservoir pressure range of 3000 to 23,000 psi and reservoir temperature range of 1500° to 11,000°R. These reservoir conditions, in conjunction with variation in nozzle-throat diameter, resulted in Mach numbers of 30 to 70 and Reynolds numbers of 4×10^5 to 5×10^6/ft.

Results and Discussion

Pitot pressure surveys in the nozzle test section showed, in general, that the pitot pressure was essentially constant across the inviscid core. A value of the effective-area ratio $(A/A^*)_{eff}$ corresponding to the mean of the measured pitot pressures across the core, was determined from mass flow considerations.[5] Assuming the displacement thickness at the nozzle throat to be zero, the nozzle displacement thickness was obtained from the nondimensional expression

$$\delta^*/x = \tan\theta - (d^*/2x)[(A/A^*)_{eff}]^{1/2} \quad (1)$$

Figure 1 shows the effect of reservoir pressure on nozzle displacement thickness for a given geometric area ratio of 2.03×10^4 ($d^* = 0.150$ in. and $x = 122$ in.) and reservoir temperature of approximately 3800°R. The nozzle displacement thickness is observed to decrease approximately 27% $[\Delta(\delta^*/x) = -0.013]$ as the reservoir pressure increases nearly eightfold from 3000 to 23,000 psi. For this change in $p_{t,1}$, there was an accompanying increase in M_∞ from 41 to 50 and in $R_{\infty,x}$ from 4.3×10^6 to 2.25×10^7. As shown in Fig. 1, the empirical relations of Refs. 1 and 2, in terms of M_∞ and $R_{\infty,x}$, predicted values of δ^*/x approximately twice those of the present data and Ref. 1 failed to predict the trend of decreasing δ^*/x with increasing $p_{t,1}$. The empirical relation derived by Whitfield and presented by Edenfield in Ref. 3 underestimated the present data by approximately $\frac{1}{3}$, but predicted the trend accurately. For the case of hypersonic flow over a flat plate, the displacement thickness in air is about $\frac{3}{5}$ that in helium for the same value of Mach number