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Technical Notes

Observation of an Ablating Surface in Expansion Tunnel Flow

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Nomenclature

c	=	specific heat, J/kg/K
K_i	=	constant, 1.37×10^{-4}, $kg^{1/2}m$
k	=	thermal conductivity, W/m/K
$\dot{q}_S$	=	stagnation-point heat flux, W/m^2
r_{eff}	=	effective nose radius, m
t	=	exposure time, s
u	=	flow speed, m/s
x	=	penetration depth, cm
x^*	=	$x/(2\sqrt{\alpha t})$
α	=	thermal diffusivity, $\frac{k}{\rho c}$, m^2/s
ΔT_S	=	temperature change, K
ρ	=	density, kg/m^3
$\sqrt{\rho c k}$	=	thermal product, $J/m^2/K/s^{1/2}$

I. Introduction

ABLATIVE products ejected from an ablating surface, such as the thermal protection system (TPS) of a hyperbolic reentry vehicle, and their coupling to the chemically reacting, radiating shock layer about the vehicle's forebody, form a complex, mutually interactive, dynamic system that is poorly understood [1]. Hydrocarbon-based ablators, such as carbon phenolic, have a complex role, as the resultant carbon-based compounds are both strong absorbers and emitters of radiation, thereby greatly altering the radiative heat flux to the vehicle. Thermal and chemical conditions in a shock layer can be highly nonequilibrium. As a result of the high temperatures encountered, chemical species dissociate, ionize, and recombine, often forming new species. At sufficient enthalpies, species reradiate significant heat fluxes in all directions, including to the body itself.

Expansion tube facilities are the ground-based test facilities most closely able to simulate the high-enthalpy and chemically reacting shock layers characteristic of superorbital reentry flows. These are impulse facilities with brief steady test periods of the order of 100 μs. However, ablation is a chemical and physical phenomenon previously considered to require prior heating, the associated outgassing of which may affect the test conditions within an expansion facility. Ablation simulation in expansion facilities is therefore difficult and has been limited to a subset of ablative heat shield phenomena, such as gaseous product effusion from the forebody surface during the brief steady test time [2] and simulation of a preheated graphite layer [3].

However, the creation of sources of radiating material originating from the epoxy used to repair damaged spots on the windward surface of test models was noticed during previous work in X2. Subsequent analysis showed that, with an insulating substrate, the surface temperature increases enough to release ablative products within the steady test time of approximately 50 μs.

This led to a new method of studying ablation in impulse facilities. The epoxy employed in this study is Araldite Five Minute Everyday (Huntsman Corporation). Proof-of-concept experiments were conducted in the X2 expansion facility at the University of Queensland with a 60° sphere–cone model, with and without an epoxy coating. High-speed camera and spectrometric results show the epoxy coating ablates during the steady test time.

II. Analytical Study

To evaluate whether the surface temperature would be sufficient to produce vaporization of the insulation, a one-dimensional (1-D) semi-infinite analysis was performed using an empirical estimation of the stagnation-point heat flux. Conditions taken in the analysis of heat flux to the epoxy coating are given in Table 1.

Analysis of the heat flux uses the Zoby stagnation-point heat flux approximation for convective heat flux to the (cold) nose of the model [7]:

$$\dot{q}_S = K_i \sqrt{\rho u^2} \frac{u^2}{\sqrt{r_{\text{eff}}}} \tag{1}$$

The Shultz and Jones temperature change for constant heat flux, 10 and 1% step function thermal pulse penetration depth approximations for insulating materials during the exposure time [6], are also used:

$$\Delta T_S = \frac{2\dot{q}_S}{\sqrt{\pi}} \sqrt{\frac{t}{\rho c k}} \tag{2}$$

$$x = 2x^* \sqrt{\alpha t} \tag{3}$$

$$x = 0.3\sqrt{t} \tag{4}$$

A surface temperature change for epoxy of 178 K in 50 μs is calculated, which is sufficient for the epoxy coating to commence ablation during the steady test period. The 10% temperature penetration depth is 6 μm in 50 μs. As this is much smaller than the 1.5-mm-thick epoxy coating, the surface curvature can be neglected, thereby permitting a 1-D semi-infinite analysis of the heat flux to the coating and its ablation behavior.

III. Description of Experiments

A. Experimental Facility

X2 is a free-piston driven, high-enthalpy facility that can be operated as either a shock or expansion tube facility [8]. For this series of experiments, X2 was operated in expansion tunnel mode.

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Table 1 Conditions used in epoxy heat flux analysis

Condition	Value	Reference
Test gas density, g/m^3	0.532 ± 0.150	Present work
Test gas speed, m/s	9200 ± 400	Present work
Effective nose radius, mm	27.0 ± 0.5	Present work
Exposure time to heat flux, μs	50 ± 1	Present work
Epoxy density, kg/m^3	1260 ± 150	[4]
Epoxy specific heat, J/kg/K	2110 ± 150, at 473 K	[5]
Epoxy thermal conductivity, W/m/K	0.188 ± 0.002	[4]
Epoxy α, m^2/s	$(1.7 \pm 0.8) \times 10^{-7}$	Present work
Epoxy sublimation temperature, K	630 ± 10	Present work
x^*	1	[6]
Zoby stagnation-point heat flux, MW/m^2	14.97 ± 0.02	[7], present work
Temperature change, K	178 ± 1	[6], present work
10% temperature penetration depth, μm	6.0 ± 0.5	[6], present work
1% temperature penetration depth, μm	21 ± 3	[6], present work

Luminosity from substantial portions of the model and shock-layer flow was visualized using a Shimadzu HPV1 high-speed charge-coupled device (CCD) video camera recording at 500 kfps with a 1 μs exposure time. Radiation from chemical species in a narrow 3.9-mm-long strip of the field of view parallel to and including the stagnation streamline was spectrally resolved using an Acton Research Spectro Pro 2300I UV spectrograph fitted with a 150 line/mm diffraction grating and coupled to a Princeton Instruments PI-max intensified CCD camera. Spectra were collected across this window over a 10 μs interval midway through the 80 μs steady test flow period.

B. Experimental Conditions

A 47.9 MJ/kg 9.2 km/s air test gas condition for Earth reentry simulation in the X2 expansion tunnel was used in this study. In this condition, the calculated freestream has a static pressure of 342 ± 40 Pa, a density of 0.532 ± 0.150 g/m^3, a translational temperature of 1896 ± 400 K, a vibrational temperature of 3359 ± 600 K, and an effective flight velocity of 9788 ± 60 m/s.

The model used is a mild steel 60° sphere–cone with a 22.8 mm base radius and nose-to-base radius ratio of 1.2. For the ablating surface tests, the forward surface of the model was coated with epoxy, allowed to cure and then machined to a 1.5 mm thickness with the same shape and outside diameter of the original steel forward surface.

IV. Discussion of Results

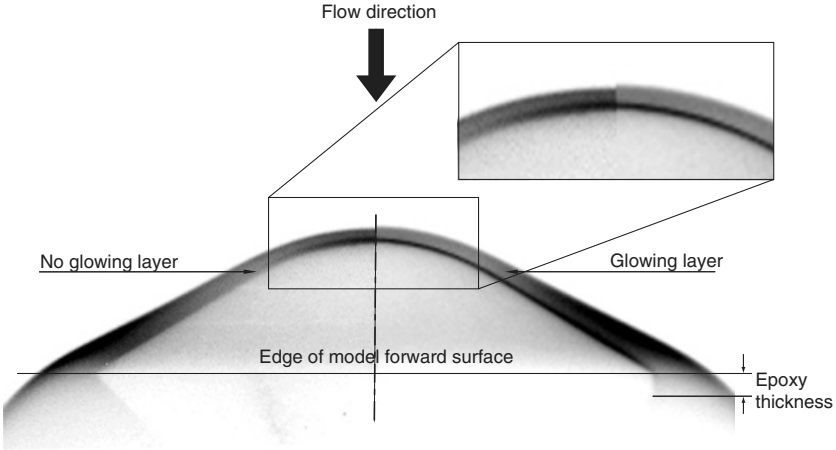
A. High-Speed Camera

The high-speed camera images show a uniform response in the shock layer when no coating is employed, as shown in Figs. 1a and 2. The camera detects significantly less light where the line of sight first intersects the model. This indicates the image is created by radiative emission from a hot, optically thin shock layer, as lines of sight immediately above the model surface pass through a significantly greater length of luminous gas than those that terminate at the model surface. The model would appear more luminous if either the surface is glowing or if the glowing layer is gaseous and optically thick. As the model appears less luminous, this indicates the glowing layer is gaseous and optically thin.

The uniform image response over the axisymmetric model implies the shock-layer gas irradiance is high immediately behind the shock and decreases rapidly as the model surface is approached.

Images taken when an epoxy coating is present show a thin (~0.2 mm thick) glowing layer along the entire upper edge of the model, as shown in Figs. 1b and 2. The layer first appears approximately 20 μs after the arrival of the primary starting shock, well ahead of the steady flow period, which begins 30 μs later. The glowing layer remains throughout the steady flow, growing in irradiance, though not noticeably in thickness.

As a glowing layer is formed only when a coating is employed, the glowing layer is considered to be the ablation layer (the region in the



a) No coating b) Epoxy coating

Fig. 1 Negative grayscale image of high-speed camera footage at 40 μs into steady test time: a) no coating and b) epoxy coating.

shock layer where the high concentrations of ablation products emanating from the coating meet the oncoming flowfield). The axisymmetric flow implies the glowing layer covers the entire surface of the model. As presented previously for an uncoated model shock layer, the ablation layer is gaseous and optically thin, as the thin glowing layer appears luminous above the upper edge of the model and less luminous for lines of sight intersecting the model. The glowing layer cannot be a radiating solid-coating surface, as this would cause the model to appear luminous and fade toward the upper edge of the model, which is the opposite of the results shown in Fig. 1.

B. Spectrometer

The spectrum of signal irradiance in the ablation layer (on the centerline, 0.35 mm from the stagnation point) in the 310–530 nm wavelength range is shown in Fig. 3 alongside the signal irradiance in the same region, in a nonablating shock layer.

The formation of carbon-based species is of interest, not only due to their importance as radiators but also because the only significant source of carbon is the TPS (represented in these experiments by the epoxy coating). The decomposition and dissociation of the heavier hydrocarbons in epoxy results in the formation of carbon- and light-carbon-based species.

Measurements show that use of an epoxy coating results in greatly increased CN and C_2 radiation, much greater than when no coating is employed. Cyanogen is the major source of shock-layer luminosity. Its formation occurs primarily by the reaction,

$$N_2 + C \leftrightarrow CN + N \tag{5}$$

Cyanogen violet transitions are the dominant radiating species in a nitrogen- and carbon-containing gas in the 250–550 nm wavelength range. The cyanogen (violet transitions) $\Delta v = 0$ structure has a peak signal irradiance approximately five times greater in the case of the epoxy coating (1.05 $\mathrm{mW/m^2/nm}$) than without a coating (0.225 $\mathrm{mW/m^2/nm}$).

The radiation increase can only be explained by a growth in cyanogen and C_2 number densities close to the model surface. Radiative emission increases rapidly with temperature; however, postshock dissociation reactions combined with radiative and convective heat loss cool the shock layer near the model below the shock-layer temperature, immediately behind the shock.

The combination of cyanogen in the shock layer when a coating is not employed and uniform (axisymmetric) shock-layer luminosity implies that cyanogen or its constituent components are present in the test gas. Nitrogen is readily available in air, while some carbon is inherent in the facility.

This increase in cyanogen in the ablation layer when an epoxy coating is employed is considered to be due to chemical reactions between carbon-containing ablation gases emitted by the epoxy coating and nitrogen in the test gas. These increases in cyanogen and C_2 are further evidence that the glowing layer is an ablation layer.

Second-order spectral lines were also obtained (not shown here) and used to estimate the shock-layer temperature, in conjunction with the SpecAir radiation spectra program [9]. Initial estimates give ablation layer translational and vibrational temperatures of $8700 + 500$ K. As this is much greater than the model wall temperature, the difference between experiment and flight equilibrium wall temperatures may not significantly affect the heat flux analysis.

C. Comparison of Measurements

Signal distribution from the radiating species in the shock layer, as measured by both the spectrometer and high-speed camera, is shown in Fig. 2, with and without an epoxy coating for the region of the flow monitored by the spectrometer. The spectrometric data is averaged over the 320–530 nm wavelength range. The high-speed camera is most sensitive between 400 and 700 nm. The high-speed camera data used is a time average over the same 10 μs period to which the spectrometer is exposed.

There is considerable agreement on signal distribution between the spectrometer and high-speed camera, despite their differing wavelength sensitivities. Both instruments show radiating species are approximately uniformly distributed in the axisymmetric shock layer when a coating is not used. This is consistent with a nonablating shock layer and implies the existence of a high irradiance layer immediately behind the shock and a decrease in irradiance toward the model surface.

In the case of an epoxy coating, both instruments record an increase in radiation near the model upper edge, which is considered to be due to increases in species generated by chemical reactions between the test gas and epoxy layer ablation products. This is consistent with an axisymmetric ablating shock layer and implies the ablation layer is optically thin across the 320–700 nm sampled wavelength range.

Ideally, posttest measurements of the model could be made to definitively determine whether ablation has occurred. Unfortunately, posttest time conditions in the expansion tunnel are highly turbulent and lead to further ablation of the epoxy, as well as severe damage to the model. For this reason, visual examination of the epoxy for material degradation and shadowgraph or scale measurements to determine epoxy surface regression are not valid. The occurrence of ablation can only be measured by recording data during the test time. Data from two independent instruments used in this study, the high-speed camera and spectrometer, both point to the occurrence of ablation.

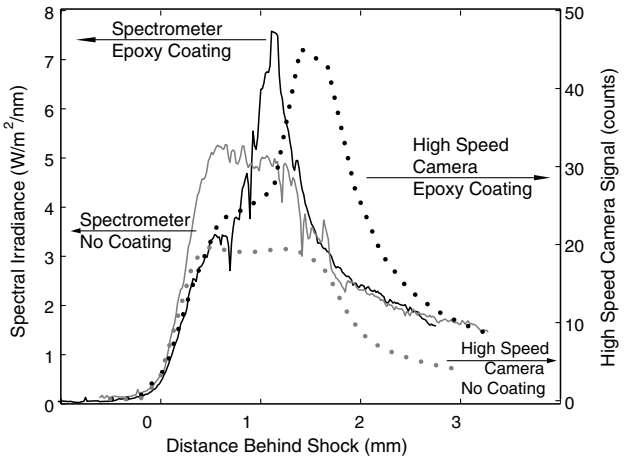


Fig. 2 Distribution of the radiation behind the bow shock along the stagnation streamline.

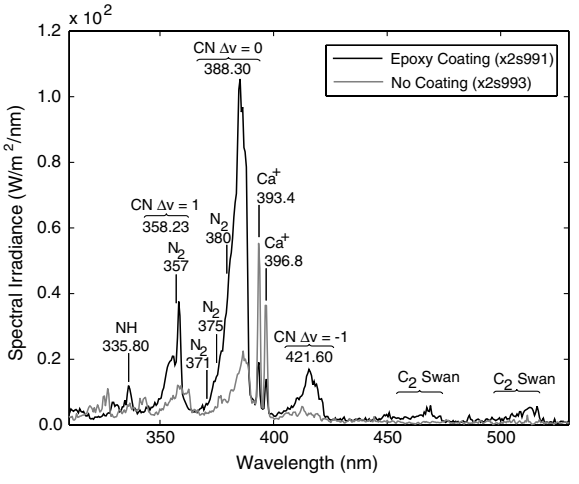


Fig. 3 Spectral irradiance in ablation layer measured on centerline 0.35 mm from stagnation point.

V. Conclusions

An ablating shock layer was produced with an epoxy coating on an axisymmetric model during the 80 μs steady test flow produced in a high-enthalpy superorbital expansion tunnel. Both spectrometric and high-speed camera data show ablation to have occurred and ablative products to have become entrained in the shock layer through the formation of a glowing layer containing a fivefold increase in cyanogen near the model surface when an epoxy coating is employed. The high concentration of cyanogen inferred from the data is considered to result from chemical reactions between the epoxy ablation gases and the air test gas. This now opens the possibility for extensive studies of ablating radiating flows in the expansion tube facility at the University of Queensland.

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