Erosion of Graphite Surface Exposed to High-Temperature Supersonic Hydrogen Gas

OM P. SHARMA*
Princeton University, Princeton, N.J.

Theme

THE NERVA flight engine as well as the current nuclear rocket engine under development has a nozzle extension made of a graphite composite material. Recently, an experimental study was therefore conducted to obtain erosion rates of a graphite composite (AGCarb-101) when exposed to high-temperature supersonic stream of hydrogen gas.[1] We have developed a theoretical model based on laminar boundary-layer flow equations to predict these erosion rates. A satisfactory agreement is obtained between the results of computation, and the available experimental data.

Contents

In order to understand the motivation for some aspects of the theoretical model, we describe briefly the relevant features of the experiment mentioned earlier.[1] A continuous supply of hydrogen gas at high pressure and temperature was allowed to flow through a specially designed water-cooled conical nozzle, and the specimen (AGCarb-101) was aligned with the nozzle and placed at a fixed position downstream of the throat. The duration for each test varied from $\frac{1}{2}$ to 1 hr. The backsurface of the specimen was heated by an ATJ graphite heating element in order to achieve higher surface temperatures. The detailed measurements in each test run consisted of erosion rates, and pressures at four different locations along the specimen, while the temperature was measured only at one fixed location in the specimen.

The erosion of the specimen involves heat transfer, mass transfer and chemical reaction. These processes take place within the boundary-layer region over the surface of the specimen. For preliminary analysis, the main flow in the nozzle is treated as one-dimensional, isentropic (equilibrium), and laminar. It is reasonable to assume steady flow because of the small magnitudes of the observed erosion rates. Since there occurs a significant change in the temperature of the gas along the nozzle, variation in γ_{H_2} (the ratio between the specific heats of hydrogen gas at constant pressure and volume) due to temperature cannot be completely ignored. To keep the calculations simple, we use two constant average values of γ_{H_2} such that one of them ($\gamma_{H_2, I}$) is applicable for the region starting from the chamber to the leading edge of the specimen while the other ($\bar{\gamma}_{H_2}$) is used for the flow over the specimen.

The kinetic data dealing with the reaction of a graphite composite with hydrogen is not available. Therefore, the results obtained by Clarke and Fox[2] for the reaction rate of a graphite filament with hydrogen are incorporated in this model. Clarke and Fox[2] concluded on the basis of their experimental studies that, below 3000°K, the reaction of graphite with hydrogen between 0.01–1.0 atm. was a surface reaction. It is also found that methane gas is essentially the dominant product in the temperature and pressure range of our interest. Thus, we assume the following single step over-all reaction,

$$C(s) + 2H_2 \longrightarrow CH_4 \qquad (1)$$

The equations describing the steady axisymmetric laminar boundary-layer flow, under the assumption of Fick's law of binary diffusion, are well known,[3] and will not, therefore, be written down here. Note that the general energy boundary condition at the eroding surface requires a solution of the heat-transfer problem within the specimen. A realistic treatment of heat transfer within the specimen for the present experimental situation is too complex, and will also involve some poorly known parameters. Therefore, a known constant value of the surface temperature is assumed. The governing equations are transformed into the locally similar form by introducing new independent variables obtained by combining the Levy and Mangler transformations and the Howarth-Dorodnitsyn transformation.[3] The transport properties are calculated from the expressions based on kinetic theory, and the properties of the mixture are then determined by making use of the empirical equations.

The transformed equations are solved for different test conditions by modifying suitably the numerical scheme described in Ref. 4. In the present calculations, we obtain, in addition to the erosion rates, the detailed profiles of velocity, temperature, and species mass fraction as well as the rate of heat transfer at the specimen surface. The general features of these profiles are similar to those commonly observed in other boundary-layer flows. Since the surface temperature of the specimen is not known a priori, a couple of computer runs are necessary to get a value of surface temperature which gives erosion rates close to the experimental points.

The computed erosion rates for five different test conditions are shown in Fig. 1. The agreement between the calculated curves and the experimental points is thus extremely good in tests W-111, W-112, and W-115, whereas there is an appreciable error for test conditions of W-142. Because of the small magnitude of erosion rates, the amount of hydrogen gas consumed during the erosion process is found to be extremely small; $Y_{H_2, w}$ (the mass fraction of hydrogen gas at the surface) being generally close to 0.999. Thus, under the assumption of constant temperature of the specimen surface, the erosion rates can be calculated directly from the empirical expression for the reaction rate due to Clarke and Fox by setting $Y_{H_2, w}$ equal to unity, and by using the values of p_w (the pressure at the specimen surface) obtained from a solution of equations governing the external flow. As an example of the nature and amount of heat transfer taking place at the specimen surface, a plot of heat flux, $q_w[=k_w(\partial T/\partial y)_w]$, against the nondimensional distance along the specimen (x/L) is shown for the conditions of test run No. W-110 in Fig. 2, which indicates that heat is being transferred from the gaseous phase to the specimen. Since q_w is dependent on a choice for the initial value of $\bar{x}[=(x/L)]$ at which the integration of the governing equations is begun, the results have been obtained for two values of $\bar{x}_{ini}$. However, this effect becomes insignificant towards the downstream portion of the specimen.

Received April 11, 1972; synoptic received June 27, 1972. Full paper available from National Technical Information Service, Springfield, Va., 22151, as N72-28569 at the standard price (available upon request). This research was supported by NASA Headquarters Contract NGR 31-001-230. The discussions with W. A. Sirignano during the progress of this work are gratefully acknowledged.

Index categories: Material Ablation; Reactive Flows; Nuclear Propulsion.

* Member of the Research Staff, Department of Aerospace and Mechanical Sciences. Member AIAA.

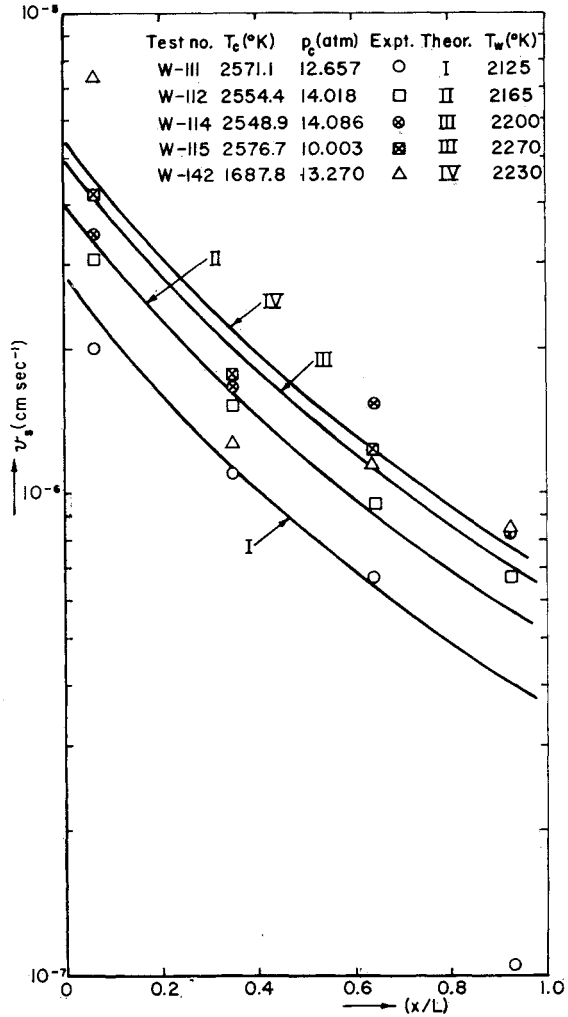

Fig. 1 Comparison of the computed and the measured erosion rates for different stagnation conditions.

In view of the reasonable agreements for the trends as well as magnitudes of the computed curves with the experimental points, the surface reaction model appears adequate in the prediction of erosion rates for specimen surface temperatures less than 3000°K. Further improvements in the model

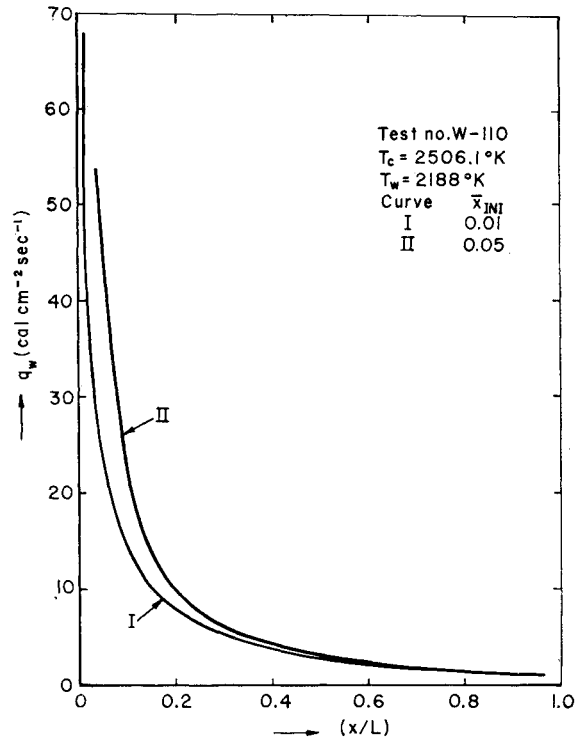

Fig. 2 Heat-transfer rate along the specimen surface.

can be achieved by including the dissociation and the turbulent effects as well as the coupled heat transfer problem within the specimen.

References

[1] Inouye, H. H., Claassen, L. B., and Shurley, L. A., "Final Test Report: AGCarb-101 Corrosion/Erosion Evaluation Program," 7750: R0834, April 1970, Aerojet Nuclear Systems Co., Sacramento, Calif.

[2] Clarke, J. T. and Fox, B R., "Reaction of Graphite Filaments with Hydrogen above 2000°K," *The Journal of Chemical Physics*, Vol. 46, No. 3, Feb. 1967, pp. 827–836.

[3] Lees, L., "Laminar Heat Transfer over Blunt-Nosed Bodies at Hypersonic Flight Speeds," *Jet Propulsion*, Vol. 26, No. 4, April 1956, pp. 259–269.

[4] Sharma, O. P. and Sirignano, W. A., "On the Ignition of a Pre-Mixed Fuel by a Hot Projectile," *Combustion Science and Technology*, Vol. 1, No. 6, May 1970, pp. 481–494.