Figure 1 shows a comparison of calculated temperature, pressure, and mass fraction of uncondensed vapor for both an exact (computer) solution and the present approximate solution. The calculations are for a zinc vapor in helium expansion. The stagnation chamber temperature and pressure, and mass fraction of zinc are 4500°K, 4500 psia, and 0.6, respectively. The frozen flow solution is shown for reference. If at each area ratio the latent heat used is adjusted for the change in local temperature, the present solution is very close to the exact solution far downstream of the saturation point as can be seen in the figure. The comparison indicates what might have been expected concerning the region of validity of Eq. (13). The plot of q at the bottom of the figure shows that by an area ratio of about 15, most of the vapor has been condensed and the present approximate solution is very good downstream of this point.

It can be seen from the figure that the difference in q between that predicted by the exact solution and by the present approximate one becomes small as q becomes small. This indicates that a quick check on the region of validity of the approximate solution can be made by calculating T from Eq. (13) and then computing q from Eq. (4) to see if q is indeed small enough for the solution to be valid.

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Ballistic-Range Measurements of Vibrational-Nonequilibrium Effects for Cone-Cylinders at Supersonic Speeds

George S. Campbell* and Paul C. Klimas†
University of Connecticut, Storrs, Conn.

Introduction

The strong dependence of shock-standoff distance on the degree of vibrational excitation and dissociation in the shock layer has been observed in several published papers. This aerodynamic effect was utilized by Schwartz and Eckerman[1] to determine the vibrational relaxation time of chlorine by firing small spheres in a ballistic range. Aerodynamic calculations for spheres are quite complicated, and so the use of cones with attached shock waves should facilitate comparison between theory and experiment. Ballistic-range experiments by Stephenson[2] were conducted with this in mind. The present studies were undertaken with objectives and experimental methods similar to those of Stephenson. They differ from the NASA studies primarily in the use of a diatomic gas that is much simpler than air and in the emphasis on flow near detachment.

The tests were conducted using 0.375-caliber models fired through a chlorine atmosphere at ambient pressures from 6 to 200 mm Hg. Mach numbers for the tests ranged from approximately 2 to 3, which includes the detachment region for the 45° cone cylinders chosen for the experiments. Many of the details of this investigation, along with numerous theoretical calculations, are given in Ref. 3.

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* Professor of Aerospace Engineering. Associate Fellow AIAA.

† NDEA Fellow; presently at Naval Air Systems Command, Washington, D. C.

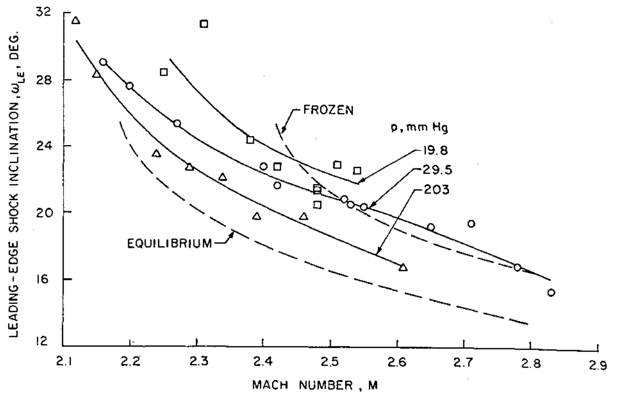

Fig. 1 Leading-edge shock-wave inclination for cone-cylinders in chlorine.

Measurements and Accuracy

The measurements reported in this Note were obtained by firing the cone-cylinder models through a test section containing chlorine and sealed by thin diaphragms. The cylindrical base of the models had a length to diameter ratio of 1.0, the model diameter being 0.375 in.

Commercially-supplied chlorine (Matheson Company High Purity Grade) was used in the experiments. Water contained in the gas was removed by passing the gas through a moisture absorbent containing phosphorous pentoxide. The maximum impurity level due to residual air in the test section was in all cases under 0.4 mm Hg. Pressure of the test gas was measured by a Texas Instruments Fused Quartz Pressure Gage Model #140 with an open-port Bourdon tube referenced to vacuum.

Model velocity was determined by the breaking of two printed-circuit papers separated by a known distance (12.12 in. ± 0.03 in.). The total random error of the velocity-measuring system is estimated to be 0.7%, an rms sum of errors associated with the triggering apparatus and the counter used to record the time interval. The second of the velocity-circuit papers triggered a Beckman and Whitley #5205 point light source with a light duration under 1 μsec. Other components of the schlieren system used to view the shock wave included two 5-in.-diam lenses, a knife edge, and a projection lens giving a 2:1 magnification at the film plane.

Results and Discussion

The effect of vibrational nonequilibrium on the shock-wave shape for the cone-cylinder models is shown in Fig. 1, which gives the leading-edge inclination of the shock wave over a range of Mach numbers at several values of ambient pressure. Repeated measurement of the inclination from the schlieren photographs generally resulted in values within 1° or 2° of the mean value plotted in Fig. 1. Also shown in Fig. 1 are equilibrium and frozen-flow predictions for an infinite cone using Dorodnitsyn's one-strip integral technique. The data shown in Fig. 1 exhibit the usual trend of increasing

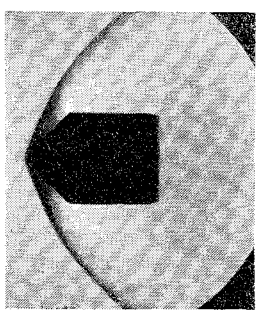

Fig. 2 Schlieren photograph of shock wave about cone-cylinder in chlorine at Mach number of 2.24 and ambient pressure of 202 mm Hg.

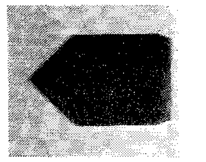

Fig. 3 Schlieren photograph of shock wave about cone-cylinder in chlorine at Mach number of 2.25 and ambient pressure of 5.9 mm Hg.

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

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

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.

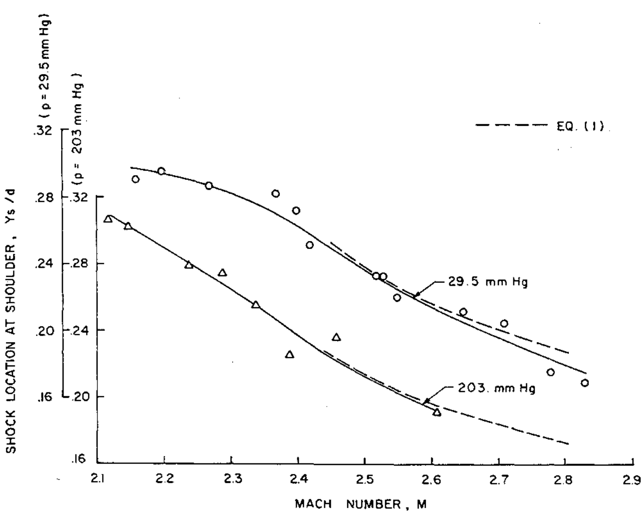

Fig. 4 Comparison of theory and experiment for shock-wave location at shoulder of cone-cylinder in chlorine.

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

John J. Bertin,* William D. Conine,† and Michael J. Nipper‡

University of Texas at Austin, Austin, Texas

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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* Assistant Professor, Department of Aerospace Engineering and Engineering Mechanics. Member AIAA.

† Graduate Student, Department of Aerospace Engineering and Engineering Mechanics. Member AIAA.

‡ Graduate Student, Department of Aerospace Engineering and Engineering Mechanics.