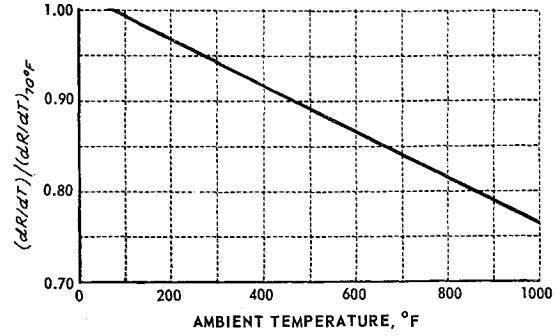

Fig. 1 Variation of thin film sensitivity with temperature.

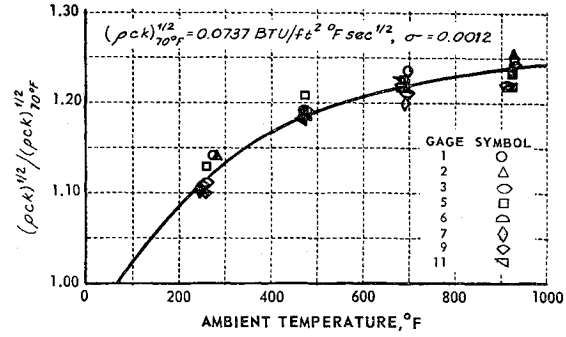

Fig. 2 Variation of $(\rho ck)^{1/2}$ with temperature #7740 Pyrex.

to 1000°F. To convert gage measurements to surface heat flux, it was necessary to make an accurate calibration in this temperature range of the electrical and thermal properties of the gage, which comprised a thin, platinum-alloy film deposited on a pyrex substrate.[2] These calibration results represent an extension in temperature range of similar measurements made by Skinner[3] who employed conventionally constructed gages that have an upper, steady-state temperature limit of approximately 400°F.

The calibration of the thermal properties of the pyrex substrate was accomplished using the electrical pulsing technique described by Skinner.[3, 4] Certain refinements were added to the circuit arrangement, and the method of reading the recorded data traces was modified.[2]

At a temperature of 70°F, the mean value of $(\rho ck)^{1/2}$ (where ρ is density, c is specific heat, and k is thermal conductivity) for pyrex was measured as 0.0737 Btu ft^{-2} °F^{-1} sec$^{-1/2}$ with a standard deviation from the mean of 0.0012. This value is in close agreement with 0.0743 ± 5% reported by Skinner and 0.074 ± 16% reported by Vidal.[5] These data indicate a high degree of uniformity in the properties of pyrex specimens and further justify the widespread use of pyrex as a gage substrate.

To measure the variation of $(\rho ck)^{1/2}$ with temperature in the interval to 1000°F by the technique indicated, it was necessary to account for the nonlinearity in the resistance-temperature characteristic of the thin platinum films.† Thus for a unit change in temperature, the change in film resistance would be expected to be function of the ambient temperature. Gage resistance-temperature measurements were taken in the range to 1000°F, and a least-squares function fitted to these data. A second-degree equation in temperature provided a satisfactory fit. By normalizing the change in gage sensitivity (i.e., the incremental change in resistance for an incremental change in temperature dR/dT), very little numerical deviation between gages was found. Accordingly, the gage data were pooled into one composite relation that is plotted in Fig. 1 and described by Eq. (1)

$$(dR/dT)/(dR/dT)_{70°F} = 1.018 - 2.59 \times 10^{-4}T \quad (1)$$

where T is the ambient temperature in degrees Fahrenheit.

The data of Fig. 1 contrast with the results given in the pertinent references cited,[3-5] where dR/dT was taken as a constant to temperatures of 400°F. It is probable that the restricted temperature range in which these investigations were made (400°F was the approximate maximum steady-state value attained) obscured the temperature effect reported here.

Applying corrections for changes in gage sensitivity with temperature, the normalized variation of $(\rho ck)^{1/2}$ with temperature was evaluated. The results, summarized in Fig. 2, represent a smaller effect of temperature and exhibit less scatter than has been reported previously. For example, in the range where a comparison of results is possible, Skinner[3] and Hartunian[6] determined the mean $(\rho ck)^{1/2}$ ratio at 400°F as 1.375 and 1.54 (extrapolated), respectively, compared with a mean of 1.165 given in Fig. 2. One factor that accounts partially for the smaller thermal dependence is the correction applied for the decrease in gage sensitivity with temperature.

The data in Figs. 1 and 2 are important to the interpretation of measurements taken with thin-film resistance thermometers in applications at elevated steady-state temperatures and when large amplitude transient temperatures are involved.

† Liquid Bright Platinum solution #05-X, Hanovia Liquid Gold Division, East Newark, N. J.

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Hypervelocity Stagnation Point Heat Transfer in a Carbon Dioxide Atmosphere

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Nomenclature

P_w = stagnation point wall pressure
P_3 = pressure behind bow shock of model
R_N = model nose radius
V_3 = flow velocity behind bow shock of model
V_f = simulated flight velocity
ρ_3 = density behind bow shock of model

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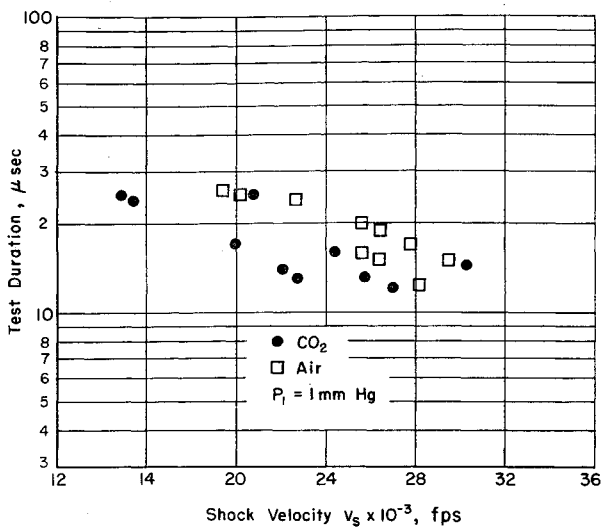

Fig. 1 Test duration measurements at a position 15 ft from the diaphragm station.

IN order to design planetary atmospheric re-entry vehicles, it is important that the presently available theoretical solutions for the re-entry heat transfer problem be verified for atmospheres other than air. Thus, there have been several experimental investigations[1, 2] of stagnation point heat transfer in a carbon dioxide atmosphere. These investigations for the most part have been limited to simulated flight velocities of 26,000 fps and less.

The original interest in carbon dioxide stemmed from the high percentage of CO_2 which was believed to make up the atmosphere of Venus. Although this is not believed to be the case now, the problem of convective heat transfer in a CO_2 atmosphere is still of interest from the viewpoint of understanding the general planetary re-entry heating problem. Thus, this present investigation was undertaken in which stagnation point convective heating measurements were made in a high-enthalpy, carbon dioxide, shock-tube-generated flow at simulated flight velocities ranging from 24,000 to 36,000 fps.

The facility used for these measurements was the Ohio State University arc driven shock tube.[3] This is a constant area shock tube having a 4-in. i.d. and driven by a 200,000-j capacitor bank discharging through a coaxial electrode arrangement. The driver gas is normally helium. The driven tube, 28 ft in length, terminates in a dump tank, and the high-enthalpy, supersonic free-jet at the driven tube

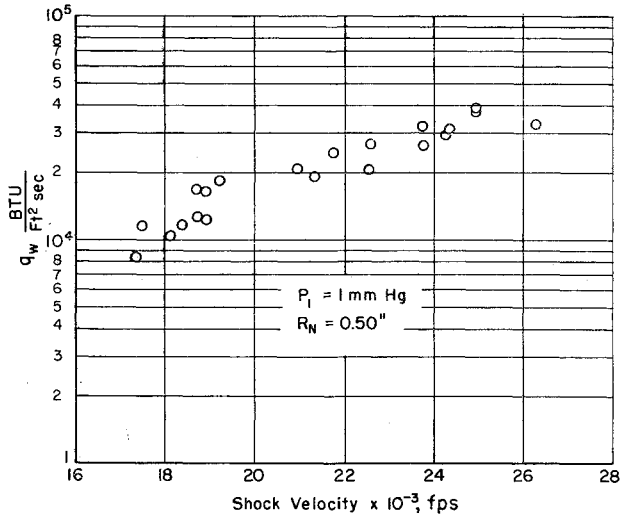

Fig. 2 Experimental stagnation point heat transfer measurements in a carbon dioxide atmosphere.

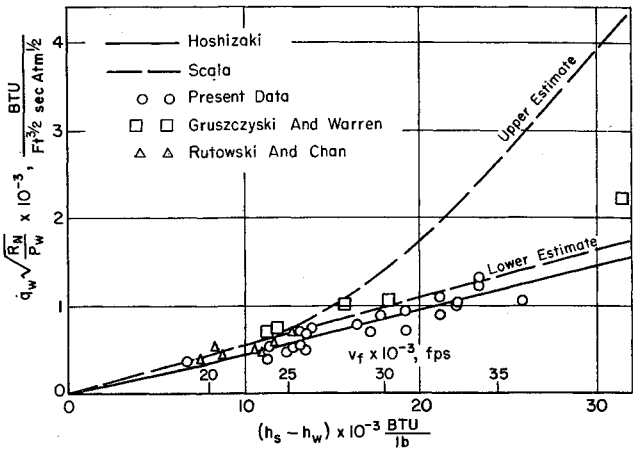

Fig. 3 Comparison of experimental heat transfer data and theoretical predictions.

exit was used as the test region during this experiment. Shock velocity measurements were made through the monitoring of ionization probes flush-mounted in the wall of the tube. Although no test duration measurements were specifically made during these experiments, a previous investigation of test durations in a shock tube using carbon dioxide indicated that adequate test times were available. These results, shown in Fig. 1, were obtained at a distance of 15 ft from the diaphragm station through the monitoring of radiative emission with a photomultiplier. Since the present measurements were performed at a distance of 28 ft from the diaphragm, a longer test time would be expected.

The procedure used to produce a carbon dioxide atmosphere for testing was first to evacuate the shock tube to a pressure on the order of 50 μ, then fill the tube with CO_2 to a pressure of approximately 1 atm, and finally to evacuate the tube to the operating pressure of 1 mm Hg. Since the leak rate of the tube is relatively low, on the order of 5 to 10 μ/min, the percentage of CO_2 in the test gas in all cases was greater than 98%.

Calorimeter-type heat transfer gages mounted at the stagnation point of a 1-in.-diam pyrex sphere were used in this investigation. The calorimeter gages were 0.001-in.-thick platinum, and the general circuit arrangement was quite similar to that described in Ref. 4. In analyzing the data, the results of the dynamic calibrations reported in Ref. 4 were used.

The stagnation point convective heat transfer results obtained in this investigation are shown in Fig. 2. The present results were obtained at a driven tube pressure of 1 mm Hg. These same data are presented in a parametric form in Fig. 3 and compared with other available data[2, 5] and also with the theoretical predictions of Scala[5] and Hoshizaki.[6] In computing the theoretical heat transfer rate as predicted by Hoshizaki, the velocity gradient was evaluated using a modified Newtonian pressure distribution. The flow properties were determined from Refs. 7 and 8 with the stagnation point pressure P_w being approximated as equal to $P_3 + \frac{1}{2}\rho_3 V_3^2$. Although there is considerable scatter in the data, general agreement does exist between the present data and the theoretical predictions. It also can be seen that the present data are in general agreement with the earlier results of Rutowski and Chan[2] (in which the gas mixture was 90% CO_2, 10% N_2) and the recently published results for CO_2 of Gruszczynski and Warren.[5]

It should be noted that there are apparently no serious ionization effects at enthalpy levels up to 25,000 Btu/lb. At higher enthalpies, the data of Ref. 5 obtained using various mixtures of carbon dioxide, nitrogen, and argon indicate an increase in convective heating greater than that predicted by theory. However, these data are open to question because of a possible lack of adequate test time. Thus, it is

felt that the present theories, such as shown in Fig. 3, are adequate for the prediction of stagnation point heating during planetary re-entry at flight velocities up to the order of 35,000 to 40,000 fps.

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Thermal Ionization behind Strong Shock Waves

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Introduction

THIS paper is concerned with the flow of an ideal ionizing gas[1, 2] through a strong normal shock wave under nonequilibrium conditions. The present analysis is similar to that used by Freeman[3] for the flow of an ideal dissociating gas through a strong normal shock wave. The Bray and Wilson equation[4] for the net rate of ionization is used so that the approach to a final equilibrium ionization level behind the shock wave can be predicted. The concept of different temperatures for atoms (ions) and electrons is taken into account by considering the conservation of energy for electrons. The present paper thus formulates the strong shock problem for the ideal ionizing gas so as to allow one to determine the nonequilibrium flow properties and, in particular, the nature of the variation of the two temperatures as they approach equilibrium.

Flow through a Normal Shock Wave

In order to determine the variation of the shock parameters in the nonequilibrium region behind the shock, it is necessary to formulate the conservation laws for an ideal ionizing gas. In a coordinate system moving with the shock front, the flow is steady. Thus, the fluxes of mass, momentum, and energy across any plane behind the shock front must be equal to the same fluxes across a similar plane ahead of the shock wave. Using the concept of the ideal ionizing monatomic gas,[1, 2] these three conservation equations can be written for strong shock waves as follows:

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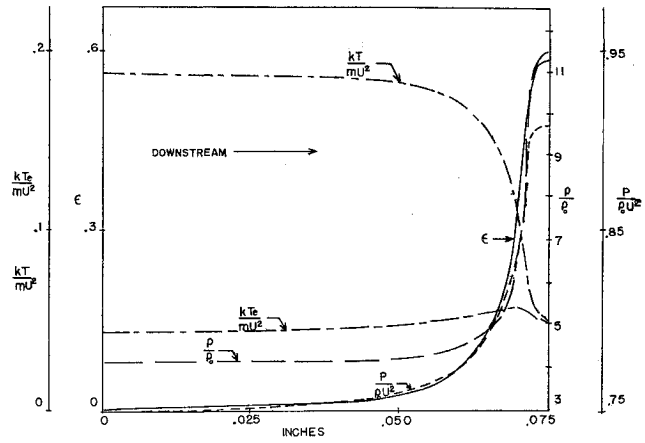

Fig. 1 Results of two-temperature analysis for strong shock ($\lambda = 1$ and $\rho_0/\rho_{ion} = 1.7 \times 10^{-7}$).

Mass

$$\rho u = \rho_0 U \tag{1}$$

Momentum

$$p + \rho u^2 = \rho_0 U^2 \tag{2}$$

Energy

$$i + (u^2/2) = U^2/2 \tag{3}$$

where the enthalpy of the gas is

$$i = \tfrac{5}{2}(k/m)[T + \epsilon T_e] + (k/m)T_{ion}\epsilon \tag{4}$$

In these equations, ρ_0 and U are the given values of density and velocity ahead of the shock, and p, ρ, and u are the pressure, density, and velocity behind the shock front. In Eq. (4), k is Boltzmann's constant, m the mass of the atom, T the temperature of the atoms and ions, T_e the electron temperature, ϵ the degree of ionization, and T_{ion} the ionization potential of the gas in degrees Kelvin. In the region behind the Rankine-Hugoniot shock front, the gas is assumed to be inviscid and without heat conduction and radiation energy flux.

The equation of state is

$$p/\rho = (k/m)[T + \epsilon T_e] \tag{5}$$

Two additional equations are required to specify the thermodynamic quantities completely, namely, an equation for the net rate of ionization and an equation relating the two temperatures T and T_e.

Since the flow is steady, the changes are purely convective, and the equation for the net rate of ionization in the nonequilibrium region can be written in the form[4]

$$u\frac{d\epsilon}{dx} = A\rho^*\epsilon(1-\epsilon)T_e^{*3/2}\left(\frac{T_{exc}}{T_e}+2\right)\exp\left(-\frac{T_{exc}}{T_e}\right) - A\rho^{*2}\epsilon^3\left(\frac{T_{exc}}{T_e}+2\right)\exp\left(\frac{T_{ion}}{T_e}-\frac{T_{exc}}{T_e}\right) \tag{6}$$

where x is a coordinate measured normal to the shock wave in the downstream direction and u is the velocity of the gas in this direction. In Eq. (6), T_{exc} is the energy of the first excited state of the gas expressed in degrees Kelvin, A is a constant (for argon, $A = 3.349 \times 10^{16}$ sec^{-1}), and the dimensionless density ρ^* and temperature T_e^* are defined as[2]

$$\rho^* = \rho/\rho_{ion} \qquad T_e^* = T_e/T_{ion} \tag{7}$$

In Eq. (7), ρ_{ion} is the characteristic density and, for argon, has the value $\rho_{ion} = 2.9326 \times 10^2$ slugs/ft^3.