effort also will be continued to determine the power and flow range over which the thruster design may be operated successfully.

Conclusions

Although there are a number of difficult problems associated with the development of a plasmajet thruster in the 1-kw size range, it has been demonstrated that satisfactory performance (1100 sec with 35% efficiency) can be attained. The problem of obtaining satisfactory life with the small physical dimensions involved is particularly difficult and will require continued development of the unit.

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Experiments on Recombination Effects in Rocket Nozzles

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Rocket engine experiments with the RP-1/oxygen propellant system are described. Essentially, the experiments consist of measurement of flow rates, chamber pressure, nozzle pressure profile, and static gas temperature in a large (30:1) expansion ratio nozzle. The measured static pressures and temperatures are compared to theoretical predictions for frozen (chemical reaction inhibited) and equilibrium expansion processes. It is found that near-frozen conditions exist at low (below 1.6) oxidizer-to-fuel (O/F) ratios, and near-equilibrium conditions exist at higher (above 2.0) O/F ratios. The measurements at the higher O/F ratios agree with predictions based upon partial-equilibrium calculations using available reaction rate data from laminar flame and shock tube studies. The near-frozen experimental pressures at low O/F ratios indicate that solid carbon and methane (expected from equilibrium calculations) were not produced sufficiently fast to maintain chemical equilibrium.

ROCKET engine performance is usually quoted in terms of the two limiting cases of frozen or shifting equilibrium nozzle expansion processes. Frozen expansion results if all reaction rates are so slow that the combustion products are exhausted before chemical reaction can occur. Shifting equilibrium results if all reactions proceed fast enough in the nozzle that the local chemical composition everywhere is that associated with thermodynamic equilibrium. Although the difference between frozen and equilibrium expansion is frequently important, the number of possible reaction paths and the paucity of applicable rate data have discouraged analytical determination of the exact conditions to be expected with even the most common propellant systems. Definitive experiments also appear to be lacking, although some data on this subject have appeared recently and will be discussed later.

As part of a study of recombination and condensation effects in rocket nozzles,[4] experiments have been performed to provide quantitative data on recombination effects. The results of these experiments, along with techniques for predicting and detecting recombination effects, are described in this paper.

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Experimental Equipment

A rocket engine of nominal 1000-lb thrust level provides the desired stagnation pressure (usually 400 psia) and temperature (2000° to 3700°K) conditions. The only unusual feature of this engine is its relatively large combustion chamber, characterized by an L^* (ratio of chamber volume to throat area) of 125 in. This large chamber provides relatively complete combustion as evidenced by experimental characteristic velocities that average 98.3% of the theoretical equilibrium values for uncooled chamber operation (average deviation of 1.5%). Although the engine is equipped to handle a variety of liquid, gas, and slurry propellants, RP-1 fuel and gaseous oxygen were used for these experiments.

The products of combustion are expanded in a conical nozzle of 15° half angle, 1.25-in. throat diameter, and 30:1 exit area ratio. The nozzle is made of copper and is water-cooled at the throat. The nozzle exhaust is discharged at a pressure of about 0.1 atm into a supersonic diffuser section that exhausts into the atmosphere.

Information on conditions in the nozzle is obtained from both a series of static pressure measurements between the throat and the nozzle exit and static temperature measurements obtained at various stations. The pressure ports are connected to transducers through a commutating system that allows a single transducer to sense a number of pressures. The transducer outputs are recorded by an oscillograph.

Static temperature measurements have been obtained using both manual and automatic sodium-line reversal tech-

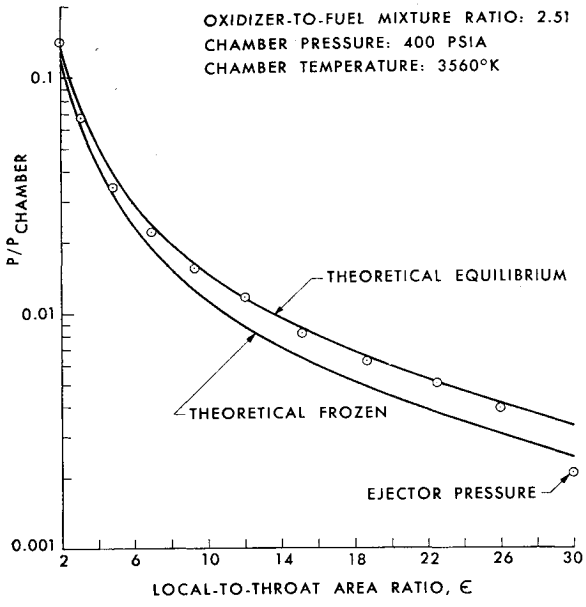

Fig. 1 Static-pressure ratio vs area ratio

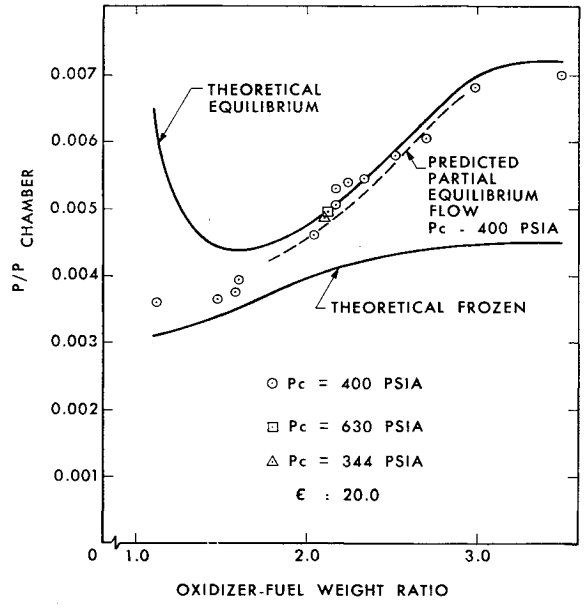

Fig. 2 Static pressures at a local-to-throat area ratio of 20

niques (1).[5] Early measurements were obtained manually; i.e., an operator, using a laboratory stand spectroscope, observed the sodium D-line intensity emitted by the flame (which had previously been seeded with minute amounts of sodium) against the continuous background of radiation provided by a tungsten ribbon-filament lamp. These emission and transmission measurements were made through quartz windows located at a local-to-throat area ratio of 20. During the run, the operator manually varied the lamp intensity until the condition of reversal was obtained. Subsequent temperature measurements have been made using an automatically recording photoelectric spectrometer (2). This apparatus was specially built to provide an alternating rapid scan capability; that is, it observes two different wavelengths for equal periods of time, and travel between the wavelengths is essentially instantaneous. Thus, reversal temperature measurements are obtained by observing successively the spectral line wavelength and then an adjacent wavelength.

Experimental Results

Data have been obtained for the RP-1 oxygen system at oxidizer-to-fuel ratios between 1.12 and 3.49. Two of the tests were at chamber pressures of 345 and 630 psia, whereas the remaining runs were at a nominal chamber pressure of 400 psia.

A typical pressure profile is shown in Fig. 1, wherein the attainment of equilibrium conditions is indicated. Fig. 2 presents a summary of the pressure data interpolated from the pressure profiles at an area ratio of 20. These data indicate that equilibrium conditions exist for oxidizer-to-fuel ratios above 2.0 but that large departures from equilibrium pressures occur below an oxidizer-to-fuel ratio of 1.6.

The corresponding temperatures measured by the manual sodium-line reversal technique at area ratio 20 are presented in Fig. 3. These data substantiate the pressure measurements in indicating equilibrium flow in the nozzle for O/F ratios above 2.0. These particular data were obtained through windows, since the low nozzle static pressure at area ratio 20 would not permit open observation ports. The fact that the experimental values are about 150° to 200°K higher than the predicted values (see below) may readily be ascribed to the deposition of soot on the windows. Soot deposition has the effect of lowering the relative intensity of the comparison source, which must pass through two windows, and thus the operator must increase the lamp intensity, recording a higher-than-actual value of lamp current and therefore lamp and flame temperature. In fact, at O/F ratios below 2.0, the windows became completely obscured, accounting for the lack of data at these low mixture ratios.

The theoretical equilibrium and frozen pressures and temperatures shown in Figs. 1–3 are calculated for one-dimensional isentropic flow. The effects of boundary layer displacement thickness, viscous dissipation and heat transfer, and nonaxial flow have been examined. Provided that the boundary layer momentum and energy thicknesses are small compared with the nozzle radius (and are of the order of the displacement thickness), the freestream properties are correctly given by regarding the flow area as reduced by the displacement thickness.

The displacement thickness effect was computed for a typical case and was found to be small compared to the difference between frozen and equilibrium flow. The effect of nonaxial flow was evaluated by considering the actual flow to be source-like, i.e., radial. This causes a pressure correction opposite to that of the displacement thickness and

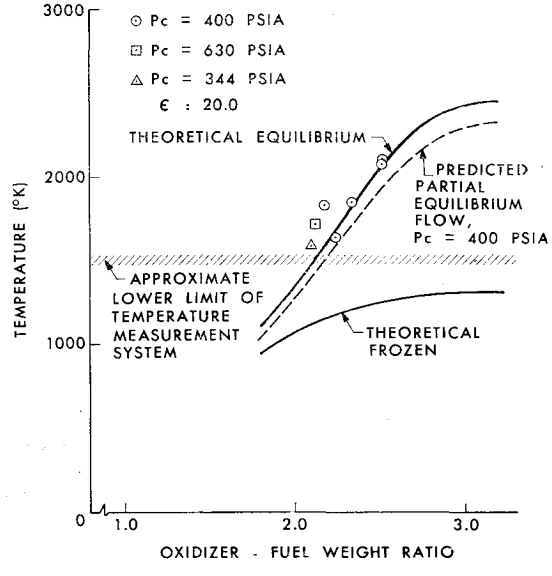

Fig. 3 Static temperatures at a local-to-throat area ratio of 20

[5] Numbers in parentheses indicate References at end of paper.

Table 1 Chemical composition (moles per 100 g) and reaction enthalpy release (percent of stagnation enthalpy) of RP-1/GOX in a rocket nozzle

O/F		H	OH	C(s)	CO_2	O	O_2	CH_4	$\Sigma\Delta H/H_s$, %	T, °K	P_{eq}, atm
1.3	Chamber	0.0081	...	...	0.081	...	...	0.0001	...	2054	27.2
	$\epsilon = 20$	...	...	0.42	0.565	...	...	0.054	...	890	0.142
	$\Delta H/H_s$ released, %	0.1	...	12.9	0.2	...	...	2.4	15.6	...	...
1.8	Chamber	0.100	0.032	...	0.274	0.0016	0.0005	...	...	3083	27.2
	$\epsilon = 20$	...	...	...	0.720	...	...	...	...	1110	0.123
	$\Delta H/H_s$ released, %	3.7	1.5	...	1.7	0.13	0.04	...	7.1	...	...
2.3	Chamber	0.180	0.206	...	0.505	0.041	0.037	...	...	3499	27.2
	$\epsilon = 20$	0.0005	...	...	0.790	...	...	...	...	1750	0.146
	$\Delta H/H_s$ released, %	5.7	8.0	...	0.89	2.9	2.6	...	20.1	...	...
2.8	Chamber	0.154	0.329	...	0.655	0.103	0.168	...	...	3586	27.2
	$\epsilon = 20$	0.025	0.033	...	1.065	0.003	0.009	...	...	2370	0.180
	$\Delta H/H_s$ released, %	3.8	11.1	...	1.3	6.6	10.5	...	33.3	...	...

about one half as large. The effect of radiative heat transfer from the freestream was estimated and found to be smaller than the other corrections. Because of the relatively minor nature of these corrections and the fact that they tend to cancel one another, they have been neglected in comparing the experimental pressure data with the theoretical predictions.

The effect of nonaxial flow on the temperature measurements is of somewhat more significance, however. If a radial gas flow pattern exists in the nozzle, the temperature of the gas on the nozzle axis is about 30°K higher (at an area ratio of 20) than the gas temperature just outside the boundary layer. Since sodium-line reversal temperatures are weighted toward the high temperature regions of nonuniform temperature distributions, the measured temperatures are estimated to be about 20°K higher than the temperatures given by the one-dimensional flow calculations. The temperatures shown in Fig. 3 have been corrected accordingly. The effect of the higher temperatures within the boundary layer has been investigated and will be discussed later.

Certain other sources of error have been investigated and accounted for. A correction for the effect of the low nozzle pressure on the line intensity [due to a low-pressure departure from equilibrium between collision-induced emission and spontaneous emission (3,4)] has been made, as well as corrections for differences in wavelength between the wavelength of calibration of the comparison source and the wavelength of spectral observation of the flame. The vibrational relaxation time of the exhaust gas under these experimental conditions is sufficiently short that the emission from excited sodium atoms (apparently related to the vibrational temperature of the gas, Ref. 5) may be considered to be a direct measurement of the translational temperature.

Comparison with Theoretical Predictions

The data presented in Figs. 2 and 3 show nearly equilibrium conditions at O/F ratios above about 2.0 and nearly frozen conditions for O/F ratios below about 1.6. The theoretical equilibrium expansion conditions are computed (on a digital computer) using the technique of free energy minimization (6).

A comparison of the concentration of calculated species in the chamber with those at area ratio 20 for an equilibrium expansion shows that reaction energy is released by recombination of hydrogen atoms and hydroxyl radicals, by combustion of carbon monoxide, by burning of H_2 with O and O_2 (at high O/F ratios), and (at low O/F ratios) by formation of methane and solid carbon. The change in mole number per 100 g of propellant of H, OH, CO_2, O, O_2, CH_4, and C (solid) between the chamber and area ratio 20 is given in Table 1 for several O/F ratios. Also given are rough values of the enthalpy release associated with the change in mole number, assuming the following overall reactions and corresponding heats of reaction (at 2500°K):

$H \rightarrow \frac{1}{2} H_2$	54 kcal/mole
$OH + \frac{1}{2} H_2 \rightarrow H_2O$	69 kcal/mole
$CO + H_2O \rightarrow CO_2 + H_2$	5.5 kcal/mole
$2\ CO \rightarrow C(s) + CO_2$	36 kcal/mole
$O + H_2 \rightarrow H_2O$	121 kcal/mole
$O_2 + 2\ H_2 \rightarrow 2\ H_2O$	121 kcal/mole
$CO + 3\ H_2 \rightarrow CH_4 + H_2O$	51 kcal/mole

The third and fourth reactions must be taken together in determining the enthalpy release associated with production of CO_2 in the nozzle. The reaction enthalpy release is normalized by the stagnation enthalpy of the gas and recorded in Table 1 as a percentage.

A survey of the literature (6-17) on reaction rates has been made, and the most rapid reaction mechanism has been selected for each overall reaction. These have been used in the present calculations and are listed in Table 2. The reaction rates given here should be treated as lower limits to the true reaction rates. Data and reaction schemes that are obtained in the future may provide faster reaction mechanisms but will not reduce the rates of the reaction mechanisms that have been used here.

The reaction rate constants are defined in terms of the rate of change in mole number of one of the products of reaction; that is, for $A + B + C \xrightarrow{k} AB + C$

$$\rho DX_{AB}/Dt = \rho u(dX_{AB}/dx) = k[A]\ [B]\ [C]$$

where ρ is the mass of gas per unit volume, u the gas velocity, X_{AB} the mole number of AB per unit mass of gas, $[A]$ the concentration of specie A in moles per unit volume, and x the axial nozzle coordinate.

The formation of methane in the nozzle requires a kinetic mechanism involving reduction of CO or CO_2 by H_2O or H_2. Some information on the reverse reaction (oxidation of methane to form carbon monoxide) has been obtained at high temperature (16,17). However, there is not sufficient information on the reaction mechanism from which to predict the rate of formation of methane from the products of RP-1/GOX combustion, nor is there sufficient information concerning the kinetics of solid carbon formation to predict the rate of formation of carbon in the nozzle used in these experiments. It can be concluded, from the near-frozen experimental pressures at low O/F ratios, that the net rate of carbon formation is too slow to maintain equilibrium expansion under these conditions of temperature, pressure, and nozzle expansion rate.

Table 2 Reactions and reaction rate constants used in RP-1/GOX nozzle flow

Reaction	Rate constant	References
(1) $H + H + H_2O \xrightarrow{k_1} H_2 + H_2O$	$k_1 = 7.6 \times 10^{15}$ cm^6/mole^2-sec	7–9
(2) $H + OH + H_2O \xrightarrow{k_2} H_2O + H_2O$	$k_2 = 1.6 \times 10^{17}$	7–9
(3) $H + H_2O \xrightarrow{k_3} OH + H_2$	$k_3 = 1 \times 10^{15} e^{-(25{,}000)/RT}$ cm^3/mole-sec	10,11
(4) $H + O_2 \xrightarrow{k_4} OH + O$	$k_4 = 5 \times 10^{14}\, e^{-(18{,}000)/RT}$	12,13
(5) $H_2 + O \xrightarrow{k_5} OH + H$	$k_5 = 3 \times 10^{14}\, e^{-(6000)/RT}$	13,14
(6) $CO + OH \xrightarrow{k_6} CO_2 + H$	$k_6 = 5 \times 10^{12}\, e^{-(7000)/RT}$	15

The reaction rates listed in Table 2 have been compared with the reaction rates required to maintain equilibrium at each point in the nozzle. For the gas properties of interest here, it can be shown that reactions 3–5 are sufficiently rapid that they are maintained in quasi-equilibrium; i.e., the forward rate is very nearly equal to the reverse rate. The rate limiting reactions are then 1, 2, and 6. Reactions 1 and 2 together accomplish the conversion of O, O_2, H, and OH to H_2 or H_2O. The available rate of conversion is

$$\rho u(d/dx)\{X_H + X_{OH} + 2X_{O_2} + 2X_O\}_{av} = [H_2O][H]\{2\,k_1[H] + 2\,k_2[OH]\} \quad [1]$$

This must be compared with the total required rate of conversion in the nozzle

$$\rho u(d/dx)\{X_H + X_{OH} + 2\,X_{O_2} + 2\,X_O\}_{req} \quad [2]$$

Wherever the required rate is much less than the available rate, equilibrium conditions will exist in the expansion. If the available rate drops below the required rate, the conversion cannot continue rapidly enough to maintain equilibrium, and the sum $(X_H + X_{OH} + 2\,X_{O_2} + 2\,X_O)$ will remain nearly constant. Reactions 3–5 may continue to shift the individual values, X_H, X_{OH}, X_{O2}, X_O, but without affecting the foregoing sum. Little energy is transferred in these exchange reactions, and there is no change in the molecular weight of the gas. Therefore, the subsequent nozzle expansion will behave as though the species concentrations were frozen. Following Bray (18), it is assumed that the species concentrations are frozen at the point at which the available reaction rate equals the required rate.

The same comparison is made of the available rate of conversion of CO to CO_2 by reaction 6 with the rate of conversion required to maintain equilibrium expansion.

It is found that the available and required conversion rates of H, OH, O, and O_2 cross over further upstream in the nozzle than do the conversion rates of CO. Beyond the first crossover point, the partial freezing of OH increases the available rate of conversion of CO (via reaction 6) above the value calculated by using the (lower) equilibrium expansion concentration of OH. This shifts the second crossover point further downstream. Taking the first crossover point and the shifted second crossover point, the enthalpy that is expected to be frozen out is computed as before and presented in Table 3 as a percentage of the stagnation enthalpy.

The quantity ϵ_1 in Table 3 is the approximate expansion area ratio at which the required and available rates of conversion of H, OH, O, and O_2 are equal. The quantity ϵ_2 is the approximate value of the expansion area ratio for which the required and available rates of production–conversion of CO are equal, based on nonequilibrium concentration of OH.

The influence of freezing of the reactions on the subsequent flow properties in the nozzle can be taken into account by an approximate theory based on small perturbations of the equilibrium nozzle flow. The nozzle flow associated with freezing of the reactions is treated as a nozzle flow with heat loss and a decrease in the molecular weight when compared to equilibrium flow. The decrease in temperature is given by (19)

$$\frac{d(\Delta T)}{T} = \frac{dh}{C_pT}\left[1 + \frac{\gamma - 1}{1 - 1/M^2}\right] - \frac{dW}{W}\,\frac{\gamma - 1}{1 - 1/M^2} \quad [3]$$

where ΔT is the difference between the gas temperature for reaction rate limited nozzle expansion and that for complete equilibrium expansion. Assuming small changes in temperature, Eq. [3] can be integrated numerically according to

$$\frac{T_k - T_e}{T_e} = \frac{\Delta T}{T_e} = \int_{\epsilon_f}^{\epsilon} \frac{dh}{C_{p_e}T_e}\left[1 + \frac{\gamma - 1}{1 - 1/M_e^2}\right] - \int_{\epsilon_f}^{\epsilon} \frac{dW}{W}\,\frac{\gamma_e - 1}{1 - 1/M_e^2} \quad [4]$$

where subscript e represents equilibrium flow conditions, ϵ_f is the area ratio at the freezing point in the nozzle, T_k is the gas temperature obtained from this kinetic calculation, dh and dW are heat loss and decrease in molecular weight (defined by Shapiro, Ref. 19, to be positive for heat addition and molecular weight increase) due to the freezing of the reactions. The change in the gas velocity beyond ϵ_f is then computed from the energy conservation equation in the form

$$\frac{\Delta u}{u_e} = \frac{\Delta h - C_{p_e}\Delta T}{u_e^2} \quad [5]$$

The change in gas pressure is computed by using the gas law and conservation of mass to obtain

$$\Delta p/p_e = -(\Delta u/u_e) + (\Delta W/W) + (\Delta T/T_e) \quad [6]$$

The results of computations for the RP-1/oxygen system are shown in Figs. 2 and 3 along with the experimental data. Generally good agreement between the calculations and the experimental data is found to exist. An increase in the reaction rates 1 and 2 (k_1 and k_2) by a factor of 3 would cause the predicted conditions virtually to coincide with the conditions for an equilibrium expansion.

An exact method of calculating specific impulse for the nonequilibrium case approximated by the Bray criterion is presented by Baier, Byron, and Armour (20).

Table 3 Approximate enthalpy (percent) expected to be frozen in RP-1/GOX nozzle flow

O/F	H	OH	CO_2	O	O_2	$\Sigma\Delta H/H_s$, %	ϵ_1	ϵ_2
1.8	0.4	0.1	1.4	...	...	1.9	1.6	2.4
2.3	1.8	1.7	...	0.2	0.2	3.9	2.5	>20
2.8	1.2	3.5	...	1.4	3.7	9.8	4.2	>20

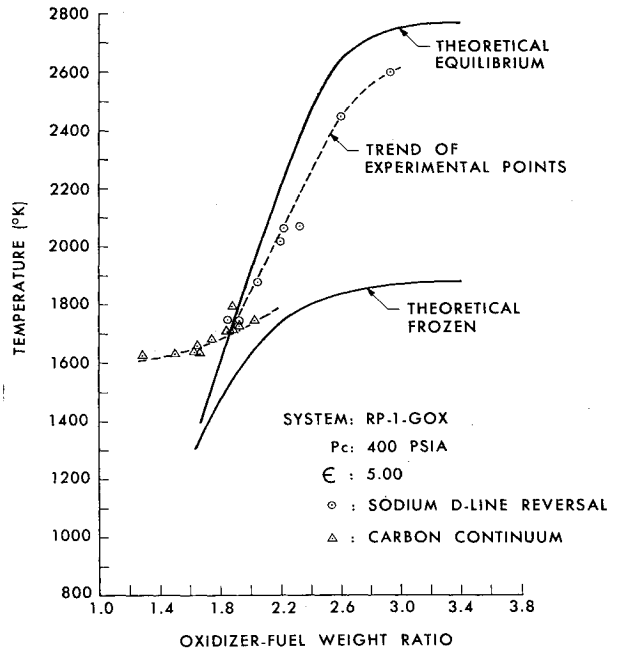

Fig. 4 Temperature as a function of oxidizer-to-fuel ratio: optical observations through ports

Discussion

Publications by Simmons (21) and Simmons and De Bell (22) have reported nozzle exit temperature trends associated with frozen expansion values at O/F ratios above 2.2, between equilibrium and frozen values at O/F ratios varying from 1.8 to 2.2, and in excess of both equilibrium and frozen theoretical values at O/F ratios below 1.8, which results are in disagreement with the data presented here as well as those of Ferriso (23). Simmons' results were obtained by attributing the static gas temperature to measured values of the carbon particle temperature. He postulated that these results implied the existence of frozen flow. The fact that Simmons' temperatures at higher O/F ratios exceeded in magnitude the theoretical frozen values was attributed to additional burning of the exhaust products in their passage through the nozzle. As for measured temperatures exceeding both theoretical frozen and theoretical equilibrium at low O/F ratios, Simmons and De Bell suggested that this was caused by a failure of assumptions made in the thermochemical calculations of the theoretical values.

A more likely explanation is that boundary layer or mixing layer effects may control observed temperatures based on any optical technique when the O/F ratio is low, and that measurements based on the presence of carbon or other condensed phases will be in error for high O/F ratios at which these condensed phases will not exist in the freestream in quantity. The former effect seems plausible when one considers that temperatures at some regions of the boundary layer will be much higher than in the freestream, and emission from the freestream may be entirely overcome when the freestream static temperature is low; even an optically thin emission zone at high temperature may overcome a much more optically thick zone at low temperature. This same restriction applies to measurements based on emission from atomic emitters, since emission from cold freestream emitters will be overcome by those in the hotter regions of the boundary layer.

The second effect, that is, the error inherent in temperature measurements based on carbon emission at higher O/F ratios, may be attributed to the lack of carbon in the hot freestream. Equilibrium calculations (24) predict that appreciable amounts of solid carbon will not exist in the freestream of the RP-1-gaseous O_2 propellant system at O/F ratios above 1.8. Observed carbon particle emission at O/F ratios greater than 1.8 can therefore be expected to originate from cooler regions of the flow where quantities of condensed carbon may be present. Such regions may exist, for example, in the cooler portions of the boundary layer or in the mixing layer beyond the nozzle exit. Emission from carbon in these regions may then produce the observed values if the amount of solid carbon in the hotter freestream is insufficient to produce enough continuum radiation to overcome the boundary layer emission. Other methods, such as the sodium D-line reversal technique, will still retain their validity provided the presence of the emitting species in the freestream is assured regardless of the temperature.

In order to test this hypothesis, a series of measurements using both the sodium D-line reversal and carbon emission techniques was obtained. These tests used an atmospheric exhaust nozzle with an area ratio of 7.66. Temperature measurements were obtained with an automatic recording spectrometer (25) through windowless ports located at area ratio 5, where the nozzle static pressure is close to atmospheric pressure for the operating conditions of these tests. The lack of a pressure potential across the window allowed the supersonic nozzle flow to bridge the gap without any measurable flow disturbances appearing.[6]

The results of these tests are shown in Fig. 4. Sodium D-line measurements yielded temperatures in good agreement with theoretical kinetic predictions at O/F ratios above 1.8. Below 1.8, the sodium D-lines were not strong enough to provide reliable temperatures. Carbon emission measurements indicated temperatures that followed a trend similar to that reported by Simmons, although no carbon emission was observed above an O/F ratio of 2.1.

These results support the argument advanced; that is, that boundary layer emission is controlling at low O/F ratios, but only species existing in the freestream may be relied upon for temperature measurements at higher O/F ratios.

Conclusions

1 Pressure and temperature measurements in the expansion nozzle are in good agreement with theoretical predictions if proper account is taken of the reaction kinetics and the coupling between reactions.

2 Near-equilibrium expansion conditions can be achieved with the RP-1/oxygen propellant system if the O/F ratio is above 2.0. Of course, for nozzles that differ substantially in size or contour from the nozzle used here, the required reaction rates have to be recalculated. Larger or more gradually diverging nozzles will tend to maintain equilibrium conditions further along the nozzle.

3 High temperatures in boundary layer or mixing layer regions can control optically observed static temperatures when the freestream temperature is low. On the other hand, a shortage of the appropriate emitting species in the freestream at high temperatures (as in the case of solid carbon) can permit domination of the observed temperature by a high concentration of emitters in the low temperature regions of the flow. Appropriate caution must be exercised in applying optical techniques to the measurement of static gas temperatures.

Acknowledgment

The authors wish to express their gratitude to L. W. Chick Jr. and other members of the Experimental Equipment Activity of Aeronutronic's Research Laboratories for their capable conduct of the experiments.

[6] In order to check that flow was indeed undisturbed, static pressure measurements were made just downstream of the window and compared with measurements made at the same axial location, but 90° apart circumferentially, and the results verified this assumption.

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Experiments with Two-Dimensional, Transversely Impinging Jets

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Experiments on the interaction of transversely impinging two-dimensional jet flows were performed in which a low pressure control jet flow interacted with a relatively high pressure power jet flow. The ratio of the control jet to the power jet supply chamber gauge stagnation pressure was adjusted at 0, 10, and 15%. Shadowgraphs of the power jet alone, as well as the corresponding interacting jet flows, were recorded to establish the nature of and changes in the shock structure. The jet flows were traversed by a pitot tube to record the pitot pressure distributions at various locations downstream of the power jet exit. It was discovered that with the addition of only a small percent control jet flow, the normal shock front of the highly underexpanded power jet flow changed to an oblique shock structure and, downstream of the previous location of the normal shock which appeared in the power jet flow alone, the maximum recovery stagnation pressures were proportionally much higher. The mechanism for this behavior of the normal shock is proposed. Possible practical importance of this behavior of interacting jet flows with reference to aerodynamic noise, supersonic diffuser losses, etc., is also pointed out. For the power jet flow alone it was found that by considering the actual jet boundaries as simply an extension of the actual nozzle, the average axial flow quantities, computed from the area-Mach number relation using the observed cross-sectional area of the jet flow, agreed quite favorably with the experimental results.

Introduction

DURING the last decade or two, scientific and engineering research on jet propelled high speed airplanes, missiles, and rockets has advanced at a phenomenally rapid pace. As a result of this accelerated emphasis and application of jet flows in numerous important developments, considerable basic jet flow investigations have been undertaken by a large number of research workers.[1] In comparison with the existing knowledge of the behavior of a single free jet flow, relatively less work has been done on the important basic aspects of the interaction of jet flows with external

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