Temperature Measurement in a CW HF Chemical Laser Plenum

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The stagnation temperature of the SF_6—He gas mixture of a continuous-wave HF supersonic diffusion laser was measured by observing the emission spectra of excited HF (v) molecules when trace amounts of H_2 were injected into the hot plenum gas. Since the plenum pressure was high (from one to three atmospheres), the mean free path was very short and collision frequency high, so that rotational equilibrium was expected to be obtained. Hence, rotational temperatures deduced from the spectra should represent the gas translational temperature well. When compared with the temperatures predicted from plenum pressure and mass flow measurements, the measured temperatures were 10-36% higher. The difference is concluded to be the result of heat loss to the wall of plenum and throat, a factor not considered in the predictions.

Nomenclature

a	= sound speed, cm/sec
A	= cross-sectional area of flow, cm^2
A_{ul}	= Einstein probability for spontaneous emission from upper to lower state, sec^{-1} $ster^{-1}$
B	= plenum wall area, cm^2
c	= velocity of light, cm/sec
E	= rotational energy level, cm^{-1}
h	= Planck's constant, 6.626×10^{-27} erg-sec
I	= intensity, $erg\text{-}sec^{-1} - cm^{-2}$
J	= rotational quantum number
k	= Boltzmann's constant, 1.3805×10^{-16} erg K^{-1}
K	= thermal conductivity, W/cm-deg
$\mathring{m}$	= mass flow rate, g/sec
$N(v)$	= vibrational number density, cm^{-3}
p	= pressure, $dyne\text{-}cm^{-2}$ or psia
q	= heat-transfer rate, W/cm^2
$Q(v,T_r)$	= rotational partition function
R	= gas constant, erg K^{-1} gm^{-1}
S	= self-absorption factor, $0 \le S \le 1$
T	= temperature, K
v	= vibrational quantum number
γ	= ratio of specific heats
δ	= boundary-layer thickness, cm
η	= transmission factor of optical system
τ	= optical depth
ρ	= density, g/cm^3
ω_{ul}	= frequency of vibration-rotation transitions, cm^{-1}
Superscript	
*	= throat conditions
Subscripts	
r	= rotational
0	= plenum stagnation condition
1	= before heating
2	= after heating

Introduction

IN a continuous-wave HF chemical laser, the gas in the plenum, He or N_2 and SF_6 or F_2, is heated to dissociate the fluorine compound to produce F atoms for the so-called "cold reaction";

$$F + H_2 \rightarrow HF\ (v) + H$$

Heating may be accomplished through the use of an electric arc discharge,[1] and the extent of the dissociation of the fluorine compound is dependent on the temperature obtained in the plenum. Consequently, the measure of this temperature is very important in assessing the availability of F atoms for the HF laser

In the supersonic diffusion HF laser at The Aerospace Corp., SF_6 is heated by mixing it in the plenum with arc-heated He. The temperature is usually determined by the pressure ratio method, which is as follows. From gas dynamic considerations, the mass flow is through a nozzle is given by

$$\mathring{m} = \rho^* a^* A^* = (2/\gamma + 1)^{\frac{1}{2}(\gamma + 1/\gamma - 1)} \rho_0 a_0 A^* \quad (1)$$

Since $a^2 = \gamma R T$ and $\rho = p/Rt$

$$\mathring{m} = \gamma^{\frac{1}{2}} (2/\gamma + 1)^{\frac{1}{2}(\gamma + 1/\gamma - 1)} A^* p_0 / (RT_0)^{\frac{1}{2}} \quad (2)$$

For a constant mass flow and two different plenum temperatures T_{01} and T_{02}, one obtains

$$\frac{T_{02}}{T_{01}} = \frac{\gamma_2}{\gamma_1} \frac{R_1}{R_2} \frac{(2/\gamma_2 + 1)^{(\gamma_2 + 1)/(\gamma_2 - 1)}}{(2/\gamma_1 + 1)^{(\gamma_1 + 1)/(\gamma_1 - 1)}} \left(\frac{p_{02}}{p_{01}} \right)^2 \quad (3)$$

assuming that effective throat area remains constant. If T_{01} is room temperature, then γ_1 and R_1 are known; p_{01} can be measured along with $\mathring{m}$. If the gas flow is then heated, T_{02} can be determined in terms of T_{01} and the pressure ratio p_{02}/p_{01}. The reliability of the pressure ratio method for determining T_{02} depends on the reliability of the assumption that the effective area remains constant and the reliability of the estimates for the gas properties in the heated flow represented by R_2 and γ_2. This analysis can be computerized, which then permits an iteration to account for the variation of gas properties with temperature. This has been done in The Aerospace Corp. NEST[2] program to obtain equilibrium value estimates for plenum temperature.

It was determined to try to measure the plenum temperature directly so as to obtain an estimate of the validity of the pressure ratio method. Previous efforts to measure the plenum temperature in an SF_6 plenum, either directly, by thermocouples in the plenum, or indirectly, by observing stagnation temperature in the laser cavity on the centerline of one of the nozzles in the laser nozzle bank, always resulted in thermocouple destruction. The thermocouple failed before it reached the stagnation temperature, probably because of the hot, corrosive fluorine.

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A spectrographic method was, therefore, proposed in which trace amounts of H_2 introduced into the plenum would react with the F atoms to form small amounts of excited HF. Through observation of the emission from these molecules, it was expected that the rotational temperature could be obtained.[3,4]

In this report, the results of such measurements are presented, along with the details of the technique. A comparison of the temperatures thus measured with those obtained from the pressure ratio method is also included.

Facilities and Experimental Apparatus

The Aerospace Corp. supersonic diffusion laser facility was employed in these tests, using as the nozzle bank a test nozzle plate that had seven 0.191-in.-diam holes as nozzles.

Observation of radiation from the plenum gas was accomplished as shown in Fig. 1. A spectrograph, the 0.267-m Perkin-Elmer Model 98 with grating blazed for 3 μm, was installed in a vertical position above the plenum on a table capable of very fine axial and transverse motion. Included in the movable optical system was a GE 105 quartz lens of 4⅜ focal length to focus the emission. This instrument looked down into the plenum through quartz windows installed top and bottom in the plenum block 1⅛ in. from the centerline of the nozzle bank (Fig. 2). The quartz window employed had good transmission properties below 2.6 μm, so this limited the range of radiation that could be observed. Furthermore, the spectrum of water vapor has strong absorption bands starting just beyond 2.5 μm. Hence, it became clear that the convenient rotational structure to observe (to avoid flushing) was the $R_{1\rightarrow 0}(J)$ lines, which ranged from 2.499-2.283 μm (J =1-15. An indium arsenide, photovoltaic detector cooled with a dry ice-acetone slurry was used to detect the radiation. Its signal was displayed, after appropriate amplification, on an Offner Dynograph recorder. Appripriate amplification included a Princeton Applied Research Model HR 8 lock-in amplifier, together with chopper and reference frequency supply located within the monochromator housing.

In this work, it is assumed that rotational equilibrium exists, so that the rotational temperature is a good representation of the gas translational temperature. At the plenum pressures and temperatures usually obtained (i.e., 1-3 atm, 2000K), the collision frequency is of the order of 10^{10} sec^{-1}, while rotational equilibrium is obtained in 10-100 collisions. Hence, rotational equilibrium is expected in 1-10 nsec. This time is short relative to the residence time of the gas molecules in the stagnation region in the field of view of the optical system, which is >10 μsec.

Rotational temperature is related to radiation intensity by

$$\frac{I(v,J)}{\eta(2J+1)A_{ul}\omega_{ul}} = \frac{CN(v)S}{Q(v,T_r)} \exp - \left\{ \frac{hc}{kT_r} E(v,J) \right\} \quad (4)$$

The intensities of two rotational lines in a given branch are related by

$$\ln \left[\frac{I(v,J)}{\eta(2J+1)A_{ul}\omega_{ul}} \right]_1 - \left[\frac{I(v,J)}{\eta(2J+1)A_{ul}\omega_{ul}} \right]_2 = -\frac{hc}{kT_r}(E_1 - E_2) \quad (5)$$

In essence, if the radiation is identified, then J, A_{ul}, ω_{ul} and $E(v,j)$ are known.[3] Hence, a measurement of the relative intensities of two lines provides hc/kT_r and, thus T_r. This relation is adequate when the medium is optically thin, i.e., there is negligible self-absorption, and $S(0)$ is unity. An examination of the optical depth of the medium for the R_{1-0} (J) branch[4] indicated that, at the partial pressure levels of HF employed, the optical depth was negligible, at least for J values from which the rotational temperature was determined. As a criterion for the choice of $R(J)$ lines used, $S(\tau)$ was required to be between unity and 0.850. For an isolated Doppler-broadened spectral line and a slab radiative medium, this requires τ to be no greater than 0.480. Depth τ is the product of the line-of-sight dimension and the volume absorption coefficient at line center[3] for the given $R(J)$ transition. A relative intensity calibration was performed to ac-

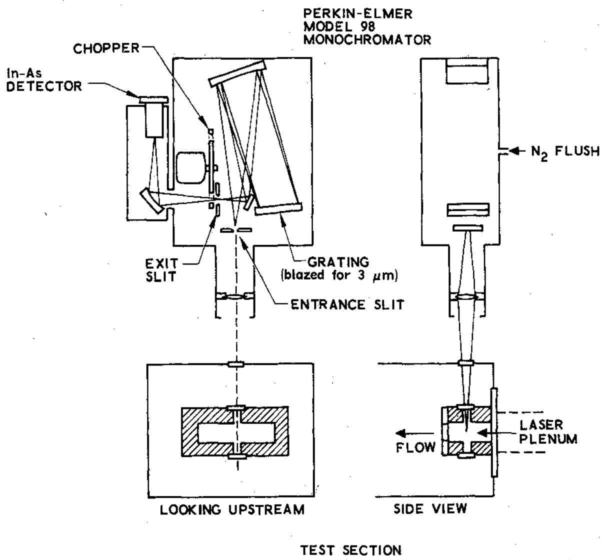

Fig. 1 Supersonic diffusion laser with monochromator for plenum temperature measurement.

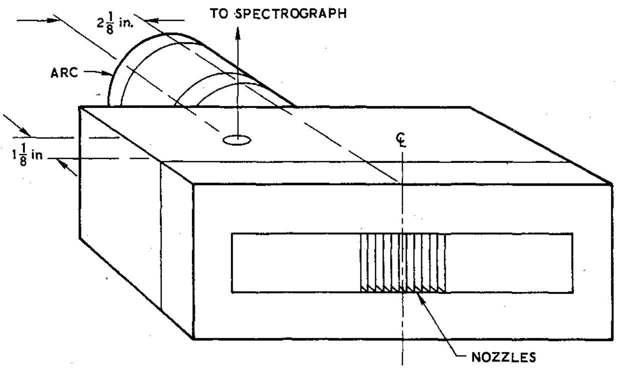

Fig. 2 Location of port for plenum temperature measurement.

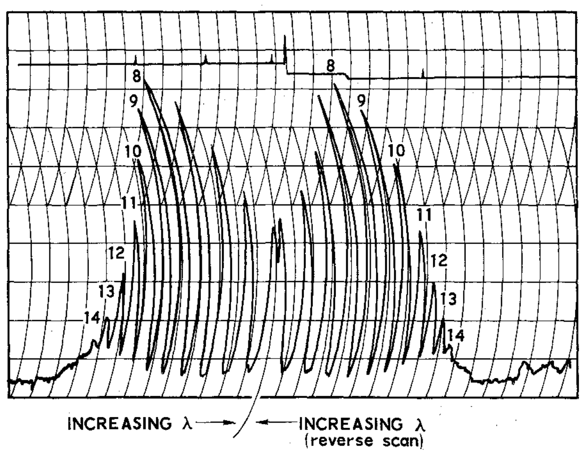

Fig. 3 Typical spectra for the $v=1\rightarrow 0$ transition. The R branch is shown with J quantum numbers from 8-14 identified. Two scans, one a reverse scan, are made per run. Flow conditions: 2.3 g/sec He, 7.35 g/sec SF_6, 0.2 g/sec O_2, and 0.0025 g/sec H_2. Plenum pressure = 21.65 psi, 63kW are power. Monochromator slit width = 300 μm.

count for the wavelength dependent transmission factor η of the instrument system. A water-cooled blackbody source, operated at temperatures from 800 to 1200 K, provided the calibration radiation source.

Results and Discussion

Laser plenum temperatures were measured, as previously outlined for two electric arc power levels, for gas compositions ranging from 4.6 g/sec of He and 3.2 g/sec SF_6 to 2.3 g/sec He and 11 g/sec SF_6. After considerable testing with varying amounts of H_2 injected into the plenum, a value of 0.0025 g/sec was finally selected, which provided adequate radiation signal from the Hf (v) formed, but was small enough that no detectable change occurred in the plenum pressure. As previously noted, this value was small enough that the medium was optically thin for the higher J values.

Typical of the rotational spectra observed in these tests are those shown in Fig. 3 for Test 8 from Table 1. Plots of intensity as a function of rotational energy level for the determination of temperature are shown in Fig. 4. In the tests, the wavelength was scanned from 2.25-2.41 μm and then reverse-scanned back to 2.25 μm. Thus, two observations of each line intensity were obtained per test. To minimize the effects of optical thickness, data have been observed in the rotational "wings" of the band, i.e., large J lines. Points on the semilogarithmic graph in ascending J, which do not exceed an optical depth of 0.480, have been used to determine T_r. Therefore, transitions beginning with $R(9)$ would be used in Fig. 5. For the illustrated case, the estimated optical depth τ for $R(8)$, assuming vibrational-translational equilibrium, is 0.590, which exceeds 0.480. Depth τ for $R(9)$ is 0.469.

Plenum temperatures determined from the spectral observation are listed in Table 1, along with plenum pressures and the gas flows for which they were measured. These temperatures are also plotted in Figs. 5 and 6 as a function of SF_6 mass flow for two helium mass flows and two arc power levels. Also included in Figs. 5 and 6 are the plenum temperatures calculated by the plenum pressure ratio previously outlined. The large scatter in the temperature measurements (±10%) is probably because of the limited precision with

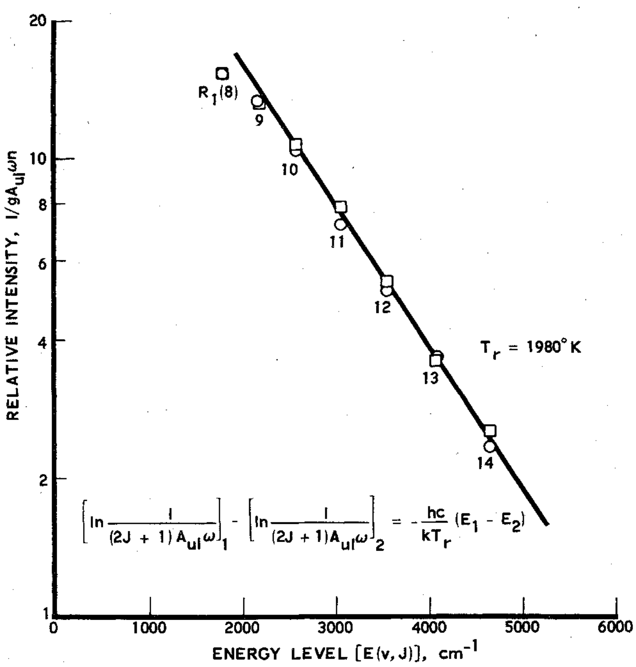

Fig. 4 Relative intensities of $R_{1-0}(J)$ lines as a function of rotational energy level. Rotational temperature is determined from the slope hc/kT_r of the line through the data.

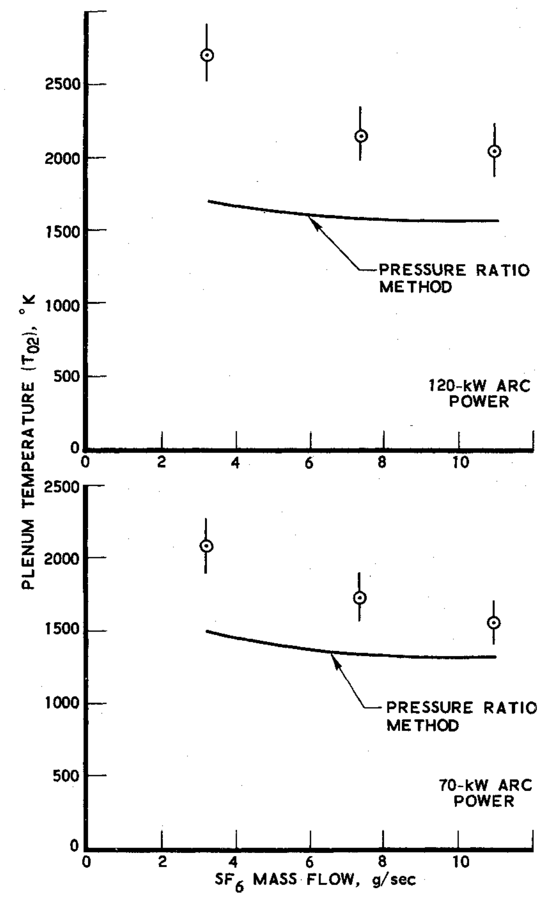

Fig. 5 Plenum HF rotational temperature compared with pressure ratio method at He mass flow of 2.3 g/sec.

Table 1 Mass flow, pressure, and temperature in the laser plenum

Test	He (g/sec)	SF_6 (g/sec)	O_2 (g/sec)	H_2 (g/sec)	p_{02} (psi)	p_{01} (psi)	T_{02}(calc) (K)	T_{02}(meas) (K)	Arc I (amp)	Arc v (v)
1	4.6	3.2	0.1	0.0025	26.8	11.6	1501	2074	300	240
2		7.3	0.2		33.2	15.0	1333	1720	300	260
3		11.0	0.4		39.5	18.3	1300	1562	300	280
4		3.2	0.1		31.5	11.2	1694	2550 2700	470	270
5		7.3	0.2		38.8	15.0	1578	2070 2220	470	295
6		11.0	0.4		42.9	18.0	1567	2045	470	300
7	2.3	3.2	0.1		10.9	7.8	1588	2426	300	220
8		7.3	0.2		24.6	13.8	1539	1980	300	250
9		11.0	0.4		29.6	18.50	1521	1697	300	260
10		3.2	0.1		18.6	7.1	1588	2640	470	210
11		7.3	0.2		23.4	9.6	1554	2040	470	230
12		11.0	0.4		27.5	11.8	1551	1990	470	240

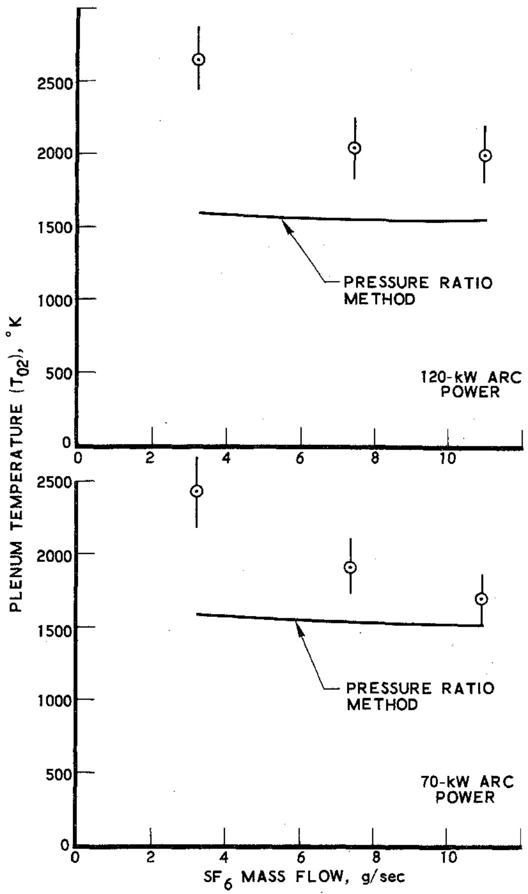

Fig. 6 Plenum HF rotational temperature compared with pressure ratio method at He mass flow of 4.6 g/sec.

which the slope of the intensity-energy curve can be measured. Evidently, the temperature measured in the plenum by spectral means is higher than that computed by the pressure ratio method. Further, the higher the temperature, the greater the disparity between calculated and measured values. This is perhaps to be expected. The pressure ratio method relies on being able to back-calculate plenum temperature from a throat temperature, on the assumption that no heat is lost as the gas flows from plenum to throat. This is unrealistic. Measurements of inlet and outlet water temperatures for the block containing throat inlets, throats, and nozzles showed heat losses of 20-30% of total input electrical power. Most of this loss was confined to the throat inlet and throat regions, since downstream from the throat gas temperature drops rapidly on supersonic expansion and, therefore, so does heat loss. Thus, a difference in temperature up to 30% between that measured in the plenum and that determined from the pressure ratio is not unexpected.

If a heat loss of 30% of total input power is assumed, an order of magnitude of the plenum thermal boundary-layer thickness δ can be obtained. This is done by assuming a temperature gradient between wall and core in the plenum of $(T_{02}-T_B)/\delta$ and a heat flow to the wall of q/B. If laminar flow is assumed

$$q/B=K(T_{02}-T_B)/\delta \qquad (6)$$

where K is assumed to be 1.4×10^{-3} W/cm deg. For the case with the highest power input (120 kW), the thermal boundary-layer thickness estimate is 0.2 mm. This is a negligible dimension relative to the height of the plenum, which is 1.5 in. This means that the thermal core through which the spectrograph looks is essentially uniform in temperature, and the measurement requires no correction for temperature gradient along the line of sight.

Summary

The temperature of the SF_6-He gas mixture in the plenum of a supersonic diffusion laser was measured by observing spectra of the HF(v) molecules when trace amounts of H_2 were injected into the hot plenum gas. Because the plenum pressures were relatively high and the mean free path very short, rotational equilibrium was expected to be obtained. Thus, the rotational temperature obtained from the observed spectra was expected to equal the gas translational temperature.

Precision of the temperature was ± 10%, largely because of the limited precision involved in the measurement of the slope of the intensity data. The observed values are about 10-36% higher than temperatures obtained from a pressure ratio method. This difference is probably because of the wall heat loss that occurs between plenum and throat, which was not taken into account in the pressure ratio method.

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