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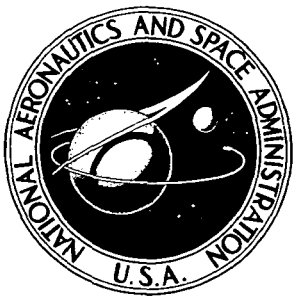

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OPTICAL MEASUREMENT OF STATIC TEMPERATURE AND HYDROXYL RADICAL PROFILES IN A HYDROGEN-FUELED SUPERSONIC COMBUSTOR

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16. Abstract

Profiles of static temperature and hydroxyl radical concentration were measured in a two-dimensional supersonic combustor test section 22.8 cm downstream of hydrogen injection. A high-pressure gas generator supplied vitiated air to the test section at Mach 2.44, atmospheric pressure, and a total temperature of about 2240 K. Room-temperature hydrogen was injected through a 0.40-cm step slot at Mach 1 and matched pressure. The measurements utilized a noninterfering spectral line absorption technique in which narrow ultraviolet emission lines of the hydroxyl $^2\Sigma^+ - {}^2\pi$ electronic transition are absorbed by the broader absorption lines in the combustion gas. Comparison of the measured temperature profiles with theoretical calculations showed good agreement.

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OPTICAL MEASUREMENT OF STATIC TEMPERATURE AND HYDROXYL RADICAL PROFILES IN A HYDROGEN-FUELED SUPERSONIC COMBUSTOR

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SUMMARY

Measurements of static temperature and hydroxyl radical concentration were made in a two-dimensional supersonic combustor. Vitiated air was supplied to the combustor at Mach 2.44, atmospheric pressure, and a total temperature of about 2240 K. Room-temperature hydrogen was injected through a step slot, parallel to the main stream at Mach 1.0 and atmospheric pressure. Data were taken at nine points across the stream 22.8 centimeters downstream of the hydrogen injection station. The measurements utilized the spectral line absorption technique in which narrow ultraviolet emission lines of the hydroxyl $^2\Sigma^+ - {}^2\pi$ electronic transition are absorbed by the broader absorption lines in the combustion gas. Comparison of the results with theoretical calculations showed good agreement in temperature, but the measured hydroxyl concentration differed markedly from the theoretical.

INTRODUCTION

The development of advanced, hypersonic aircraft will require airbreathing engines in which combustion takes place in a supersonic airstream. In order to design effectively the supersonic combustor of such an engine, reliable analytical techniques are required to describe the mixing and combustion processes. To develop analytical techniques requires that experimental data be available to test the analysis.

Reference 1 presents detailed probe measurements of total temperature, pressure, and gas composition made for supersonic combustion of hydrogen in a vitiated airstream using stepped wall injection. The results of a computer program to describe the mixing with equilibrium combustion are also presented in reference 1.

The purposes of the tests described in this report were to demonstrate a measurement technique which would produce no flow disturbance in a supersonic combustor and to provide experimental data to check the analysis of Kurkov (unpublished data obtained at the Lewis Research Center). To this end, profiles of static temperature and hydroxyl radical (OH) concentration were measured in the mixing and combustion zone of the combustor of reference 1.

The measurement technique made use of the spectral line absorption method described in references 2 to 4 in which narrow ultraviolet emission lines of the hydroxyl $^2\Sigma^+ - {}^2\pi$ electronic transition are absorbed by the broader absorption lines in the combustion gas.

Conditions in the combustor were Mach 2.44, atmospheric pressure, and a total temperature of about 2240 K. Hydrogen was injected at room temperature, Mach 1.0, and atmospheric pressure. Run times were limited to 3 seconds because of the use of uncooled hardware.

EXPERIMENTAL APPARATUS

Facility

Figure 1 is a schematic of the combustor test section. A detailed description of the hardware can be found in reference 1. Briefly, upstream of the test section was a high-pressure hot-gas generator which burned an oxygen-hydrogen-nitrogen mixture. The proportions were fixed so that the resulting hot-gas stream had an oxygen concentration equal to that of air. The hot gas, with total temperature of about 2240 K, was expanded through a contoured nozzle which produced a Mach 2.44 parallel flow stream at the entrance to the test section. Pressure at the test-section entrance was approximately atmospheric. The test section at the entrance was 5.1 centimeters wide and 8.9 centimeters high.

In the test section, room-temperature hydrogen was injected along the wall, from behind a 0.40 centimeter step slot, parallel to the vitiated airstream at Mach 1 and atmospheric pressure. From the step slot the test-section height increased linearly from 9.4 to 10.1 centimeters at the measuring station.

Runs were limited by the use of heat-sink hardware to a length of 3 seconds.

Optical System

For the OH absorption studies, the downstream test-section windows were replaced with brass plates containing a line of 0.32 centimeter diameter holes, and thus

the windows were eliminated as a source of beam attenuation. Two sets of plates were fabricated, which enabled measurements to be made on 0.32 centimeter centers across the stream 22.8 centimeters downstream of the slot. The length of the optical path through the test section L was the test section width, 5.1 centimeters.

The optical system is shown schematically in figure 2. The OH lamp, which is described in references 3 and 4, was a water-cooled, end-view capillary discharge tube. Water vapor was supplied to the lamp at a pressure of about 1 torr by pumping on a sulfuric acid solution which was maintained at 0° C in an ice bath. A power supply provided 40 milliamperes at about 5000 volts to the lamp for these tests. The emission from the lamp was chopped and focused on the test-section centerline with a quartz lens. The beam emerging from the other side of the test section was reflected by a spherical mirror to a focus on the entrance slit of a 1/2-meter grating monochromater. The monochromater was used in the second order, and this provided good separation of the spectral lines of interest, which were in the 0-0 band starting around 0.307 micrometer. The line intensity was measured by a photomultiplier located at the exit slit. The photomultiplier output was amplified with a lock-in amplifier, and the signal recorded on an X, Y-recorder.

DATA ANALYSIS

The optical technique used to determine OH concentration and temperature in this study was developed and used in the work of references 2 and 4. This method relies on the absorption of the narrow ultraviolet emission lines of the OH $^2\Sigma^+ - {}^2\pi$ electronic transition by the broader absorption lines in the combustion gas. The absorption coefficient α can be computed from the experimental data:

$$\alpha = \frac{\ln \frac{I_o}{I}}{L} \tag{1}$$

where L is the path length in the absorbing gas, which was taken to be the width of the test section. All symbols are defined in the appendix.

The OH concentration is given in reference 3 as

$$N_{OH} = \frac{\mathcal{Q}_R \mathcal{Q}_V b_D \alpha}{F A_k T_{J'J''}} e^{(hc\omega_k/kT)} 2.40\times10^{12} \tag{2}$$

The Doppler line half-width b_D is determined from reference 5 as

$$b_D = \nu \sqrt{\frac{2kT \ln 2}{Mc^2}} \tag{3}$$

A listing of the spectral lines used in calculating N_{OH} and their related constants is given in table I.

The OH number density is converted to mole fraction through use of the perfect gas law:

$$[OH] = N_{OH} \frac{kT}{p} \tag{4}$$

Before equation (2) can be evaluated, the temperature must be determined. This is done, as described in references 2 and 3, by plotting $\ln(\alpha/A_k T_{J'J''})$ as a function of $hc\omega_k/k$ for a number of different spectral lines. Assuming rotational equilibrium, the resulting straight line has a slope of 1/T. This type of plot is referred to as a Boltzmann plot. Figure 3 shows a typical Boltzmann plot for an optical path located at y = 1.85 centimeters from the wall of the test section.

EXPERIMENTAL PROCEDURE

To determine temperature, absorption measurements for a number of different spectral lines are required. Because of the short run times available, about 3 seconds, it was necessary to duplicate the same run conditions a large number of times and change the monochromater setting between runs. A reading of emission line intensity with no absorbing gas present was recorded before and after each run. If the prerun and postrun levels were not the same, within about 2 percent, the run was discarded. During a run, conditions would change slightly because of heating of the test section. In order to be consistent, the data plot was always read at the same time relative to gas-generator shutdown.

Figure 4 shows a typical data recording. The top trace was taken immediately before the run started. The bottom trace is the gas-generator pressure and indicates when the run began and ended. The middle trace is the measured line intensity after attenuation in the test section. The point on the plot marked Read is 0.5 second before shutdown and is the point where data are picked off for each run. This procedure is consistent with the technique used in reference 1.

After a series of runs was completed at one location, the optical system was realined through the next window hole and another series of runs initiated. Because of the large number of runs required to gather data, 226 for the conditions reported here,

there was not time to investigate other combustor conditions. Overall, data were collected from nine different locations across the stream, ranging from 0.6 to 6.0 centimeters above the wall, all at an axial location 22.8 centimeters downstream of the hydrogen injection step.

RESULTS AND DISCUSSION

A Boltzmann plot, like that shown in figure 3, was constructed from the data at each of the nine locations. The data on each plot were fit to a straight line by using a least squares technique. The temperature for each location was then determined as the reciprocal of the slope of the line fit to the data. Figure 5 is a plot of static temperature as a function of distance from the wall.

Once the temperature profile was determined, the concentration of the OH radical could be calculated from equations (2) and (4).

The result of this calculation is figure 6, where OH mole fraction is plotted as a function of distance from the wall. Included in figures 5 and 6 are curves theoretically calculated by Kurkov. The calculations include the effects of wall boundary layer in the free stream, initial nonequilibrium composition, and finite rate chemical kinetics. The kinetic mechanism considers 18 reactions involving nine species, including HO_2 and hydrogen peroxide (H_2O_2). The turbulent Lewis and Prandtl numbers are assumed to be unity.

There is excellent agreement between theory and experiment in the location of the peak of the temperature and concentration profiles.

In figure 5 the measured temperature profile shows a slower approach to free-stream conditions than does the calculated. This difference is probably due to a combination of assumptions in the theory and averaging effects in the experiment. The theoretical calculations are for two-dimensional flow, whereas the experiment surely includes three-dimensional effects, particularly within the combustion region. The optical measurements are, effectively, averages over the cross section and along the length of the beam. This averaging is weighted heavily toward higher temperature regions.

The cause of the discrepancy in magnitude between predicted and measured OH mole fraction in figure 6 can be explained primarily as a path length effect. Although the temperature calculation does not depend on the value of the optical path length, the OH concentration is inversely proportional to path length. In the experiment, the flow was not necessarily uniform across the test section. In reality, there was an influence of the side walls, and possibly the combustion was not uniform. A shortening of the active optical length by these effects would yield a higher measured value of [OH].

SUMMARY OF RESULTS

The absorption of ultraviolet radiation by the hydroxyl radical was used to measure the temperature and concentration profiles across a two-dimensional supersonic combustor test section. Measurements were made 22.8 centimeters downstream of the point where hydrogen was injected parallel to the free stream and at matched static pressure. The purpose of these measurements was to demonstrate the technique in a combustor and to compile data against which to compare analytical calculations. The results of the temperature measurements showed good agreement with theoretical calculations. The measured hydroxyl concentration profile showed a peak where expected, but the magnitude was well below that calculated.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 15, 1973,
501-24.

APPENDIX - SYMBOLS

A_k	relative transition probability
b_D	Doppler line half-width
c	speed of light
F	constant in eq. (2) (from ref. 2); $F = 2.0 \times 10^{-4}$
h	Planck's constant
I	measured line intensity after passing through absorbing gas
I_o	measured line intensity before passing through absorbing gas
k	Boltzmann's constant
L	active optical length in test section
M	mass of OH molecule
N_{OH}	number density of OH
[OH]	mole fraction of OH
p	static pressure
$\mathcal{Q}_R$, $\mathcal{Q}_V$	rotation and vibration partition functions
T	static temperature
$T_{J'J''}$	correction factor for vibration-rotation interaction (ref. 4)
α	absorption coefficient per unit length, cm^{-1}
ν	wave number of spectral line, cm^{-1}
ω_k	lower state energy level, cm^{-1}

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TABLE I. - CONSTANTS USED FOR HYDROXYL ULTRAVIOLET ABSORPTION DATA REDUCTION

[From ref. 6.]

Rotational line	Wave number, ν, cm^{-1}	Lower state energy level, $\frac{hc\omega_k}{k}$, K	Relative transition probability, A_k	Correction factor, $T_{J'J''}$
$Q_{1,5}$	32403.5	783.	42.2	0.978
$P_{1,2}$	32390.9	120	12.7	.998
$Q_{1,6}$	32381.0	1106	50.6	.969
$Q_{2,7}$	32304.8	1551	51.0	.969
$Q_{1,9}$	32297.4	2379	75.8	.938
$Q_{2,11}$	32189.9	3522	84.2	.926
$Q_{2,12}$	32152.0	4147	92.5	.912
$Q_{1,13}$	32142.7	4765	108.8	.881
$Q_{1,15}$	32045.4	6257	125.2	.847

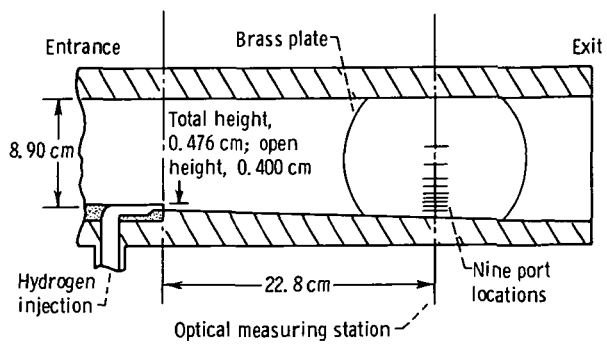

Figure 1. - Schematic side view of combustor test section.

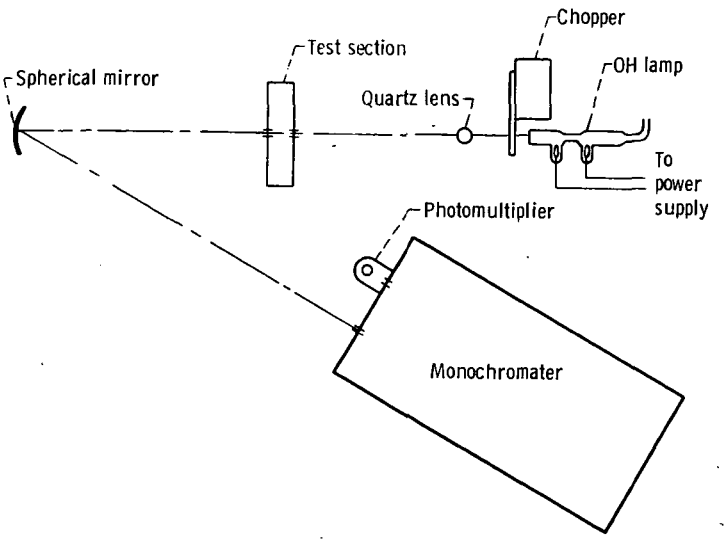

Figure 2. - Schematic layout of optical system.

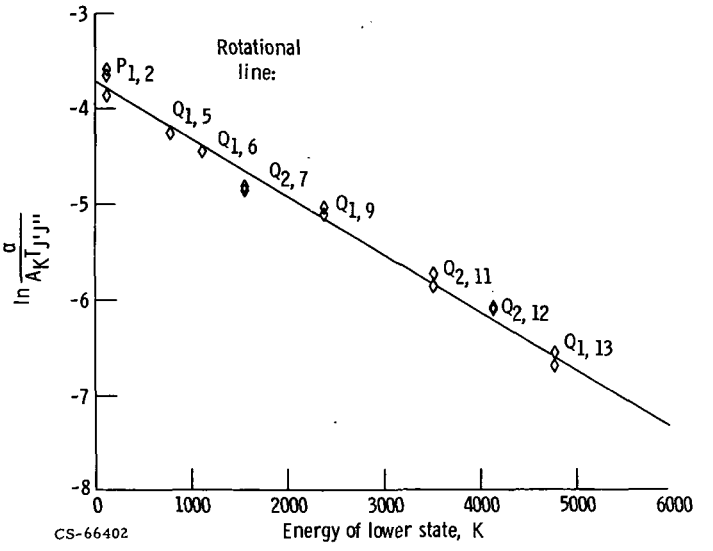

Figure 3. - Boltzmann plot of hydroxyl absorption measurements taken 1.85 centimeters from wall 22.8 centimeters downstream of injection step. Rotational temperature, 1654 K.

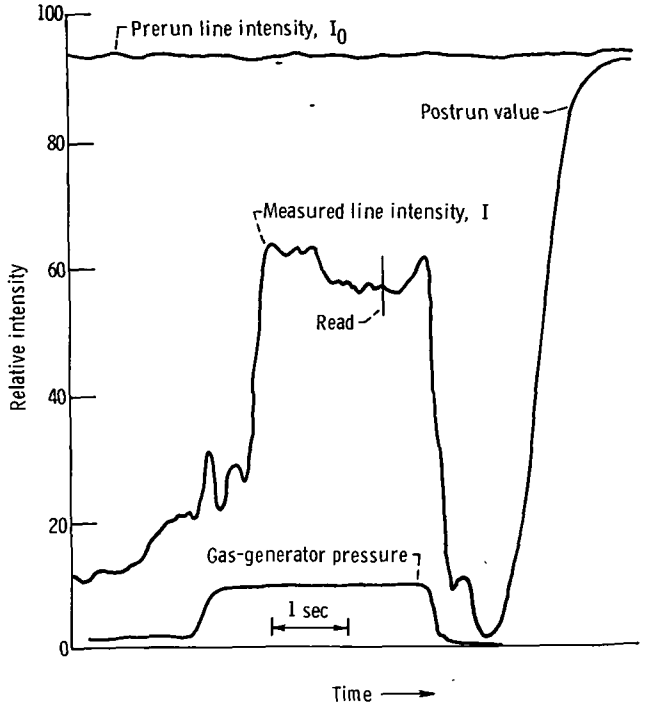

Figure 4. - Typical data recording for $P_{1,2}$ line taken 1.52 centimeters from wall 22.8 centimeters downstream of injection step.

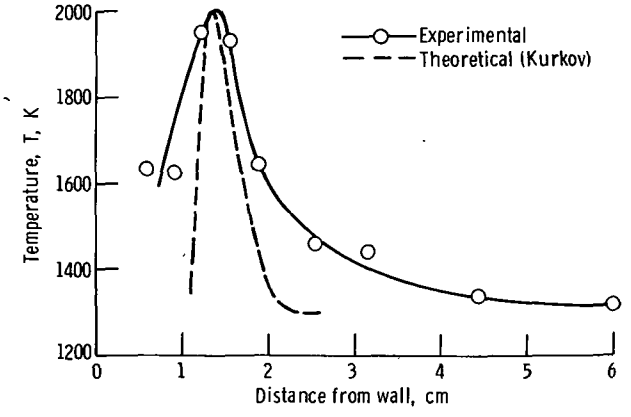

Figure 5. - Temperature profile measured by spectral line absorption 22.8 centimeters downstream of injection slot.

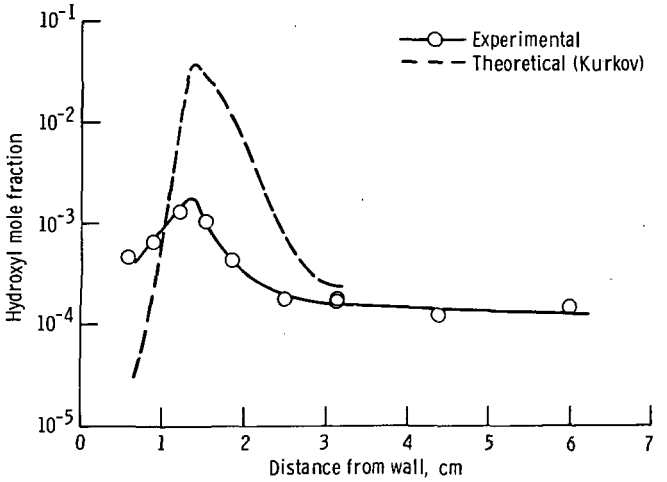

Figure 6. - Hydroxyl mole fraction profile measured by spectral line absorption 22.8 centimeters downstream of injection slot.

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