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ABSORPTION OF ULTRAVIOLET RADIATION IN THE REFLECTED REGION OF A SHOCK TUBE

by

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Abstract

Absorption coefficients of high temperature air have been measured photoelectrically over the temperature range from 2000 to 4350°K and wavelength range 2300 to 3000Å. The experiments were performed within 1cm of the end wall in the reflected region of a pressure driven shock tube. A high pressure mercury-xenon arc lamp, operating in a continuous mode, was used as the background source for the probing radiation. The results agree well with theoretical calculations and existing experimental data where comparisons could be made.

Introduction

In the past several years a great deal of theoretical work has been done on the radiative properties of high temperature air and its constituents which extend down into the ultraviolet and vacuum ultraviolet regions of the spectrum. Much of this work has been motivated by the need to access the influence of radiation on the heat transfer to high velocity reentry vehicles and the manner in which it modifies the high temperature flow field created by them. As reentry velocities increase it will be necessary to direct more attention to the radiative properties of high temperature air in the ultraviolet and vacuum ultraviolet regions of the spectrum since an increasingly larger amount of energy will be invested in these spectral regions.

If radiation effects are to be included in heat transfer calculations, some degree of confidence should exist in the use of theoretical values for the radiative properties of high temperature gases. Therefore, if possible these properties should be measured experimentally to determine if there is reasonable agreement between theory and experiment.

In radiation gas dynamics, one of the most important properties is the absorption coefficient of the gas. At the present time there is a paucity of experimental work on this property. In particular, of the experimental work that has been published on the absorption coefficients of high temperature gases, only the results at a few selected wavelengths and temperatures have been obtained in the spectral region less than 3000Å. Values of the absorption coefficient for air reported herein were measured photoelectrically in the reflected region of a shock tube over the spectral range 2300-3000Å and the temperature range 2000-4350°K. These results represent the initial phase of a program to measure experimentally the absorption coefficient of various gases at elevated temperatures over a broad spectral range.

By using the reflected region of a shock tube, temperatures are attainable which are approximately twice the temperature behind the incident shock wave. Since the gas behind the reflected shock wave is brought to rest by the reflecting wall and is in equilibrium for several hundred microseconds, a stationary volume of gas at an elevated temperature is available for performing absorption measurements.

The governing relation for the emission and absorption of radiation in a participating medium is the equation of transfer. Applied to the problem consider herein, where we assume (a) negligible emission from the gas and (b) the absorption coefficient is independent of position in the test gas, the solution to this equation is given by

\[ I_\lambda(x_1) = I_\lambda(0) \exp(-\alpha_\lambda x_1) \]

Here \( I_\lambda(x_1) \) is the specific intensity of the radiation leaving the medium at \( x=x_1 \) parallel to the \( x \) axis, \( I_\lambda(0) \) is the specific intensity of the radiation entering the medium at \( x=0 \) and parallel to the \( x \) axis and \( \alpha_\lambda \) is the volumetric absorption coefficient at wavelength \( \lambda \) of the medium occupying uniformly the region of space between \( x=0 \) and \( x=x_1 \). Thus, measurement of \( I_\lambda(0) \) and \( I_\lambda(x_1) \) along with a knowledge of \( x_1 \) (the shock tube width) then permits \( \alpha_\lambda \) to be computed.

Experimental Apparatus

The basic experimental arrangement is shown in Figure 1. The shock tube was a simple pressure-driven device. The test section was constructed from extruded aluminum 4.5m long with a 5cm square cross-section. The driver section was made from a 1.83-Pi long by 10.2cm inside diameter stainless steel tube. Incident shock velocities were measured at three positions upstream of the observation station by thin film resistor transducers which were mounted flush in the top of the tube wall. The transit time between the first and second and the second and third transducers were recorded by a pair of microsecond counters (Hewlett-Packard 523CR).
To determine the absorption coefficient of the heated air, a Hanovia 977B-1, 1000 watt, high pressure mercury-xenon arc lamp was used as a background source. The arc is enclosed in a fused silica bulb which allows the lamp to radiate energy below 2000A. The lamp was operated as a continuous source at 300V, and 32 volts DC. The noise level of the lamp was measured to be less than ±2% of the average DC level of the lamp. The arc lamp was housed in a metal housing with the inside walls mirrored. A parabolic mirror is mounted behind the arc to reflect as much of the energy as possible in the desired direction. An adjustable fused silica condensing lens is mounted in the lamp housing to focus the intensity of the lamp at a desired point.

The arc lamp intensity was measured at a predetermined wavelength by an RCA 7200 photomultiplier tube with a fused silica window. The photomultiplier tube was a 120 micron wide exit slit mounted in the focal plane of a three-quarter meter Jarrel-Ash plane grating spectrophotometer. The grating was ruled at 15,000 lines per inch which gave a reciprocal linear dispersion of 20A/mm at the exit slit.

To determine as precisely as possible the wavelength of radiation impinging upon the cathode of the photomultiplier tube, a dial with 100 divisions was mounted on the wavelength drive mechanism of the spectrophotograph grating. This allowed the grating angle to be set to an accuracy of at least three decimal places with an interpolation on the fourth decimal place. This gave an accuracy of better than ±5A in setting the grating at a predetermined wavelength. The driving mechanism was calibrated with a low pressure mercury source.

The output of the photomultiplier tube was displayed on a Tektronix 565 oscilloscope with a scope camera attachment to record the absorption traces. The last thin film resistor transducer (mounted less than 9 cm from the center of the observation windows) was used to trigger the oscilloscope.

Operating the lamp in a continuous mode yielded good absorption traces (as depicted in Figure 2) and alleviated the necessity of pulsing the lamp as was done in references (4-11). Tests were made which verified that the intensity of radiation from the gas was negligible over the temperature and wavelength range considered when compared against the arc lamp intensity. A recent study by Klein et al. indicated that the brightness temperature when operated in the continuous mode is of sufficient magnitude to use as a source for absorption measurements at much higher temperatures.

Both bottled and laboratory air were used in the test section with no observable difference in measured absorption coefficients. The air was processed through a dryer to remove as much of the moisture content as possible. Commercial helium at pressures up to 1,000 psi was used to drive the shock tube. Prior to each test, the test section was evacuated to a pressure of less than 10⁻⁶ mm Hg, then flushed with dry air and evacuated again to a pressure of at least 6x10⁻⁸ mm Hg. Before introduction of the test gas. The apparent leak rate of the test section was found to be 6x10⁻⁷ mm Hg per minute. Test section pressures ranged from 0.5 mm-100 mm Hg, depending upon the test conditions desired in the reflected region. After every third run the inside of the tube was cleaned with an acetone swab to remove bits of diaphragm material that had been accelerated down the tube by the driver gas.

The test section observation windows were made from 6 mm thick fused silica discs, epoxyed into a machined slot. These were also cleaned after every third run since they became slightly clouded after a few runs.

Results

The initial shock tube runs were made with the center of the observation windows located at a distance of 4.4 cm from the reflecting wall. Typical results of performing absorption measurements behind the reflected shock wave at this point are shown in Figure 3. The arrival of the cold gas contact region and the influence of the interaction of the reflected shock wave with the wall boundary layers is quite evident. The interpretation of such traces to determine the absorption coefficient would be questionable. Several authors have studied this interaction phenomena and have cautioned against the use of this region for quantitative measurements. Mark, Byron and Rott and Davies have shown that the growth thickness of this phenomena is approximately proportional to the distance from the reflecting wall. Therefore, an end plate plug was machined which brought the reflecting wall within 1 cm (actually 3/8 in.) of the point of observation. A typical absorption trace using the end plug is shown in Figure 2. The influence of the boundary layer interaction has become negligible and the arrival of the cold contact region has been delayed sufficiently to allow a quantitative measurement of the absorption coefficient to be made. All the data presented here was taken within 1 cm of the reflecting wall. It was discovered later that Appleton and Steinberg had also inserted an end plug in their shock tube and obtained valid data at a point 1 cm from the reflecting wall. These workers also made some measurements at a point 0.3 cm from the reflecting wall without any noticeable change in their results.
In all the observations, the state of the gas behind the reflected shock was calculated from a knowledge of its initial state and the measured shock velocity using the equation of state and the conservation of mass, momentum and energy equations. The error in measured shock velocity was found to be less than 1% throughout the experiments.

Using the oscilloscope traces and an optical comparator, the transmission of the gas, i.e., the ratio \( I_s(x)/I_0(0) \) needed in Eq. 1 to determine \( a_\lambda \) was obtained. However, since \( a_\lambda \) is a function of the density of the absorbers it was convenient for data presentation to replace \( a_\lambda \) in Eq. 1 by \( a_\lambda p / \rho S \). Here \( \rho S \) is the initial (unshocked) test gas pressure (in atmospheres) and \( \rho S \), is the ratio of the density of the reflected region to the initial (unshocked) density. This reduces all the absorption coefficients to a density corresponding to a pressure of one atmosphere and the initial test gas temperature of 300°K (this being the average laboratory temperature). \( a_\lambda \) then has units of \( \text{atm}^{-1}\text{cm}^{-1} \).

Numerous data points were obtained at the same temperature and pressure. The wavelength was varied from 2300\AA to 3000\AA in 100\AA increments allowing the gathering of eight data points at the same temperature and pressure. Runs were made with different test section pressures but resulting in the same temperatures behind the reflected shock wave. This was a result of the good reproducibility with both mylar and scored aluminum diaphragms.

The absorption coefficients calculated from these runs when reduced to a pressure of one atmosphere and 300°K agreed very well with one another.

The data obtained is present in two forms. At a temperature of 2500°K, 3000°K, 3500°K, 4000°K and 4000°K, the absorption coefficient is plotted as a function of wavelength. These plots are shown in Figures 4-7 with the experimental values of GENERALOV, LOSEV and TEREHENINA\(^6\) and theoretical points from CHURCHILL, et al\(^2\) included for a comparison.

Figures 8-11 show the variation of the absorption coefficient at a given wavelength, over the temperature range of 2000-4350°K. In each case a comparison between theory and experiment is made where it is possible.
Discussion of the Results and Conclusions

The experimental results obtained from the work discussed herein agree well with the theoretical and experimental data mentioned previously where comparisons could be made. Inspection of Figures 4-11 will show that the experimental data reported here agree better with the theoretical calculations of CHURCHILL, et al. than those of GENERALOV, LOSEV and TEREBOLENA. However, their data was plotted with approximately a 10% variance in pressure and perfect agreement would not be expected. The error in measured shock velocity of their work was reported to be 3% which leads to an error in temperature of ±150°K. The error in the temperature in this work was approximately 50°K. One will further notice that better agreement between theory and experiment was obtained at the longer wavelengths than at 2300Å and 2400Å. APPLETION and STEINBERG reported discrepancies between their experiments and theoretical calculations in the vacuum ultraviolet. This supports the trend detected here and is evidence enough for continued experimental work in this area.

References