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MOLECULAR DENSITY DETERMINATION OF WATER VAPOR IN A 10⁻⁴ TO 10⁻² TORR VACUUM ENVIRONMENT BY ULTRAVIOLET ABSORPTION

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ABSTRACT

A new sensor has been developed for water vapor molecular density measurement in NASA's space environment simulation chambers at the Johnson Space Center. Its intended use is to obtain measurements in the exit planes of supersonic nozzles without disturbing the plume flow field in the chamber. A laboratory version of the sensor has been built and tested in a static pressure environment to determine its sensitivity. Water vapor absorption cross sections were determined in in the molecular density range 10^{13} to 10^{15} molecules/cm^3 (3.1 x 10^{-4} to 3.1 x 10^{-2} torr, respectively). The results show the sensor is extremely sensitive in detecting water vapor, and that its useful measurement range exceeds 10^{15} molecules/cm^3. Design features of the sensor are reviewed and the results of the test program are discussed.

INTRODUCTION

A test program has been initiated in chamber A at the National Aeronautics and Space Administration (NASA)-Johnson Space Center (JSC) to investigate operational characteristics of supersonic nozzles for directing and controlling water vapor. These nozzles will be tested in a simulated space environment and evaluated to determine how efficiently they concentrate and direct water from spacecraft evaporative heat sinks.

To aid in nozzle performance evaluation, a water vapor molecular density sensor was developed and tested at the JSC. This sensor was designed to measure molecular densities at the nozzle exit plane without disturbing the plume flow field in the vacuum chamber.

This paper describes the effort required to develop a sensor for water vapor molecular density

measurement, and calibrate the sensor over the molecular density range 10^{13} to 10^{15} molecules/cm^3.

Sensor Description

The sensor consists of a sealed hydrogen lamp, a magnesium fluoride (MgF_2) lens, and a nitrous oxide (NO)-filled ionization chamber. The lamp is filled with hydrogen gas at a pressure of 8 torr. The clear aperture of 8 mm. is covered with a 1-mm.-thick $Mg F_2$ window. The detectors are NO-filled ionization chambers with windows of $Mg F_2$ and apertures of 0.53 mm. The ionization chambers are operated at 50 VDC in the saturation region with unity gain.

The radiation from the source is collected by a 3.75-cm. $Mg F_2$ lens with a focal length of 7.6 cm. The source-to-detector distance is 10.1 cm. This array yields a 1000-percent increase in detector output over that without the lens.

The $Mg F_2$ lamp and detector windows eliminate any radiation of wavelengths shorter than 1150 Angstroms, and the NO gas ionization upper limit occurs at approximately 1350 Angstroms. Hence, the bandwidth of the system is about 200 Angstroms, and the useful wavelength range is from 1150 to 1350 Angstroms.

Theoritical Considerations

Water vapor has been found to be highly absorbing in the wavelength range 1150 to 1350 Angstroms. The maximum absorption cross section over this range is reported to be in excess of 20 megabarns (1 mb = 10^{-18} cm^2, ref. 1). The measurement of absorption cross section is based on the Lambert-Beer law (ref. 2):

$$I_\lambda = I_0 \exp(-\sigma_\lambda nL) \tag{1}$$

where I_0 is the incident radiation flux of wavelength λ; I_λ is the flux transmitted through the absorbing gas; σ_λ is the absorption cross section; n is the molecular density of the absorbing gas; and L is the absorption path length.

The Lambert-Beer law is valid only for truly monochromatic radiation of infinitely narrow bandpass. However, previous studies have shown that if the

absorption cross section does not vary or is a slowly varying function of the wavelength over a given bandpass, an effective cross section can be measured for this bandpass (ref. 3).

When the semilog plot of $\log_{10}(I_0/I_\lambda)$ versus the molecular density, n, is a straight line, the absorbing medium is said to follow the Lambert-Beer law. However, if the sensor bandwidth is greater than the line width of the discrete structure, the linearity relation does not hold, and a "pressure effect" is observed. In this situation, a working curve for the sensor must be constructed over the nonlinear portion of the curve to obtain useful measurements (ref. 3).

Experimental Procedure

Calibration of the water-vapor molecular-density sensor was accomplished in a small (1-meter diameter, 1.5-meter length) vacuum chamber. This chamber was capable of attaining pressures in the 10^{-7} torr range using two 4100 liter/sec oil diffusion pumps. A millitorr gage was used to determine the pressure and, hence, the molecular density of the absorbing gas. An ionization gage was installed near the millitorr gage to measure the background pressure before the diffusion pump gate valves were closed and water vapor was admitted into the chamber. After the background pressure had stabilized around 1×10^{-6} torr, a heated inlet tube was used to introduce water vapor into the chamber. The water vapor pressure was controlled in the range 3.1×10^{-4} to 3.1×10^{-2} torr at the sensor using a variable orifice valve. Inlet tube pressure and temperature were monitored outside the chamber. The test setup and sensor configuration are shown in figure. 1.

The molecular density at the sensor was determined from the relation (ref. 4):

$$p = nkT \qquad (2)$$

where p is the pressure in torr measured by the millitorr gage, n is the molecular density of the absorbing gas in molecules/cm^3, k is the Boltzmann constant, and T is the gas temperature in °K.

Experimental Results

To calibrate the sensor and determine its sensitivity (measurement range), a plot of absorbance vs water vapor molecular density was obtained as a working curve over the range 10^{13} - 10^{15} molecules/cm^3 (3.1×10^{-4} to 3.1×10^{-2} torr, respectively). This

working curve is shown in figure 2. As indicated in this figure, the absorbance exhibits nonlinear behavior for increasing molecular densities and varies between 0.004 and 0.63 (99.1 and 23.4 percent transmittance respectively). This result was expected since the sensor bandwidth (1150 to 1350 Angstroms) is greater than the line width of the discrete structure of the hydrogen spectrum produced by the radiation source.

The sensor accurately measures absorbances as high as 1.0 (10 percent transmittance). At a molecular density of 10^{15} molecules/cm^3, the measured absorbance was 0.63. Hence, this test result indicates the molecular density range of the sensor exceeds 10^{15} molecules/cm^3.

The effective absorption cross section for each point shown in figure 2 was calculated and plotted as a function of molecular density. This curve is presented in figure 3. As indicated by this curve, the absorption cross section varies between 23 and 58 megabarns over the molecular density range 1×10^{13} to 1×10^{15} molecules/cm^3.

An interesting aspect of this curve is that it rises rapidly, reaches a peak at a molecular density of 8×10^{13} molecules/cm^3 (2.5×10^{-3} torr), and then falls off rapidly. By the time the molecular density has increased to 1×10^{15} molecules/cm^3 (3.1×10^{-2} torr) the absorption cross section has decreased from 58 to 25, which represents a $\Delta\sigma/\sigma$ loss of 57 percent.

CONCLUSIONS

Absorption measurement in the wavelength range 1150 to 1350 Angstroms is an extremely sensitive technique for water vapor molecular density determination. The useful measurement range for the sensor tested was determined to be from approximately 1×10^{13} molecules/cm^3 (3.1×10^{-4} torr) to densities in excess of 1×10^{15} molecules/cm^3 (3.1×10^{-2} torr). The absorption cross section, which establishes the limits of the sensor's sensitivity, was found to be dependent on molecular density.

Values calculated for the absorption cross section agree well with values reported in the literature. The sensor was found to have the highest absorption cross section (58 megabarns) at a molecular density of 8×10^{13} molecules/cm^3 (2.5×10^{-3} torr). Additional tests will be performed on the sensor to determine the upper limit of the molecular density measurement range.

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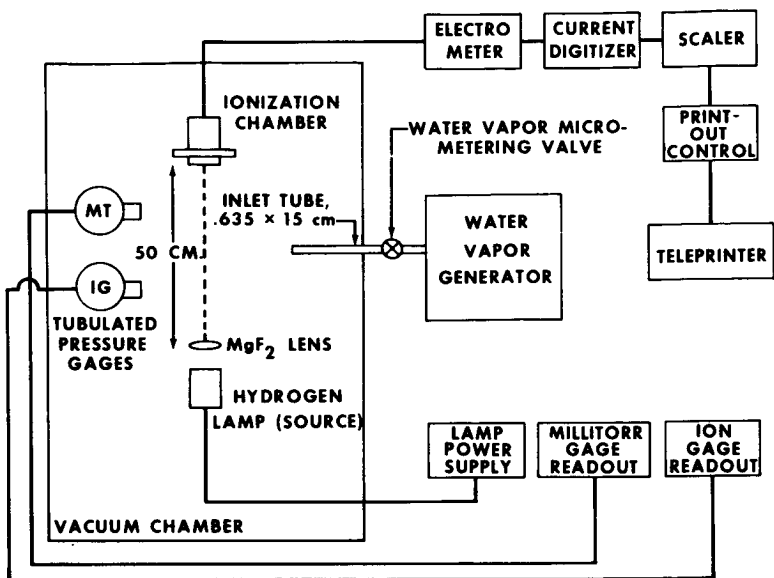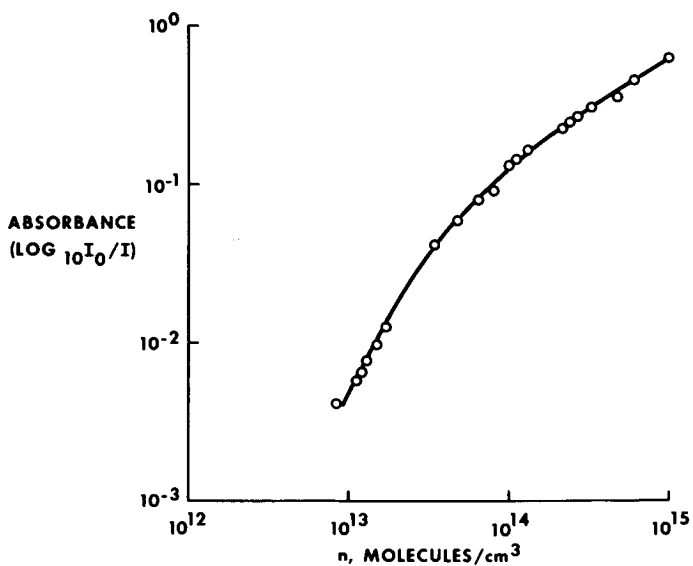
Fig. 1 – Test setup block diagram

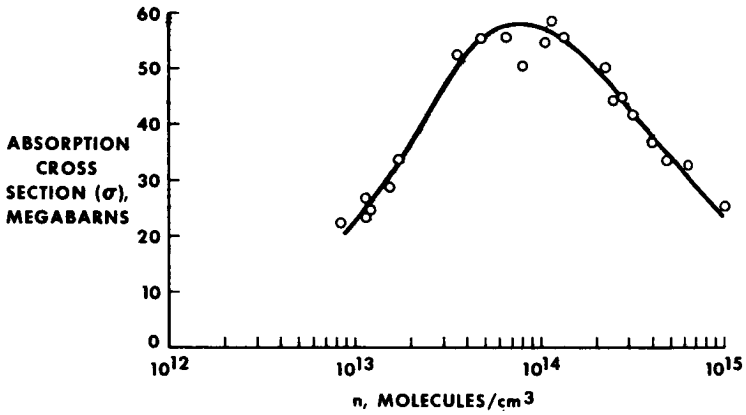Fig. 2 – Absorbance as a function of water vapor molecular density

Fig. 3 – Absorption cross section as a function of
water vapor molecular density