Laser-Based Measurement of Carbon Dioxide Absorption Spectra at Simulated Atmospheric Conditions

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Abstract

The ability to accurately measure the concentrations of carbon dioxide in the terrestrial atmosphere has become a crucial step towards understanding climate change, combustion, and other areas of atmospheric science. NASA’s decadal ASCENDS mission seeks to identify the sources and sinks of natural carbon and its movement throughout the atmosphere with the long-term goal of understanding and predicting changes in climate. Colorado State University has developed a bench-top, near-infrared cavity ring-down spectroscopy (CRDS) system for measuring concentrations of carbon dioxide in a gas sample. The motivation for continuing the project is to integrate a temperature and pressure-controlled gas system that allows for the CRDS system to take measurements at various operating conditions. The CRDS system allows for replication of specific atmospheric conditions at varying altitudes with the ability to alter the temperature and pressure of the gas sample. The data collected will be used by atmospheric scientists to improve their own atmospheric models and carbon dioxide measurement techniques.

1. Introduction

Colorado State University’s CRDS optical system measures absorption coefficients along a certain laser frequency range at a given temperature and pressure. These absorption coefficients inversely correlate to the intensity of the laser beam inside the testing cavity. The center of the laser frequency scanning range is chosen to correspond with a wavelength at which carbon dioxide absorbs light. As a result, light energy from the laser beam is absorbed when it comes into contact with carbon dioxide particles in the testing cavity. Through some calculations in LabView, the optical system is able to determine the concentration of carbon dioxide in a given sample of gas.

In order to determine whether CRDS technology can be used to accurately measure carbon dioxide concentrations at different levels in Earth’s atmosphere, a temperature and pressure control system has been developed that can simulate the temperatures and pressures that are experienced at a wide variety locations within the atmosphere.

2. Experimental Setup

The experimental setup shown in Figure 1 consists of three main systems. The first of these is the optical system, which consists of the diode laser, high reflectivity mirrors, testing cavity, and other optical components. The second is the temperature control system, which consists of an immersion chiller, a heat transfer fluid bath, and insulation. The third is the pressure control system, which consists of a series of ball valves and a vacuum pump.

Figure 1: Experimental Setup
2.1 Optical System

The optical system utilizes a diode laser operating in the infrared region of the electromagnetic spectrum. The diode laser is shown in Figure 2. A laser diode driver controls the current experienced by the laser and gives the laser the ability to scan back and forth across the electromagnetic spectrum. The temperature experienced by the laser is adjusted using a laser temperature controller. The beam emitted by the laser passes through a fiber optic cable to an isolator, which prevents the laser from being damaged by the beam being reflected back into the laser itself. After passing through the isolator, the beam enters an acousto-optic modulator, which can alternately direct the beam straight forward or deflect the beam through a series of mirrors and into the testing cavity. High reflectivity mirrors are placed on either side of the testing cavity in order to reflect the beam back and forth through the testing cavity. Because the mirrors are not perfectly reflective, part of the beam exits the cavity and enters a photo detector, which emits a voltage that corresponds to the amount of light energy that enters the detector. The photo detector is shown in Figure 3.

2.2 Temperature Control System

The temperature of the testing cavity is controlled using a heat transfer fluid bath and an immersion chiller. A rectangular stainless steel box surrounds the stainless steel testing cavity. Duratherm XLT-120 heat transfer fluid is then inserted into the box such that it completely covers the testing cavity. The temperature of the testing cavity is decreased by inserting the immersion probe shown in Figure 4 from a Cole-Parmer EW-01283-60 refrigerated chiller into the heat transfer fluid bath. The temperature of the cavity is increased by deactivating the immersion chiller and allowing the heat transfer fluid bath and thus the testing cavity to return to the temperature of the surrounding air. The increase in temperature is slowed by Thermasheath-3 insulation placed around the stainless steel box.

Figure 2: Diode laser

Figure 3: Photo detector

Figure 4: Immersion probe in heat transfer fluid bath in stainless steel box surrounded by insulation

2.3 Pressure Control System

The pressure of the gas sample inside the testing cavity is adjusted using ball valves and a vacuum pump. To decrease the pressure, the ball valve located at the inlet of the cavity is closed and the ball valve located at the outlet of the cavity is opened. A vacuum pump attached to the outlet of the cavity is then activated, removing part of the gas sample from the cavity. The outlet ball valve is then closed. To increase the pressure, the outlet ball valve is closed and the inlet ball valve is opened. A secondary inlet ball valve is then rapidly opened and closed to allow some of the surrounding gas to enter the cavity.

3. Data Collection and Analysis

Data is collected with a LabView program through a data acquisition card. The temperature of the testing cavity is determined by measuring the voltages across
thermistors attached to the outside of the testing cavity. The LabView program then converts the voltages into temperatures by performing calculations related to the properties of the thermistors. The pressure of the gas mixture inside the testing cavity is determined by reading a voltage from a pressure transducer attached at the inlet of the testing cavity. The LabView program converts this voltage into a pressure.

Absorption data at a given temperature and pressure is gathered by taking voltage measurements from the photo detector. A voltage trigger level is selected in the LabView program. Once the energy in the cavity is greater than the trigger level, a signal is sent to the acousto-optic modulator which directs the laser from the cavity. This allows for the energy to dissipate or ringdown. LabView then measures the ringdown time. The ringdown time is then converted to absorption coefficients, which are plotted with respect to the laser frequency at which the voltage was measured. The plot of absorption coefficient with respect to laser frequency is called an absorption spectrum. Absorption spectra experience a phenomenon called broadening, in which the frequency range over which light energy is absorbed becomes wider. Broadening occurs due to both increases in temperature and increases in pressure \[1\]. Thus, it would be expected that the spectra would be wider at high temperatures than at low temperatures and wider at high pressures than at low pressures.

4. Results

Absorption spectra were taken using Colorado State University’s CRDS system at three different pressure points in 5°C increments from -30°C to 15°C. An overlay of the specific temperature and pressure points at which data were taken on the graph of desired points for the NASA ASCENDS mission are shown in Figure 5 \[2\].

Figures 6 and 7 show absorption spectra at varying temperatures for a constant pressure, while Figures 8 and 9 show absorption spectra at varying pressures for a constant temperature. As expected, broadening occurred to a greater degree at higher temperatures and higher pressures.
Figure 7: Temperature-variant absorption spectra at constant pressure of 0.5 bar

Figure 8: Pressure-variant absorption spectra at constant temperature of -30°C

Figure 9: Pressure-variant absorption spectra at constant temperature of -5°C

5. Conclusions

The temperature and pressure control systems were used to simulate atmospheric conditions specified by the NASA ASCENDS mission. The CRDS system used to measure absorption spectra at these temperatures and pressures was successful in capturing the broadening effects that were expected to occur in the absorption spectra at higher temperatures and pressures.

5.1 Potential Improvements

One way in which the project could be improved is by gathering absorption data at lower temperatures. This could be achieved through the use of an immersion chiller that can reach a lower minimum temperature. Another potential improvement is the gathering of absorption data at higher pressures. By attaching a bottled gas to the inlet of the testing cavity, the pressure of the gas inside the cavity could be increased above the pressure of the surrounding gas.
6. References
