HIGH SPECTRAL RESOLUTION EMISSION THERMOMETRY

FOR COMBUSTION APPLICATIONS

by

Adam M. Myers

A thesis submitted in partial fulfillment of
the requirements for the degree of

Master of Science
(Mechanical Engineering)

at the

UNIVERSITY OF WISCONSIN-MADISON

2005
ABSTRACT

HIGH SPECTRAL RESOLUTION EMISSION THERMOMETRY FOR COMBUSTION APPLICATIONS

Adam M. Myers

Under the supervision of Assistant Professor Scott T. Sanders

At the University of Wisconsin-Madison

Several spectroscopic emission methods were investigated for the determination of combustion gas temperature. Spectroscopic simulations based on the HITRAN database were performed to aid in sensor design and data reduction. Four sensors were created, and limited testing was performed on three of the sensors.

The first sensor was based on a tunable spectroscopic filter being used to resolve the spectrum of the water emission band near 2.6 μm. The measured water spectrum was compared to simulations to determine the temperature in a gas turbine combustor at Wright-Patterson Air Force Base.

The second sensor is based on H₂O emission in the v₁ + v₃ bands. Two emission lines located at 1404 nm and 1405 nm were used in a ratiometric manner to determine gas temperature. A third channel near these lines was used to subtract background emission. Testing of this sensor was delayed due to lower than expected light detection levels.

The third sensor is based on CO₂ emission from 4.2 μm to 4.4 μm. This region of the CO₂ spectrum possesses the unique property of being optically dense over the engine
operating range. The emissivity of this feature is unity, thus the slope of the feature can be compared to the Planck curve to determine temperature. This sensor was tested using an optically accessible engine based on the GM Triptane block.

The fourth sensor is based on a commercial optical spectrum analyzer (OSA). An OSA uses a scanning grating to direct light onto a detector. It is able to accurately resolve the wavelength and power of incoming light. The measured data is compared to simulations to determine gas temperature. Testing of the OSA sensor was performed on a hydrogen-oxygen flame and on a high-pressure, high-temperature test cell.

A high-pressure, high-temperature (HPHT) test cell was investigated and built to test a variety of sensors. The HPHT test cell consists of a heated, sealed quartz cell with a known quantity of the species under investigation inside of it. The cell is located in a pressurized vessel to keep the quartz cell from breaking. Windows on both ends of the pressure vessel allow for the testing of both emissions and laser-based sensors. The HTHP cell was tested with a commercial optical spectrum analyzer.
DEDICATION

To my wonderful family, I owe it all to you.
ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Scott T. Sanders, for providing me with the opportunity to study in the ERC, and for teaching me so much. His knowledge and patience proved invaluable in my stay here. Additionally, I would like to thank the entire ERC faculty and staff, you have all been very helpful. Special thanks goes to Ralph Braun for helping me to hone my machining and motorcycle rebuilding skills, and Susie Strzelec for handling all of the behind-the-scenes paperwork.

I would also like to thank General Motors for their financial support of my project.

Thanks are owed to Glenn Bower and all of my teammates from the Formula SAE project. This project was one I’d waited many years to do, and I don’t regret a minute of it. Memories made in the shop at 4 AM (and on game days) will never be forgotten. Formula Way, live on.

Thanks to all of my friends I met in the ERC for helping me to balance my work schedule with sufficient play. And may I never eat bacon by the pound at 1 AM again.

Finally, the biggest thanks goes out to my family. Mom, Dad, thanks for being the best parents anyone could ask for. You taught me to aim for the stars, but keep my feet on the ground. I couldn’t have done it without you, and I love you.
# TABLE OF CONTENTS

Abstract.............................................................................................................................. i

Dedication.............................................................................................................................. iii

Acknowledgements.............................................................................................................. iv

Table of Contents.............................................................................................................. v

List of Figures...................................................................................................................... ix

Chapter 1 – Background and Literature Review............................................................... 1

1.1 Gas Spectroscopy........................................................................................................ 1

1.1.1 Linestrength........................................................................................................... 4

1.1.2 Line Broadening.................................................................................................... 6

1.1.3 Absorption Spectroscopy.................................................................................... 11

1.1.4 Emission Spectroscopy....................................................................................... 13

1.2 Previous Work............................................................................................................ 16

1.2.1 Single-Channel CO<sub>2</sub> Temperature Measurement.............................. 17

1.2.2 Spatial Imaging of a Combustion Chamber...................................................... 18

1.2.3 Temperature Measurement using a Highly Resolved OH Radical Spectrum........ 18

1.2.4 Two-Color Pyrometry of Soot................................................................. 19

1.2.5 NO Concentration Measurement using a Tunable Etalon...................... 19

1.2.6 Multiple Property Measurements.............................................................. 20

1.2.7 Ratiometric Pyrometry using Chemluminescence............................... 20

1.2.8 Dual CCD camera Temperature Imaging using Two-Color Soot Pyrometry........ 21
1.2.9 Flame Imaging for Temperature and Soot Concentration………21

1.3 Temperature Measurement for Engine Control……………………..21

Chapter 2 – AOTF Water Emission Sensor…………………………………24

2.1 Broad-scan AOTF Water Emission Sensor…………………………..24

2.1.1 Acousto-Optic Tunable Filter……………………………………….25

2.1.2 Fiber Access…………………………………………………………..26

2.1.3 Detector………………………………………………………………27

2.2 AOTF Sensor Results……………………………………………………28

2.2.1 Gas turbine testing…………………………………………………...28

Chapter 3 – High Resolution Water Emission Sensor……………………..33

3.1 Emission Line Selection………………………………………………33

3.2 Spectral Filtering………………………………………………………..38

3.3 Etalons…………………………………………………………………..39

3.4 Acousto-Optic Tunable Filter………………………………………….41

3.5 Fiber Splitter……………………………………………………………..41

3.6 Etalon Pressure Vessels……………………………………………….42

3.7 Etalon Pressure Vessel Optical Setup…………………………………43

3.8 Detectors………………………………………………………………..45

3.9 Lock-in Amplifier………………………………………………………45

3.10 Fiber Access……………………………………………………………..47

3.11 System Usage……………………………………………………………49

3.12 Optical Spectrum Analyzer Line verification…………………………50

3.12.1 System setup…………………………………………………………50
3.12.2 Results.................................................................52
3.13 Efficiency testing..................................................53
3.14 Results.................................................................54

Chapter 4 – CO₂ Blackbody Emission Sensor...............................55
  4.1 Sensor Theory.........................................................55
  4.2 Experimental Setup................................................59
  4.3 Sensor Usage........................................................62
  4.4 Results.................................................................63
    4.4.1 Two-channel ratiometric measurements.................64
    4.4.2 Single channel measurements..........................67
    4.4.3 Single channel temperature measurement error........70

Chapter 5 – Optical Test Cell.................................................72
  5.1 Emission Source.....................................................72
  5.2 Heater and Insulation.............................................73
  5.3 Pressure Vessel.....................................................74
  5.4 Cell Operation......................................................75
  5.5 Results...............................................................76

Chapter 6 – Discussion and Future Work....................................83
  6.1 AOTF Based Water Sensor.......................................83
  6.2 High Resolution Water Emission Sensor......................84
  6.3 CO₂ Blackbody Emission Sensor...............................85
  6.4 OSA Based Spectroscopy.........................................86
  6.5 Optical Test Cell..................................................87
6.6 Conclusions........................................................................................................88

Bibliography..............................................................................................................89

Appendix A – Fiber Probe Adapter Drawings.............................................................91

Appendix B – Cold Boundary Layer Effects on High Resolution Water

Emission Sensor.........................................................................................................93
LIST OF FIGURES

Figure 1.1  Emission and absorption.................................................................2
Figure 1.2  Laser light production.................................................................3
Figure 1.3  Hot and cold line illustration.......................................................6
Figure 1.4  Pressure broadening illustration................................................11
Figure 1.5  Etendue principle......................................................................15
Figure 2.1  Broad-scan survey spectrum.......................................................24
Figure 2.2  Sensor system schematic...........................................................25
Figure 2.3  Sensor system picture...............................................................27
Figure 2.4  Fiber probe installation in mainburner.........................................29
Figure 2.5  Broad emission scan.................................................................30
Figure 2.6  Temperature dependence of the spectrum....................................31
Figure 2.7  Mainburner spatial uniformity....................................................32
Figure 3.1  Emission survey spectra for carbon dioxide and water...............35
Figure 3.2  Ratio vs. temperature for different line pairs..............................36
Figure 3.3  7117 and 7121 cm\(^{-1}\) line ratio vs. temperature......................37
Figure 3.4  Selected water bands..............................................................38
Figure 3.5  Etalon cell assembly.................................................................43
Figure 3.6  AOTF tested modulation efficiency vs. frequency......................46
Figure 3.7  Sensor system picture..............................................................50
Figure 3.8  OSA measurement compared to HITRAN simulation..................52
Figure 4.1  Broad emission survey spectra..................................................55
Figure 4.2  Optically dense and sparse CO\(_2\)..............................................56
Figure 4.3  Optical density for an engine cycle ..............................................57
Figure 4.4  Optimal focal length testing .........................................................60
Figure 4.5  Sensor system picture .................................................................62
Figure 4.6  Light collection path .................................................................63
Figure 4.7  Measured ratio from two channel scan .......................................64
Figure 4.8  Effects of cold boundary layer on CO$_2$ emission .......................66
Figure 4.9  Temperature vs. ignition delay, adapted from [17] .......................67
Figure 4.10  Seeded vs. non-seeded emission measurement .........................69
Figure 4.11  Temperature vs. crank Angle ....................................................70
Figure 5.1  OSA measured emission ............................................................78
Figure 5.2  Comparison of measured data to Planck curve .........................79
Figure 5.3  Smoothed derivatives of measured and simulated data ...............80
Figure 5.4  OSA water absorption ..............................................................82
CHAPTER 1 – BACKGROUND AND LITERATURE REVIEW

This chapter provides an explanation of how gas spectroscopy works, and how it is used in the study of combustion processes. Examples of previous studies using emission spectroscopy are given. Finally, a brief overview is given of how temperature measurements prove useful in engine control.

1.1 Gas Spectroscopy

Gas spectroscopy is the use of light to study gas properties. The light used may come from a source such as a laser or blackbody emitter, or may come from the gas itself. For simple cases, the use of a laser source is called absorption spectroscopy, and the use of gas emission is known as emission spectroscopy. Spectroscopy takes advantage of the fact that gases have a unique electromagnetic signature. This signature varies based on the gas properties, such as temperature, pressure, and concentration.

The unique signature for every species arises from the quantum nature of the energy contained in the molecule. Generally, spectroscopy relies on the internal energy of the molecule, contained in three modes: rotation, vibration, and electronic. Quantum physics dictates that energy levels in these three modes are discrete, which gives the unique spectral signature of each species.

Emission spectroscopy relies on the emission of a photon when a molecule transitions from a higher energy state to a lower energy state. This is known as spontaneous
emission. This change in energy is of a known value for most molecules, and emits a photon of a known wavelength. The phase of the photon and the direction it travels are random.

Conversely, if a photon of the same wavelength hits this same molecule, it can absorb the photon and raise the energy state up to the original value. This is known as stimulated absorption and is useful for absorption spectroscopy. Just as a molecule will only emit photons resulting from a drop in discrete energy states, it will only absorb photons that will raise the energy levels to one of the allowed discrete states. An illustration of absorption and emission is located in Figure 1.1.

These changes in energy states are known as transitions, and occur at a specific frequency. In this thesis, the color of light is referred to in two different ways: wavelength and optical frequency. The optical frequency is the reciprocal of wavelength, and refers to the number of waves that occupy a 1 cm length. The units on wavelength are generally either [nm] or [μm], and the units on optical frequency are cm\(^{-1}\). The units of optical frequency are also referred to as wavenumbers.

![Figure 1.1: Emission and Absorption](image-url)
The photons for absorption spectroscopy usually come from a laser. Lasers rely on a phenomenon known as stimulated emission. In stimulated emission, a gain medium is pumped up to an excited energy state with flashlamps, an electric field, or other light source. A reflection cavity is set up around the gain medium so that spontaneously emitted photons can reflect between the two mirrors. As these photons reflect back and forth, they perturb the gain medium and cause excited electrons to drop down to the ground state. This drop in energy state emits photon of the same wavelength, phase, and direction as the perturbing photon, and is known as stimulated emission. These coherent photons in turn perturb the excited electrons and the cycle builds up an abundance of coherent photons, resulting in an amplification of light. One end of the reflection cavity is partially reflective so that photons can escape from the cavity. This produces a stream of photons with the same frequency and phase, which is known as a laser beam. The process is illustrated in Figure 1.2.

Absorption and emission spectroscopy are both very useful for studying gas properties. The next section will give details of how these quantum occurrences are used to determine spectral data for simulating how light behaves.
1.1.1 Linestrength

Various internal properties of a molecule affect the spectrum of the molecule. For example, changing the temperature of the molecule will change the populations of the internal energy states of the molecule. Certain energy states will become more populated and others will become less populated, causing the intensity of the transition lines, known as linestrengths, to change with temperature. The temperature dependence of the linestrengths is shown in equation 1.1.

\[ S_i(T) = S_i(T_o) \frac{Q(T_o)}{Q(T)} \left( \frac{T_o}{T} \right) \exp \left[ -\frac{\hbar c E_i^*}{k} \left( \frac{1}{T} - \frac{1}{T_o} \right) \right] X \left[ 1 - \exp \left( -\frac{\hbar c v_{o,i}}{kT} \right) \right] \left[ 1 - \exp \left( -\frac{\hbar c v_{o,i}}{kT_o} \right) \right]^{-1} \]

Eqn 1.1

\[ S_i = \text{linestrength for transition } i \]
\[ Q = \text{partition function for molecule} \]
\[ E_i^* = \text{lower-state energy of transition } i \]
\[ v_{o,i} = \text{frequency of transition } i \]
\[ T_o = \text{reference temperature} \]

The partition function used in the linestrength equation, Q, is defined in equation 1.2.
The quantity \( g_i \), known as the degeneracy, is the number of individual states with a common energy, \( e_i \). The partition function is the energy-weighted sum of all of the known energy levels. As shown in equation 1.2, it can be split into the products of partition functions of the rotational, vibrational, and electronic internal energies. The partition function is used in a form of Boltzmann’s equation for the determination of the fraction of molecules in an energy level. This form of Boltzmann’s equation is given in equation 1.3

\[
F_i = \frac{g_i \exp\left(-\frac{e_i}{kT}\right)}{Q} \quad \text{Eqn 1.3}
\]

The differences in linestrength due to temperature give rise to the terminology of “hot” and “cold” lines. Hot lines become more intense with a rise in molecular temperature, and cold lines become more intense with a decrease in temperature, as illustrated in Figure 1.3. This allows for the use of spectroscopy in temperature measurements. A ratio of a hot and a cold line is measured and compared to simulations in order to determine temperature.
1.1.2 Line Broadening

One might expect the spectrum of a gas to consist of a number of sharply defined intensity lines plotted against an optical frequency axis. However, these lines are broadened by a number of different phenomena. For example, broadening of the line shapes occurs due to uncertainties in the energy levels caused by uncertainties in the lifetime of an energy level, as shown in Equation 1.4. Heisenberg’s Uncertainty Principle is used to quantify this natural broadening. In a collection of molecules, each one will
transition at a slightly different energy level, spectrally broadening the lineshape in a fashion weighted near the center of the transition range.

\[
\Delta E_i \geq \frac{h}{2\pi \tau_i} \quad \text{Uncertainty of energy of transition } i \quad \text{Eqn 1.4}
\]

\[ \tau_i = \text{lifetime of transition } i \]

\[ h = 6.63 \times 10^{-34} \text{ J sec} = \text{Planck's constant} \]

In terms of optical frequency, the uncertainty is given as:

\[
\Lambda \nu = \frac{1}{2\pi} \left( \frac{1}{\tau'} + \frac{1}{\tau''} \right) \quad \text{Eqn 1.5}
\]

Where \( \tau' \) is the upper energy state and \( \tau'' \) is the lower energy state of the transition.

Natural broadening of the lineshape will always occur, even for a single molecule not affected by surrounding molecules. Natural broadening occurs because spontaneous emission determines the uncertainty in time of a transition. The governing equation for natural broadening is given in equation 1.6.

\[
\Delta \nu_N = \frac{1}{2\pi} \left( \sum_{k} A_{ik} + \sum_{k} A_{jk} \right) \quad \text{Eqn 1.6}
\]
A_{ik} and A_{jk} are what are known as Einstein A coefficients. They are defined as the probability per second of spontaneous decay from the upper to the lower state. Equation 1.4 is thus proportional to the sum of all spontaneous emission probabilities over k. All of the energy states lower than i (or j for the second sum) are represented by k.

Another form of line broadening is known as collisional or pressure broadening. As the pressure increases, the molecules undergo more and more collisions. This is another form of Heisenberg broadening and can cause a decrease in the lifetime of a transition. Pressure broadening is generally more significant than natural broadening, thus natural broadening can usually be ignored. The governing equation for pressure broadening is given by equation 1.7

$$\Delta \nu_c = \frac{P \sum A X_A \pi \left( \frac{1}{2} (\sigma_A + \sigma_B) \right)^2}{\pi} \left( \frac{8}{\pi \left( \frac{m_A m_B}{m_A + m_B} \right) kT} \right)^{\frac{1}{2}}$$

Eqn 1.7

$X_A =$ Mole Fraction of species A

$\sigma =$ diameter of molecule A or B

$m =$ mass of molecule A or B

$P =$ Total Pressure

$T =$ Temperature

$k =$ Boltzmann’s constant
Another significant source of broadening is what is known as Doppler broadening. Gas molecules all have a random velocity, which causes a shift in the frequency of photons of which the molecule will absorb or emit. The governing equation for Doppler broadening is given in equation 1.8.

$$\Delta \nu_B = \nu_o \left( \frac{8kT \ln 2}{mc^2} \right)^{\frac{1}{3}}$$  \hspace{1cm} \text{Eqn 1.8}

In equation 1.8, $\nu_o$ is the original frequency of the transition, $m$ is the mass of the molecule, and $c$ is the speed of light. Doppler broadening causes a lineshape to have a Gaussian form. Natural and pressure broadening both have a Lorentzian lineshape.

The last source of broadening is artificial broadening. This is not a fundamental broadening effect, but occurs when the measuring device being used to acquire spectra has insufficient resolution and smoothes out sharp transitions. This effect can be minimized by using equipment with a narrow spectral resolution.

Pressure, Doppler, and artificial broadening are the dominating broadening effects in the study of temperature in internal combustion engines. Another broadening effects can occur due to particle charge (Stark Broadening); however, this is a minor effect in IC engine measurements and will be left out of this discussion.
In the usual case where pressure and Doppler broadening are the dominant cases, the lineshape formed is a convolution of the Gaussian and Lorentzian lineshapes. This convolution is accomplished using the Voigt function, given in equation 1.9. This function reduces to the form in equation 1.14 through the definitions contained in equations 1.10 through 1.13. This lineshape is used in determining the value of $k_v$, discussed in the next section.

\[
\phi_v(v) = \int_{-\infty}^{\infty} \phi_D(u) \phi_C(v-u) du \quad \text{Eqn 1.9}
\]

\[
a = \frac{\sqrt{\ln 2} \Delta V_C}{\Delta V_D} \quad \text{Eqn 1.10}
\]

\[
w = \frac{2\sqrt{\ln 2}(v-v_0)}{\Delta V_D} \quad \text{Eqn 1.11}
\]

\[
\phi_D(v_0) = \frac{2}{\Delta V_D} \sqrt{\frac{\ln 2}{\pi}} \quad \text{Eqn 1.12}
\]

\[
y = \frac{2u\sqrt{\ln 2}}{\Delta V_D} \quad \text{Eqn 1.13}
\]

\[
\phi_v(v) = \phi_D(v_0) \frac{a}{\pi} \int_{-\infty}^{\infty} \frac{\exp(-y^2)dy}{a^2 + (w-y)^2} \quad \text{Eqn 1.14}
\]
Broadening effects make it possible to measure pressure and concentrations of gases in an IC engine environment. Figure 1.4 shows two identical water spectra simulated at 1500K, 10% concentration, and a path length of 1 cm. The first graph is at a pressure of 5 atm and second graph is at 30 atm, and the absorbance is normalized for ease of comparison. This illustrates that the lines broaden, sometimes enough to combine multiple individual lines into single broad features. By measuring the width of the lineshape, one can determine the pressure of the molecule in the combustion chamber.

![Identical water spectra, except for pressure](image)

Figure 1.4: Pressure broadening illustration

1.1.3 Absorption Spectroscopy

The linestrength and the lineshape are both used in the determination of the value of the spectral absorption coefficient, $k_v$. The definition of $k_v$ is given in equation 1.15. As can
be seen, it is defined by the linestrength and lineshape, as well as the partial pressure of
the molecule.

\[ k_\nu = S_\nu \phi(\nu) P \]  
Eqn 1.15

The spectral absorption coefficient is used in Beer’s Law of Absorption, the fundamental
law governing absorption spectroscopy. It gives the fractional transmission of light at a
specific wavelength for a given path length and species at a specific condition. Beer’s
law is given in equation 1.16. The quantity \( \left( \frac{I}{I_o} \right)_\nu \) is known as the spectral absorbance.

\[ \left( \frac{I}{I_o} \right)_\nu = \exp(-k_\nu L) \]  
Eqn 1.16

Where I is the transmitted intensity of light, I_o is the incident intensity of light, and L is
the path length.

The value of k_\nu can thus be determined experimentally by measuring the incident and
transmitted intensities of light through a gaseous species, along with the path length of
the gas. Generally, k_\nu is calculated and used to create a series of absorption spectra,
which are then compared to the measured spectrum. For example, to measure the
temperature of a gas at a known pressure, simulations would be run for the gas at various
temperatures, and the measured spectra would be compared to the simulated. The closest match would yield the temperature of the gas.

Simulations of spectra for various species can be carried out using the HITRAN database. HITRAN is a molecular spectroscopy database started by the Air Force Cambridge Research Laboratories (AFCRL) back in the late 60’s. It is now maintained by Dr. Laurence Rothman, based at the Harvard-Smithsonian Center for Astrophysics. It contains calculated and observed spectroscopic information on a variety of molecules. The filtering software associated with HITRAN, JavaHAWKS, is used to send the desired data to simulation codes.

HITRAN contains all of the information needed to simulate molecular spectra. These values are used in the previous equations to calculate the spectral absorbance of a molecule for most any given condition. A LabView code was created with all equations necessary to calculate $k_v$. This code makes it easy to simulate various species at various conditions. JavaHAWKS is used to create the parameters necessary for the species of interest, and the front end to the LabView code allows for easy selection of the concentration, temperature, and pressure of the simulated spectra.

1.1.4 Emission Spectroscopy

Emission spectroscopy measurements require a way to simulate the emission of a gaseous species. This requires a modification of the absorption code. Simulations for emission spectroscopy are carried out in a fashion similar to absorption spectroscopy. In the
LabView absorption code, $S_{21}$ (the linestrength,) is calculated. For emission spectroscopy, $S_{21}$ is converted to $A_{21}$, an Einstein coefficient for spontaneous emission. This is accomplished via equation 1.17, and gives the emission linestrength.

$$A_{21} = \frac{S_{21}8\pi\nu^2kT}{c} \quad \text{Eqn 1.17}$$

Then power emitted is calculated using equation 1.18.

$$P_{\text{emit}} = \phi(\nu)A_{21} \frac{\text{Area}}{P/kT} \exp\left(-\frac{hc\nu}{kT}\right)\tan^2\frac{\theta}{4}h\nu \quad \text{Eqn 1.18}$$

The area term is determined by looking at the cross-sectional area of the cylindrical volume imaged by the fiber or other collection system. Pressure (P) is in Pascals, Temperature (T) is in Kelvins, the tangent term determines the solid angle collected by the collection system. In the common case of a fiber being used to collect light, $\theta$ is determined by the numerical aperture (NA) of the fiber. The fiber diameter and NA are related to the imaged volume by what is known as etendue. Etendue is a relationship between the diameter of a light source and its divergence angle, and is defined mathematically in equation 1.19.

$$d_1\sin\Theta_1 = d_2\sin\Theta_2 \quad \text{Eqn 1.19}$$
A graphical representation of the etendue principle is located in Figure 1.5. One consequence of the etendue principle is that changing the diameter of the collection fiber will not increase the amount of light collected, if proper optics are used on the collection fiber.

![Etendue principle](image)

**Figure 1.5: Etendue principle**

In addition to the above equations, the effects of molecules re-absorbing the emitted light must be taken into consideration. As the light travels through other identical molecules, some of the light will get re-absorbed. Equation 1.20 shows how this re-absorption is modeled and used to calculate the collected power from the total emitted power. The spectral absorption coefficient is used in this equation. In the limit case where the absorbance is small, $P_{\text{col}} = P_{\text{emit}}$.

$$P_{col} = \frac{1 - \exp(-k_v L)}{k_v L} P_{\text{emit}} \quad \text{Eqn 1.20}$$
1.2 Previous Work

Both absorption and emission gas spectroscopy have been used for quite some time as a measurement technique in internal combustion engines. Parameters such as temperature, species concentration, pressure, and velocity are commonly measured. Optical studies are convenient because they are generally non-invasive and can provide fast analysis of the combustion process.

The work done in this thesis focuses on highly resolved emission spectroscopy of gases. Highly resolved generally means a resolution of better than 0.1% of the wavelength, ie. better than 1.4 nm at 1400 nm. Optical transitions in the infrared (IR) spectral range are studied. Transitions in the IR consist of rotational and vibrational energy levels, commonly referred to as the rovibrational energy levels. The IR spectral region is convenient for the study of gases in IC engines because the spectra for common species such as H$_2$O, CO$_2$, and CO can be isolated.

Most previous emission diagnostic work utilizes either low-resolution spectra to determine gas parameters, or the emission of soot particles to determine temperature. One problem with the use of soot as an emitter is that the composition of soot can vary. For example, the emissivity of the soot can vary as a function of crank angle. Correlations have been made to determine the emissivity of soot [1], but they are not exact due to its complex molecular structure.
Additionally, broadband emission measurements can be affected by particle buildup on the windows or fiber, or other interferences such as soot suspended in the gas. Interferences can preferentially attenuate one wavelength more than another, leading to errors in the measurement. Single channel sensors are affected by interferences as well, as the attenuation of the signal can vary at each measurement depending on the level of interference.

The use of spectrally nearby emission features can eliminate the effects of interference on measurements. By looking at features that are spectrally close, the effects of wavelength dependant interferences are minimized. For example, soot will attenuate much more similarly if the wavelengths are spectrally close.

The following cases give examples of how emission spectroscopy has been used in the study of gas properties in combustion processes.

1.2.1 Single-Channel CO\textsubscript{2} Temperature Measurement

Temperature can be measured using a single, narrow emission feature of CO\textsubscript{2}. CO\textsubscript{2} near 4.3 \textmu m has a constant emission value across a range of crank angles in a spark-ignited engine. The value of this emissivity was determined by placing a blackbody emitter before an optically accessible engine. Light from the blackbody passed through the combustion chamber and the absorption of the CO\textsubscript{2} feature was measured. This blackbody emitter was used for calibration only, and removed after the absorption value was determined. This absorption value was converted to an emission value and used
along with Planck’s law to determine the temperature of the gas during the combustion cycle [2]. This technique is similar to one studied in this thesis, except for the emissivity of CO$_2$ is taken as a non-unity value.

1.2.2 Spatial Imaging of a Combustion Chamber

Multiple fibers can be used to resolve spatial differences inside of a combustion chamber. The fibers are arranged in a flat pattern across the combustion chamber, so that each fiber collects light from a certain region of the combustion chamber. Light from the fibers is then sent through filters to select the wavelength region of interest. The light then goes to a CCD camera, where it is then manipulated to image the entire chamber [3]. Being able to image different sections of a combustion chamber is useful due to the non-uniformity of gas properties in an engine.

1.2.3 Temperature Measurement using a Highly Resolved OH Radical Spectrum

In-cylinder gas temperatures can be measured using the emission of the OH radical near 306.36 nm. The OH radical emits strongly at this wavelength and is independent from emission from other species. Light is collected and sent through a monochromator to a CCD camera, which converts the spatially separated light into a spectrum. The spectrum is averaged over multiple cycles and compared to simulated spectra to determine the gas temperature. The concentration of NO is determined by using the temperature with the extended Zeldovich-mechanism [4].
1.2.4 Two-Color Pyrometry of Soot

Temperature can be determined by using two-color pyrometry of soot. A quartz rod is installed in the head of an engine and used to send light to a split fiber. Each leg of the fiber splitter is sent through a filter to select the desired wavelength, and photomultipliers are used to collect the light. The ratio of emission at 502 nm and 797 nm was compared to a curve-fit of Planck’s equation for the determination of temperature. The system was calibrated using a blackbody emitter [5].

1.2.5 NO Concentration Measurement using a Tunable Etalon

Highly resolved individual transitions of NO can be used to determine the concentration of NO in a background of H$_2$O at a known temperature. A Fabry-Perot Interferometer, commonly known as an etalon, is used to select an individual NO transition near 5.19 $\mu$m. The etalon has a narrow enough pass-band to select an NO transition line without selecting an H$_2$O line. The etalon was tunable over a range of approximately 8nm through the use of a piezoelectric actuator. The piezoelectric actuator moves the two plates of the etalon relative to each other to adjust the length of the interference cavity. The multiple orders from the etalon were subtracted with a monochromator, which acts as a filter with a relatively wide pass-band. The expected power output of the system was calculated using the HITRAN database, and the measured signal was compared to the predicted to determine the concentration of NO [6]. This study is similar to work done in this thesis in that it looks at highly resolved spectra.
1.2.6 Multiple Property Measurements

Band-pass filtered emission and multiple fibers can be used to collect information on CO$_2$ and H$_2$O concentration and temperature. A fiber bundle is used to collect light from a combustion chamber. Each fiber runs through a band-pass filter to select the desired wavelength. A guess value of 2200K is used to start with. CO$_2$ emission near 4.3 μm is used with this temperature to determine the emissivity and column density of the CO$_2$. Next, the guess temperature is used with the emission near 2.4 μm to find the emissivity and column density of the H$_2$O. Lastly, emission near 2.7 μm is used with the guess temperature and the H$_2$O column density to determine a new column density of CO$_2$. The two column densities are averaged and used with the emission near 4.3 μm to determine a new temperature. This entire process is repeated until the CO$_2$ column densities match, which gives the final temperature and final CO$_2$ and H$_2$O column densities [7].

1.2.7 Ratiometric Pyrometry using Chemluminescence

The excess air quantity in a gasoline engine can be determined by looking at the ratio of the intensities of chemluminescence emission from the HC and C$_2$ radicals. Rich mixtures produce stronger emission from the C$_2$ radical, and lean mixtures produce stronger emission from the HC radical. A quartz rod was placed in the cylinder head and used to collect emitted light. The light was then sent through two waveguides to interference filters in order to select the light at 431.5 and 516.5 nm. The ratio of the two signals was then compared to simulated data to determine the excess air ratio in the engine [8].
1.2.8 Dual CCD camera Temperature Imaging using Two-Color Soot Pyrometry

Imaging can be used to determine in cylinder gas temperatures in diesel engines. An endoscopic fiber arrangement is used to send light through two filters, one centered at 500 nm and the other centered at 750 nm. The filters each have a dedicated CCD camera after them to image the combustion chamber. A two-color pyrometric measurement technique is used to obtain quantitative temperature measurements from the soot in the combustion chamber. Approximately 100 cycles can be averaged before the endoscope optics become too dirty to work properly. This method can be used to obtain temperature information for non-uniform gas properties such as found in a diesel engine [9].

1.2.9 Flame Imaging for Temperature and Soot Concentration

A single CCD camera can also be used to image a flame and determine soot concentration and temperature. A prism is used to double the image coming from a flame. Two filters are placed after each “image” in order to select the regions of the spectrum of interest. Both images are captured on a single CCD camera. The system is calibrated using a tungsten lamp. Common two-color pyrometry is then used to determine the flame temperature in different regions of the flame, and then the soot volume fractions are determined from the temperatures [10].

1.3 Temperature Measurement for Engine Control

In cylinder temperature measurements can be very useful for the control of engines. The temperature of the combustion gas has a very noticeable effect on the emission produced
by the engine. For example, NO\textsubscript{x} production is directly related to the temperature history of the combustion process. When in cylinder temperatures rise above a certain threshold NO\textsubscript{x} will be produced, and remains “frozen” even if the temperature is lowered [11, 12].

Soot formation is also related to in-cylinder temperature. Soot formation occurs when fuel-rich regions partially burn, and is generally associated with low combustion temperatures. High combustion temperatures for long periods will oxidize and reduce the emitted soot [11, 12].

The need to control both soot and NO\textsubscript{x} emissions presents a problem. High combustion temperatures are needed to oxidize and reduce the soot emission, while low temperatures are needed to prevent NO\textsubscript{x} formation. This conflict is known as the soot-NO\textsubscript{x} tradeoff.

This tradeoff can be avoided by keeping the combustion temperature low enough that soot is not produced. This is accomplished through the use of large amounts of EGR. The downfalls of this method involve decreased engine power and large amounts of CO and unburned hydrocarbons. [13].

A more common method being used to reduce both soot and NO\textsubscript{x} emissions involves splitting the fuel injection into multiple pulses. This allows for the modification of the temperature-time dependence history of the engine. For example, the primary injection would be early to lower the temperature and reduce NO\textsubscript{x} production. A subsequent injection would be used to temporarily increase the temperature and oxidize soot [14].
Temperature measurements can be used in two ways to improve the soot-NO\textsubscript{x} tradeoff. The first method is a delayed control strategy. A pre-determined injection profile could be monitored to determine that the temperature profile behaves as expected. If the temperature profile deviates from the expected during the cycle, possibly due to changing load conditions, the injector can be commanded to inject with a different profile during the next cycle to reduce the NO\textsubscript{x}.

The second temperature control strategy involves the use of immediate control of the injection profile. In a multiple injection engine control scheme, temperature information from the first injection can be used to tailor subsequent injection pulses. For example, if the temperature during the first injection is low enough to produce excessive soot, the subsequent injection pulses can be increased to better oxidize it. This has the potential to greatly reduce tailpipe emissions without the need for complex/expensive aftertreatment devices.
CHAPTER 2 - AOTF WATER EMISSION SENSOR

2.1 Broad-scan AOTF Water Emission Sensor

The first method of determining temperature was based on a broad scan of the water emission band near 2.6 \( \mu \text{m} \). This portion of the spectrum is relatively free from interference of different species. It also offers fairly high emission levels. A graph of the spectrum studied is located in Figure 2.1.

![Figure 2.1: Broad-scan survey spectrum](image)

Temperature is determined by comparing the measured peak heights to simulated peak heights. Due to the presence of hot and cold lines, each temperature will produce a
different emitted spectrum. A range of simulations at different temperatures is run, and the measured data is compared to the simulations. The closest match of the peak heights gives the temperature. Temperature detection based on a broad scan has many advantages. The multiple peaks give more data points to compare to simulated values. Also, the multiple data points allow for the determination of the gas pressure and concentration. A schematic of the chosen sensor system is located in Figure 2.2.

![Sensor system schematic](image)

Figure 2.2: Sensor system schematic

### 2.1.1 Acousto-Optic Tunable Filter

In order for this method to work, the individual line strengths need to be accurately resolved. The chosen method involved the use of a device called an Acousto-Optical Tunable Filter (AOTF.) The AOTF is an interference filter that uses a crystal in which standing waves are created by vibrating the crystal at a specific frequency. An RF amplifier converts an input voltage into a high frequency signal and amplifies it to levels significant enough to allow a piezoelectric element to vibrate the crystal. The standing waves in the crystal locally alter the index of refraction in the crystal and create an
interference pattern. This pattern can be rapidly varied to allow for tuning of the diffracted wavelength over a significant range. In addition, the drive signal to the AOTF can be turned on and off rapidly to effectively act like a very high frequency signal chopper. This is useful for lock-in amplification, which is used to improve the signal to noise ratio of the collected light. Lock-in amplification is discussed in further detail in Section 3.9.

### 2.1.2 Fiber Access

For ease of use and flexibility, a fiber is used in the combustion chamber to collect the light emitted by the combustion process. In tests conducted at Wright-Patterson Air Force Base, a unique fiber collection method was devised. A 1-meter long “Anhydroguide G” fiber from Fiberguide Industries was placed inside a stainless steel tube. A sapphire ball was placed in a stainless steel mount and affixed to the stainless steel tube. This mount seals the sapphire ball from the outside environment and from the fiber. The sapphire ball is very durable and easily cleaned. This is an important consideration when dealing with harsh environments such as found in a combustion chamber. The sapphire ball acts as a lens and focuses light from the combustion process into the fiber. The end of the fiber extends from the stainless steel tube and is mechanically locked to the tube through the use of heat shrink tubing. A standard SMA connector was placed on the end of the fiber to allow for easily coupling into the sensor system.
The light from the fiber was collimated using an off-axis parabolic mirror. This collimated light was sent into the AOTF where it was spectrally filtered and chopped for the use of a lock-in amplifier. The AOTF sends the un-diffracted beam out in the same direction as it entered, and sends the diffracted light out at a 7-degree angle. Because of this, the path length after the AOTF must be long enough for the two beams to separate. To shorten this required path length, an iris was used to block the un-diffracted beam.

2.1.3 Detector

The diffracted beam was sent to another off-axis parabolic mirror where it was focused into an InAs detector with a four stage thermo-electric cooler. The 4-stage cooler allowed for detectivity levels of $6 \times 10^{11} \text{ cm}^2 \sqrt{\text{Hz}}/\text{W}$ to be achieved. The entire sensor system was secured inside of a plastic box and purged with nitrogen to remove any atmospheric water that could re-absorb the collected light. A picture of the entire sensor system is located in Figure 2.3

![Sensor system picture](image)
2.2 AOTF Sensor Results

The AOTF based sensor was initially tested using an oxy-acetylene torch as the emission source. The torch was lit away from the sensor optics to keep them from becoming covered in soot. The fiber probe was aimed at the flame and the results were verified with an oscilloscope. This test confirmed that the detector was indeed sensitive enough to measure light emission from a flame.

2.2.1 Gas turbine testing

The sensor system was taken to Wright Patterson Air Force Base to be tested on the mainburner of a research gas turbine. The gas turbine combustor provides for an ideal test subject since the combustion is steady and fairly stable. Fiber probes were placed in the mainburner in different locations to allow for temperature measurements in different sections of the mainburner. The fiber probes passed through a pressure vessel into the mainburner. A picture of the fiber probe installation with the pressure vessel top removed is located in Figure 2.4.
The first test involved scanning the AOTF over a wide range and looking at the detected spectrum. The scan was broad enough to detect multiple water emission bands. It also picked up emission from CO, which was partially obscured by H$_2$O emission. A plot of the scanned spectrum is located in Figure 2.5. This plot shows the measured spectrum plotted with the simulated spectrum. The measured spectrum follows the general shape of the simulated features, but lacks spectral resolution.
Figure 2.5: Broad emission scan

In order to obtain more accurately resolved spectrum, the scan was next limited to the water emission feature centered around 2600 nm. The scan repetition rate was set at 2 Hz and the signal was averaged 10 times to make up for decreased signal intensity. A plot of the temperature dependence of the spectrum is located in Figure 2.6
The next parameter studied was the spatial uniformity of the combustion in the mainburner. The spectrum was measured using different probes placed in the mainburner. The results, given in Figure 2.7, show that the mainburner had fairly good spatial uniformity, with the temperature difference between the two sections of the mainburner at 140 degrees Fahrenheit.
Figure 2.7: Mainburner spatial uniformity

- $T = 3270 \, ^\circ F$ (fiber #1)
- $T = 3410 \, ^\circ F$ (fiber #2)
- $\Delta = 140 \, ^\circ F$
CHAPTER 3 - HIGH RESOLUTION WATER EMISSION SENSOR

After conducting the AOTF sensor tests, two drawbacks were discovered, the scan speed of the AOTF sensor was too slow to be useful for IC engine measurements and the spectral resolution was too low to be able to fully resolve the rovibrational structure.

Because of these drawbacks, a different method was needed to obtain high-resolution water spectra emission. A high-resolution spectrum allows for a more exact comparison to simulated data. The sensor also had to have a high sampling rate, preferably fast enough to resolve spectra for each crank angle of the test engine. A method utilizing a grating to spread light onto a linear detector array was researched, but was rejected as having insufficient resolution.

It was finally decided to focus on utilizing the ratio of two individual lines to determine temperature. Two line measurements can be taken very quickly, because only two data points need to be taken for each crank angle. They can also be used to output real time temperature information, since they can be simulated beforehand and the ratios can be tabulated or curve-fit to give a correlation between detector signals and temperature.

3.1 Emission Line Selection

The first step in designing this sensor involves finding two suitable H$_2$O emission lines. The lines must consist of a hot line and a cold line, that is one line that increases in intensity with an increase in temperature, and the other line that increases in intensity
with a decrease in temperature. A larger ratio between the two lines will give greater sensitivity to temperature. In addition, the two lines must be chosen to be spectrally close to each other. This will minimize errors due to interference preferentially attenuating one channel more than the other channel. Finally, the emission from both lines must be strong enough to detect reliably.

A third portion of the emission spectrum is also used to subtract background radiation. Background radiation can come from soot or hot cylinder walls. This portion of the spectrum must be between emission lines, so that there is minimal contribution from the water to this signal. It also must be spectrally close to the two emission lines. Fortunately, this is a relatively common occurrence and is a minor consideration.

In order to find two suitable emission lines, we utilized survey simulations of water produced at different temperatures. These survey spectra were generated with our lab’s emission simulation program, utilizing the HITRAN and HITEMP databases. Survey spectra were generated for multiple species at multiple temperatures in order to look for features that can be useful in the lab’s mission to develop optical sensors to study gases in various environments. The species included in the survey were H$_2$O, CO$_2$, CO, NO, and OH. A plot of the H$_2$O and CO$_2$ emission survey spectra is shown below in Figure 3.1.
The H$_2$O spectrum was carefully analyzed by hand to find two suitable emission lines. Suitable line pairs were chosen with the criteria that they were close together and exhibited a significant ratio based on temperature changes. The chosen line pairs were located in the band shown to the far left in Figure 3.1, so it can be seen that they are weak compared to the rest of the water spectrum. A graph of the line pairs chosen and their ratio curves vs. temperature are given in Figure 3.2. The most promising lines were a pair located at 7117 cm$^{-1}$ and 7121 cm$^{-1}$, or 1405 and 1404.3 nm. These lines are very close, virtually eliminating the chance of preferential attenuation errors in the temperature. They also are far enough apart to be able to easily select each line without getting interference between the lines, such as may be the case for the 7327 and 7329 cm$^{-1}$.
1 lines. A series of plots of the 7117 and 7121 cm$^{-1}$ lines shown in Figure 3.3 illustrate how they change intensity with changing temperature.

Figure 3.2: Ratio vs. Temperature for different line pairs
The chosen line pair is located in the $v_1+v_3$ water emission band, shown in Figure 3.4. One problem with this line pair is that the intensity of the emission is not very strong, on the order of 0.1 nW/nm. Therefore, a very sensitive optical system had to be designed in order to realize high-speed temperature sensing.
3.2 Spectral Filtering

The first step in designing the sensor hardware was to choose a way to be able to select individual lines from the broadband emission coming out of the combustion chamber. These spectral filters also had to have a very low attenuation of light. Interference filters were looked at, but rejected due to their relatively wide band-pass. Fiber Bragg gratings were also investigated, but were rejected due to their need for an optical circulator and their limited tuning range. The final, and chosen, candidate was a Fabry-Perot interferometer. Fabry-Perot interferometers, hereto referred to as etalons, are ideal candidates for spectrally narrow band-pass filters. They can be designed to be spectrally...
narrow enough to select individual emission lines. They also have a fairly high transmissivity.

### 3.3 Etalons

Etalons filter light utilizing an interference effect. Two highly polished surfaces form an interference cavity. These surfaces are treated with a highly reflective coating to maximize their efficiency. The distance between the surfaces and the reflectivity of the coatings are carefully chosen to give the desired transmission properties. By having a relatively large cavity length, a narrow band-pass filter can be formed. However, etalons produce constructive interference with multiple orders, that is any integer multiple of the central wavelength will constructively interfere and therefore be passed through the etalon. The method utilized to deal with these multiple orders is discussed in section 3.4.

There are two types of etalons, solid etalons and air-gap or air-spaced etalons. We decided to utilize air-spaced etalons due to their ease of tuning without losing spectral resolution. Both types of etalons can be tuned by tilting the axis of the etalon with respect to the incoming light beam. However, this will adversely affect the spectral resolution. With air-spaced etalons, the central wavelength can be selected using a process called pressure tuning. By increasing the pressure in the air gap (and around the etalon itself in order to prevent it from bursting,) the index of refraction changes. This locally alters the wavelength so that a different wavelength is subject to constructive interference.
Etalons can also be tuned by controlling their temperature. This changes the index of refraction of the etalon material or gas in the gap for the air-spaced etalon. It also changes the distance between the reflecting surfaces. However, this method was rejected due to its limited tuning range over a reasonable temperature range.

In order to be able to pressure tune the etalon without having to resort to excessive pressures, a gas must be used that has a high index of refraction. In addition, the gas must not absorb any of the light passing through the etalon. The first gas looked at was xenon, which has an index of refraction ten times greater than that of air. It also doesn’t have any transitions in the IR, so it will not interfere with the light being studied. However, xenon is the most expensive gas in the world, and it was rejected as being too costly. From [16], Sulfur hexafluoride (SF$_6$) was chosen as a suitable gas. The index of refraction is nearly the same as that of xenon, it is a heavy molecule so it is not active in the IR, and the costs were much lower than xenon. Also, SF$_6$ is widely used in the electronics industry as an insulating gas, so it is readily available [15].

CVI Optics in England was contacted to construct the etalons. The etalons were treated with an anti-reflective coating on the outer faces to maximize the transmission of the etalons. The final specifications chosen were an air gap of 50 microns, a reflectivity of 0.92, and a clear aperture of 30 mm. This gave us a free spectral range (FSR) of 100 cm$^{-1}$, a pass-band full-width half-maximum (FWHM) of 2.65 cm$^{-1}$, and a peak transmittance of 87%.
The pressure tuning of the etalons with SF$_6$ up to 300 psi allows them to be tuned across a range greater than the FSR. This means that any wavelength could be chosen as the central wavelength, within the transmission range of the anti-reflective coatings. Practically, this allows for the selection of any line in the $v_1+v_3$ water emission band. This gives the flexibility to select another line pair if the chosen pair proves inadequate for our needs.

### 3.4 Acousto-Optic Tunable Filter

An acousto-optic tunable filter (AOTF) was used to filter out the multiple orders that would otherwise pass through the etalons. The AOTF also was used to modulate the light to allow for the use of lock-in amplification, discussed in section 3.9. The AOTF used was purchased from Brimrose Corporation and had a 15 nm passband at 1.4 μm.

### 3.5 Fiber Splitter

In order to send light from the AOTF to the three etalon cells, a fiber splitter must be used. The chosen fiber splitter had one glass 550 μm 0.22 NA fiber for the input, and three glass 550 mm, 0.22 NA fibers for the outputs. The split ratio was specified to be equal between the output legs. The fiber splitter was manufactured by Fibersense & Signals.
3.6 Etalon Pressure Vessels

In order to pressure tune the etalons, they must be placed inside of a suitable pressure vessel. The pressure vessel must be strong enough to contain 300 psi, the maximum pressure needed to tune the etalons. It must be able to hold this pressure for long periods of time so that the tuned wavelength does not drift during measurements. There also needs to be provisions for optical access in order to transmit light through the etalon.

The chosen design for the pressure vessel utilizes a stock 2” diameter tube coupler from Swagelok, Inc. This coupler was bored through to a large enough diameter to fit the etalons inside of. Axial grooves were machined into the sides of the coupler to allow for gas exchange between both sides of the etalon. A Swagelok face seal tube adaptor was threaded into the side of the coupler to allow for the introduction of the SF$_6$ gas.

The ends of the coupler were fitted with Swagelok tube fitting plugs. These plugs were extensively modified for optical access. A through hole was bored to allow light to enter the vessel. The inside of the plug was machined flat and an o-ring groove was cut into the flat surface in order to seal the plug. The outside of the light-inlet-side plugs were machined to accept a sliding mechanism used to focus light exiting from a fiber. An exploded solid model of all of the parts in the pressure vessel is shown in Figure 3.5.
It was decided to minimize the part count and to use lenses necessary to collimate the light from the inlet fiber as the sealing window in the end plugs. These lenses were designed using ZEMAX software and were built by Esco Products, Inc. These lenses did not work as well as hoped for focusing the collimated light back into the detectors, so corrective lenses were acquired from Melles Griot and placed between the pressure vessel and the detectors to maximize the light entering the detector.
3.7 Etalon Pressure Vessel Optical Setup

The first step of setting up the optics in the pressure vessel is to properly collimate the light from the input fiber through the etalon. Divergent or convergent light through the etalon will broaden the FWHM, which is undesirable. Collimation of the input light involves adjusting the distance between the fiber and the collimating lens. A tunable laser located in the lab provides the light necessary to properly do this. This laser is able to be tuned across a wavelength range of 1380-1470 nm. For collimation, the laser is scanned across the wavelength range, and a detector collects this light and outputs the signal to an oscilloscope. The oscilloscope is used to look at the FWHM of the output signal. The fiber-lens distance is then adjusted until the minimum FWHM is found. This gives the best collimation of light.

Pressure tuning of the etalons was accomplished by using the same laser source. The laser was tuned to the desired central wavelength, and light was coupled into the large diameter fibers used as the input in this sensor. The pressure vessel was pressurized to 300 psi with the SF$_6$ gas, and the gas was very slowly released while watching the signal from the detector. When the signal reached its maximum value, the valve was closed, and the etalon is now tuned to the desired wavelength. Care must be taken to very slowly bleed the gas off, or the peak signal level can be missed. The pressure vessels will hold their tune for over one day, giving sufficient time to take measurements.

The light collimation process is then repeated to account for any change due to the high pressure SF$_6$ index of refraction. This distance is then locked using a set-screw on the
fiber adjustment sliding mechanism. These distances were found to be different between the three etalon cells. This is believed to be from variations in the lenses used to collimate the light.

3.8 Detectors

The minimal amount of light being emitted by the combustion process required careful selection of the detectors. The detectors also need to be able to operate at high speeds. With this in mind, three model 2011 InGaAs detectors from New Focus were selected. These detectors have adjustable filtering and gain to tailor them to our application. The high-speed detection was necessary for our use of a lock-in amplifier.

3.9 Lock-in Amplifier

A lock-in amplifier is a device used to increase the signal-to-noise ratio of an electrical signal. Lock-in amplifiers work by band-pass filtering a signal to remove unwanted frequencies, and then amplifying the selected frequency. To use a lock-in amplifier in the two-line water emission sensor, the emitted light must be modulated at a known frequency. High speed modulation works best for the detection of low signal levels with lock-in amplification, but this must be balanced with light transmission efficiency due to the low signal level produced by the chosen line pair. The chosen modulation frequency for the AOTF was 65 kHz. From testing shown in Figure 3.6, this seemed to be the ideal frequency tradeoff between modulation efficiency and speed.
A software implementation of a lock-in amplifier was coded in LabView to be used with the LabView based data acquisition board. The board has 12-bit resolution, however, it is not very sensitive to low voltage levels, potentially causing bit-noise issues. To overcome the low signal level from the detector, a high speed, three-channel pre-amplifier was constructed using AD8009AR op-amps from Analog Devices. This pre-amp had a gain of 1000 and a low-pass cutoff frequency of 1500 Hz. Commercial pre-amps have very low noise, but were rejected due to their cost of around $1000 per channel. The noise associated with the fabricated pre-amp will be reduced with the lock-in amplifier. Function generator testing of the pre-amp showed that it worked properly.
3.10 Fiber Access

One of the major goals of the use of emission thermometry is to obtain access to the combustion chamber with minimal change to an engine. Windows change the geometry and volume of a combustion chamber, which may change the combustion and give results that are not indicative of what would happen in a real engine. With this in mind, a fiber optic placed directly in the combustion chamber was chosen as the least-intrusive way to collect light.

Since the fiber is directly exposed to the combustion chamber, it must be durable and able to withstand high temperatures. It also must be easily removable for cleaning and has to seal the combustion chamber to maintain the desired compression ratio. The fiber used was made of sapphire for its high temperature capabilities as well as high transmission in the IR region of interest. Sapphire is also very hard, and thus able to be easily cleaned when it becomes dirty.

The sapphire fiber-probe assembly used was purchased from Photran. A large core, bare sapphire fiber (550 μm diameter, 0.22 NA) was placed inside of a stainless steel tube with an ID that was 0.005” larger than the fiber OD. The connection end of the fiber was epoxied to the stainless tube to seal the combustion chamber. The fiber access end was not epoxied because the epoxy would not be able to withstand the high combustion temperatures. An SMA connector was then epoxied to the tube and end of the fiber, which provides a rigid connection to attach a patch fiber to the collection fiber assembly.
Two identical fiber probes were made with this method to allow for quick changes to be made in the event the fiber becomes dirty.

Adapters were manufactured out of stainless steel to attach the fiber-probe assemblies to the engines of interest. For the Fiat engine, an adapter was made to fit in an existing pressure transducer port in the cylinder head. For the Triptane engine, an adapter was made to fit inside of a spark plug port in the cylinder head. The adapters were both bored through to accept the fiber-probe stainless steel tubes. A Swagelok fitting was welded to the ends of the adapters, which locks and seals the tube to the adapters. The adapters themselves are threaded into the heads to seal against leakage. The complete assemblies were made to minimize the volume increase so that compression ration would not be affected. Probe adaptor drawings are located in Appendix A.

A glass patch fiber with the same diameter and NA was used to send light from the fiber-probe assembly to the sensor. This allows for flexibility in placing the large sensor assembly away from the workings of the engine. Glass was chosen over sapphire for the patch fiber due to it being less expensive, yet still providing the necessary transmission characteristics.
3.11 System Usage

The total system is used as follows:

1. Tune the etalon cells as outlined in section 3.7
2. Thread the adaptor into the head of the test engine.
3. Install the fiber probe assembly into the adaptor and tighten the Swagelok fitting
4. Attach the patch fiber to the fiber probe on one end and to the collimation assembly before the AOTF
5. Turn on the AOTF driver, set to the proper band-pass frequency.
6. Attach the detectors to the pre-amp.
7. Attach the pre-amp outputs to the data acquisition board.
8. Run the engine and take measurements.

Light is sent through the AOTF where it is spectrally filtered and modulated. Light from the AOTF is coupled into the fiber splitter where it is sent to the input side of the etalon cells. The light then gets expanded to a collimated 30 mm diameter beam and is sent through the etalons to be filtered down to the individual lines. The filtered light is then focused into the three detectors. The detector outputs its signal to the pre-amplifier, which sends the amplified signal to the LabView data-acquisition board. The lock-in amplifier software filters and amplifies the signals. The background noise channel is subtracted from the two line channels, and then the two channels are divided to give the ratio. The ratio is then compared to a curve-fit of the simulated ratio to determine the line-of-sight averaged gas temperature. A picture of the sensor system is located in Figure 3.7.
3.12 Optical Spectrum Analyzer Line verification

3.12.1 System setup

In the development of this sensor system, a verification of the existence and position of the two lines studied was desired. The simulations showed that the chosen lines should work, but the HITRAN database is known to have some line position and intensity errors. A verification of the lines gives peace-of-mind that the sensor method is possible. In addition, lines not in the HITRAN database might show up that could be more useful in the determination of temperature.

For the verification of the emission lines, an Agilent 86142B Optical Spectrum Analyzer (OSA) was used. An OSA is a commercial tool used to analyze light. An OSA works by
using a precisely controlled grating to spectrally separate light and send it to a detector. The grating is scanned across a user selectable range to resolve the light spectrum. It is able to very accurately determine the intensity and wavelength of light sent to it.

The Agilent OSA is able to resolve light down to 0.06 nm in a range from 600 to 1700 nm. For the trial experiment, a premixed H\textsubscript{2}-O\textsubscript{2} flame was used as the light source. The burner was fabricated by epoxying very fine stainless steel tubes inside of a larger stainless steel tube. This tubes-in-a-tube setup was used to stabilize the flame and to prevent the flame from flashing back into the supply lines. The hydrogen and oxygen flow rates were predetermined for the brightest flame and the flame was lit.

A commercial Thor-Labs collimation package suspended over the flame was used to collect light. The collimation package was placed approximately 4 inches over the tip of the flame to keep the flame from melting the collimation lens. Additionally, a nitrogen co-flow was sent along the outside of the burner tube to help cool the collimation package and minimize the effects of atmospheric air contamination of the signal. Light from the collimation lens was sent through a standard SMF-28 fiber to the OSA. SMF-28 fiber is a single-mode, glass core, glass clad fiber with a core diameter of 9 μm and an NA of 0.14. A larger fiber would have allowed for greater light collection, but the OSA limits the input fiber to small-core, single-mode fiber.
3.12.2 Results

The spectrum acquisition process took approximately 20 minutes per 100 nm scan due to the OSA being used in its most sensitive mode. Three scans were taken of the flame, each 100 nm wide covering the range from 1320 to 1520 nm. The acquired spectra were compared to HITRAN simulations run at atmospheric pressure, a temperature of 3000 K, and a water concentration of 80%. The simulated spectra were then scaled down so that the intensity matched the measured data. For the most part, the measured and simulated spectra were similar. However, a few line positions were different between the two. We believe that this difference resulted from slight errors in the HITRAN database. A plot of the simulated and measured data in the region of interest is given in Figure 3.8.

![Figure 3.8: OSA Measurement compared to HITRAN simulation](image)
Data from this experiment showed that the emission lines chosen for the two-line H$_2$O temperature sensor did indeed exist. It also showed that the “blue” line was not in the expected position. The blue channel etalon in the two-line H$_2$O temperature sensor was thus tuned to the actual position of the line center. Data from this experiment showed that the two-line method showed promise for being used as a temperature sensor.

### 3.13 Efficiency testing

Various parts of the emission system were tested for their individual efficiencies. There are losses associated with reflections on the ends of all fibers, and these were taken as constants for each fiber end. The AOTF was tested and found to have an efficiency of 20%, which is less than half of what it was specified to be. The collimation of light through the AOTF was also inefficient, as the lenses used are not perfectly made. The total AOTF sub-system efficiency was only about 8.7% efficient.

The 1-into-3 fiber splitter was also more inefficient than expected, with a total efficiency of 43%. In addition, the output legs had different split characteristics, with a split ratio of 28%, 37%, and 35%. Finally, the efficiency of the etalon cell assembly to the detector was diminished due to the collimation lenses not being perfect. The total system efficiency through the cells was measured at 0.4% for Cell 1, 0.4% for Cell 2, and 0.3% for Cell 3.

Overall, the total system efficiency was much lower than expected. This makes crank-angle resolved temperature measurements impossible to achieve with this system. For this reason, this sensor was not tested in an engine.
3.14 Results

The two-line water emission sensor suffered from much lower efficiency than predicted. The sensor would not be able to determine temperature from the low levels of light emitted by combustion in an HCCI engine. For this reason, it was decided to test the sensor feasibility using the HTHP test cell. The HTHP test cell emits light continuously, so averaging could be used to increase the signal to noise ratio. However, this has not yet been completed, as the HTHP test cell broke during its initial testing. Additionally, the effects of cold boundary layer effects on the measured signal ratio are located in Appendix B. Cold boundary layer effects are discussed in greater depth in Chapter 4, Section 4.4.1.
CHAPTER 4 - CO₂ BLACKBODY EMISSION SENSOR

4.1 Sensor Theory

In looking at a survey spectra simulation, a feature was noticed that showed promise of being useful in a simple temperature sensor. Near 4.3 μm, CO₂ emission approaches the emission of a blackbody. When the CO₂ emission approaches that of the blackbody, it is said to be optically dense, otherwise it is optically sparse. CO₂ seems to be the only common combustion species that can exhibit this behavior, and only near 4.3 μm. Also, the emission from other species is low in this spectral region, so there is minimal interference from them. A graph of the survey spectrum is located in Figure 4.1.

![Figure 4.1: Broad emission survey spectra](image-url)

Figure 4.1: Broad emission survey spectra
In order to exhibit blackbody behavior, the CO$_2$ number density has to be above a certain value. The number density is determined by the pressure and concentration of the CO$_2$. A graph of optically dense and optically sparse CO$_2$ is given in Figure 4.2. Additionally, any interference from other species or soot will have the effect of making the CO$_2$ emission behave as a greybody. This is because the interfering species will absorb the emitted light, and re-emit light at an intensity lower than the CO$_2$ emission intensity. Fortunately, the interference in this region is low, so the CO$_2$ emission can be considered a blackbody.
The suitability of using this feature in an IC engine was investigated by looking at the temperature, pressure, path length, and concentration of CO$_2$ in an HCCI engine. The product of path length, concentration, and pressure (PXL) was plotted vs. temperature for two different EGR levels. These plots were then compared to the simulated blackbody threshold calculated using the same parameters. Figure 4.3 shows that for the majority of the engine cycle, the CO$_2$ should be optically dense and thus useable for measuring in-cylinder temperatures.

Figure 4.3: Optical density for an engine cycle
The optically dense CO\textsubscript{2} can be used in two different ways to determine gas temperature. The first method to determine temperature involves comparing the slope of the measured spectral data with the slope of Planck’s curve across the same wavelength range. The simplest way of measuring the slope of the data is by looking at the ends of the CO\textsubscript{2} Blackbody feature, namely 4.2 and 4.4 \textmu m. This method is similar to standard two-color pyrometry, except for CO\textsubscript{2} gas being used as the emitter. The shape of the Planck curve changes according to temperature, thus gas temperature can be determined by comparing the measured slope to the Planck slope. For more accurate results, a linear array of sensors can be used along with a diffraction grating to obtain multiple measurements along the spectral width of the feature.

The second method involves measuring a single channel of the blackbody feature, and directly correlating the output intensity at a single crank-angle to a temperature. The temperatures during the rest of the crank angles are determined by comparing their intensities to the intensity at the known temperature. Since the temperature at a certain crank angle needs to be known, this method is most useful for well-controlled combustion events, such as found in HCCI combustion and shock tubes. This method also requires that all windows or fiber surfaces be relatively clean, or at least not change transmission over the measurement time period.
4.2 Experimental Setup

A sensor system utilizing two detectors was chosen for a proof of concept of the CO$_2$ blackbody sensing method. A diffraction grating was chosen as the wavelength selection mechanism due to its simplicity. The grating used was a model # 53004BK02-440R from Spectra Physics. This grating has 300 grooves/mm and a blaze wavelength of 4 µm.

An iris was used to restrict the angle of light entering the grating, decreasing the spectral width of the two channels of light. A series of gold first-surface mirrors was used to direct the light into their respective detectors. Gold is an efficient reflector of light near 4.3 µm, with a reflectivity of approximately 98%, so the reflection losses are minimal. The detectors could have been placed directly in the diffracted light path, but the use of mirrors makes the sensor more compact and easier to align.

The chosen detectors were model KISDP-1-J2’s purchased from Kolmar Technologies. These are liquid N$_2$ cooled, InSb detectors and have a responsivity of 37,500 volts per watt of received light. These detectors did not have any provisions for mounting, so an aluminum plate was epoxied to the bottom to be used for clamping the detector to the breadboard. And aluminum lens mounting system was machined and clamped around the light inlet tube to allow for the attachment of a focusing lens.

A CaF$_2$ lens was placed in the lens mount of each detector to focus the light into the detector. The focal length was chosen to minimize the spectral width of the channel without sacrificing signal strength excessively. The lens was placed in a threaded mount,
allowing the focal length to be adjusted by rotating it and moving it closer or further from
the detector. To test the spectral resolution of the detector assembly, a tunable diode
laser with a range of 1380-1470 nm was used. This wavelength range is $1/3$ of the CO$_2$
feature wavelength range, allowing the $3^{rd}$ order of diffraction from the grating to be used
for tuning and aligning the sensor.

To determine the optimal focal length, the lens was adjusted as close to the detector as
possible and the laser was scanned across its range. The peak intensity and the FWHM
of the detector signal were then recorded. This process was repeated 20 times, each time
with the lens moved one more turn out from the detector. A graph of the results from this
testing for the blue channel is given in Figure 4.4.

![Graph of Blue FWHM and Peak Voltage vs Number of Turns Out](image_url)

**Figure 4.4: Optimal focal length testing**
This focal length selection process was performed on the red channel at the same time, giving a similar focal length. The measured FWHM of the signal was then multiplied by three to give the spectral resolution at the test wavelength. The effective spectral resolution of the entire grating/lens system was approximately 28 nm for both channels. Since the CO$_2$ blackbody feature is around 100 nm wide, this relatively wide spectral resolution is adequate.

This entire setup was built on a small breadboard for transportability. The small breadboard was clamped to the large optical table to keep it from being inadvertently bumped. A plastic box was inverted and placed over the sensor for nitrogen purging of the sensor. The box was sealed to the optical table with duct tape. The mounting holes in the table are sealed, so there is no leakage of nitrogen through the holes. A flap was cut into the box to allow access to the sensor for adjustments and refilling of the LN$_2$ dewars. This flap was sealed with duct tape as well. A feedthrough for the detector power wires and the BNC detector signal lines was cut into the box and also sealed with duct tape. A picture of the detector setup is located in Figure 4.5.
4.3 Sensor usage

Testing was performed on a single cylinder optically accessible engine based on the Triptane block. Light was collected through a 0.3 inch-thick sapphire window located in a ring between the engine head and block. Sapphire attenuates light at 4.3 μm, but since the window is relatively thin, the transmission is around 70%. One problem with this setup is that the position of the window allows the piston to partially block the window when the piston is near TDC. To get rid of piston clipping effects, a piece of metal tape was placed across the bottom of the window in order to mask the portion of the window that becomes blocked by the piston.

A series of gold first-surface mirrors were used to direct the light from the engine to the CO₂ sensor. The light path was enclosed in plastic and was purged with nitrogen.
gas to eliminate absorption from atmospheric CO$_2$. A PVC pipe was placed between the last mirror and the N$_2$ purge housing around the sensor to ensure that the plastic sheeting would not block the light path into the sensor. A picture of the light collection path is located in Figure 4.6.

![Light collection path](image)

**Figure 4.6: Light collection path**

4.4 Results

Two different experiments were carried out in the optically accessible Triptane engine. The first was a two-channel ratiometric technique, and the second was a single channel technique to correlate signal intensity to temperature. Results from both experiments are given in the next two subsections.
4.4.1 Two-channel ratiometric measurements

The CO$_2$ blackbody emission sensor was constructed and coupled to the Triptane engine as outlined in section 4.1. The first test utilized the two-color method to determine gas temperature. The engine was operated with an equivalence ratio of 0.2 and at a speed of 600 RPM. A pressure transducer installed in the engine was used to trigger the scans. 100 scans were averaged together for each measurement. The measured ratio of the two channels is shown in Figure 4.7

![Figure 4.7: Measured ratio from two channel scan](image-url)
As can be seen, the ratio signal is noisy. This in itself isn’t a large problem, and can be fairly easily overcome. The major problem with the measured ratio is that it covers a much larger span than predicted. The predicted span of the ratio was around 0.1, yet the measured span is over an order of magnitude larger, making temperature measurement impossible with the data.

In trying to figure out what was occurring with the measured ratio, a theory was proposed. This theory was that there was a boundary layer of cold CO$_2$ around the edge of the combustion chamber preferentially re-absorbing the light emitted by the hot CO$_2$. This might cause a greater decrease in one channel than the other, throwing the measured ratio completely off. To test this theory, the emission code was modified to send the emission through a selectable thickness and concentration of cold CO$_2$. Figure 4.8 shows the result of this simulation. The ratio for emission with no boundary layer is 1.04, giving a temperature of 1222 K. The ratio for emission with the 1 mm boundary layer is 1.55, giving a temperature of over 2 million K. This boundary layer problem was determined to be the cause of the greatly varying ratio measurements observed.
If information about the boundary layer was known, then the ratio could be corrected for its effects. However, the boundary layer is actually a gradient that changes with every crank angle, effectively making it impossible to predict. Since the ratio could not be corrected, no further testing of the two-channel method was performed.
4.4.2 Single channel measurements

In testing of the single channel temperature measurement technique, the same boundary layer problem becomes apparent. Fortunately, from Figure 4.8, there is a part of the spectrum that is minimally affected by the cold boundary layer. By selecting this portion at the blue end of the spectrum, temperature measurements would still be possible.

For this testing, the blue channel detector was retuned to 4178nm (2393 cm$^{-1}$) in order to minimize the effects of the cold boundary layer. The single channel was sampled for 100 engine combustion cycles and averaged, giving adequate signal to noise. Based on temperature vs. ignition data from Figure 4.9 [17], the temperature at the first stage ignition is set at 770 K. The first stage ignition point was determined by taking the derivative of the pressure trace.

![Figure 4.9: Temperature vs. ignition delay](image-url)
To ensure that the signal represented blackbody emission at the first stage ignition point, it was necessary to seed the intake with CO₂. In the Triptane HCCI engine, there is no EGR, so the only CO₂ present before ignition is that which was left in the cylinder from the previous cycle and atmospheric CO₂. To determine the seeding level, the flow rate of CO₂ was slowly increased while watching the pressure trace. At the first sign of a loss of peak pressure, the CO₂ flow rate was reduced by 25% and set for the remainder of the tests. Emission from combustion seeded at this flow rate was compared to emission with a greatly increased flow rate. No difference was noticed between the pre-ignition stage of either, so the seeding level was determined to be great enough to produce blackbody behavior in the pre-ignition CO₂. A graph of the difference between seeded and non-seeded emission is located in Figure 4.10.
Temperature measurements were taken by first averaging 100 engine cycles with CO₂ seeding, and then immediately turning off the CO₂ seeding and averaging 100 non-seeded engine cycles. These two traces were then plotted on the same axes and the seeded trace was used to set the ignition point temperature. Once the temperature is set at the ignition point, the non-seeded curve directly correlates the temperature to crank angle. The non-seeded curve is used to ensure that the CO₂ seeding doesn’t affect the combustion. A plot of a measured temperature trace is given in Figure 4.11. The twin peak structure in the plot is the derivative of the pressure trace.
4.4.3 Single channel temperature measurement error

While analyzing data in the last set of measurements, it was noticed that the peak pressures were rising for every data set. This would not be a problem if the pressures were consistent between seeded and non-seeded runs, but the rise was fast enough to cause differences between the seeded and non-seeded runs. This introduces some error in the temperature measurement. Later, it was determined that the peak pressure in the engine varied by 30% over the course of the 30 minute period required to take 6 separate measurements. This was all while running at the exact same conditions. Sealing of the optical ring to the block and head was later determined as the culprit.
Additionally, the band-pass of the blue channel was wide enough to be affected somewhat by the cold boundary layer on its red side, and the drop-off in blackbody emission on the right side. This would have the effect of causing the measured temperature to be lower than the actual temperature.
CHAPTER 5 – OPTICAL TEST CELL

In order to more effectively test optical sensors, a source of continuous light emission is desired. The ideal system would have the ability to vary the emitter species, the temperature of the emitter, the concentration of the species, and the pressure of the species. It would also be able to operate for long periods of time. This section outlines the theory and construction of this high temperature, high pressure (HTHP) test cell.

5.1 Emission Source

The HTHP test cell produces light emission by heating a source. The emission source consists of a sealed glass cell containing the species to be studied. The glass cell was welded together by a glassblower out of a 1” diameter glass tube, 8 inches long, and two wedged windows. The windows used are fused silica and are uncoated commercial beam samplers. These beam sampler blanks have a wedged window to get rid of unwanted etalon interference. Etalon interference occurs when two flat pieces of material set up a reflection cavity that destructively interferes with certain wavelengths of light.

The main tube had a small diameter tube welded to its side. This small side tube is used to evacuate the cell of air and to introduce the species of interest. For the first sealed cell, water was chosen as the emitter species. The amount of water was chosen based on the volume of the cell and the ideal gas law. For the first cell, 0.5 cc of water was sealed in the tube, giving a maximum pressure of 10 atm at 1500K. This water was measured with a syringe and injected into the cell via the side tube. The water settled to the bottom of the cell, and was then frozen in liquid nitrogen. While the bottom of the tube was in the
liquid nitrogen, a vacuum pump was attached to the fill tube. After sufficient vacuum was obtained, the filler tube was heated and sealed off. Additional cells can be manufactured using this method, each containing different concentrations and species.

Originally, the cell was going to be constructed out of sapphire. Sapphire has a higher maximum temperature than glass, with sapphire’s melting point being around 2300 K vs. 1500 K for glass. In addition, sapphire is stronger than glass and less likely to deform when heated. However, a company able to seal a sapphire cell could not be found.

A company that could manufacture an unsealed sapphire cell was found, and this was considered this as an option. This setup would require a pass-through in the outer pressure vessel that would need to be sealed to the protruding finger. It would also require a controllable heat source on the end of the sapphire finger on the outside of the vessel to control the vapor pressure in the sapphire cell. This setup would be beneficial in that the species, concentration, and pressure could easily be changed. However, it was deemed impractical because of the fragile finger and its need to be at a controlled temperature. Heat transfer effects along the finger also would probably cause the sapphire to crack due to thermal gradients.

5.2 Heater and Insulation

The glass cell was then placed inside of a heavy wall stainless steel tube. The stainless tube was used to evenly conduct heat from the heater to the glass cell, ensuring that there were minimal thermal gradients in the glass tube. Two stainless steel adapter rings were
used to center the glass cell inside the stainless steel tube. These rings had two slots milled into the sides to allow for gas exchange throughout the tube. In addition, a slot was cut into the tube to allow the protrusion of the filler tube stub to slide inside the tube.

The stainless steel tube was sized to fit inside of a large AC resistance heater. This heater was sourced from Thermcraft, Inc. The heater is rated for 1500 K. It is covered in a 9 inch diameter layer of insulation to concentrate the heat and also keep the pressure vessel from heating up excessively. The heater is split into two semicircular halves to allow for easy insertion of the stainless steel tube. The heater is controlled by a 240 V, 15-amp variable transformer, or variac. The variac varies the power going to the heater, allowing the temperature to be easily controlled.

5.3 Pressure Vessel

The heater was assembled with the stainless steel tube/cell inside of it. The heater was then placed inside a 12” diameter steel pressure vessel with flanged ends. The pressure in the pressure vessel applies compressive stress to the glass cell to keep it from exploding due to the increase of internal pressure from heating the water. The pressure vessel was sourced from Hay’s Fabrication, Inc in Ohio. It is rated for 300 psi and was built to ASME pressure vessel standards. The pressure at the maximum temperature is around 150 psi, so this should be more than adequate for the application. The heater was centered in the pressure vessel using commercial fiberglass batting, which also provides for additional insulation to keep the pressure vessel cool. The end plates were both machined to accept a 1” diameter sapphire window, again wedged to avoid etaloning.
These windows were sourced from Almaz optics and are 0.25” thick, which will provide sufficient burst strength. The end plates also contain a ¼ NPT fitting to allow for the introduction of a gas. In addition, one of the end plates was machined to accept a thermocouple pass-through to measure cell temperature, and two electrical connection feed-throughs used to power the heater.

Insulation rounds of the sort used around the heater were sourced from Thermcraft, Inc., and cut into endcaps. These caps were 2” thick and filled the remaining space between the flanges and the heater. 1.5” diameter holes were cut into the endcap insulation to allow light to pass through to the windows.

5.4 Cell Operation

The operation of the HPHT test cell involves first pressurizing the outer vessel to 150 psi with a regulated supply of nitrogen. Nitrogen is used because it is not active in the IR, where most of the measurements are taken. After the cell is pressurized, the heater is turned on, and the cell is allowed to heat up to the desired temperature. The glass cell temperature is measured using a thermocouple placed inside the stainless steel tube. Care must be taken that the pressure in the outer vessel does not drop below the calculated pressure at given temperature inside of the glass cell, or the cell might explode.

Once the glass cell is at the desired temperature, the HTHP test cell is ready to use. The HTHP test cell is flexible in that it allows for measuring both optical emission and optical absorption. The windows in the end-plates of the pressure vessel are co-linear, allowing
a laser beam to pass through the glass cell for absorption measurements. For emissions measurements, a commercial optical spectrum analyzer (OSA) was first used to analyze the emission.

5.5 Results

The trial run of the HTHP test sensor was conducted using aluminum plugs in place of the sapphire windows due them being 5 weeks overdue. The cell was first pressurized and all of the leaks were attended to. Next, the heater was turned on to test that it worked. When the heater reached approximately 450 K, the o-ring used to seal the aluminum plug to the end plate popped out of its retaining groove, rapidly de-pressurizing the pressure vessel. Fortunately, the gas pressure inside of the glass cell was not high enough to cause it to burst.

The o-ring came out of the retaining groove because a non-standard groove was machined into the end plate to allow for the use of a smaller sapphire window, which was cheaper. To fix this problem, 2” diameter wedged glass windows of 0.375” thickness were sourced from Esco Products. The end plates were removed and re-machined with a standard o-ring groove for a 1.5” diameter –218 o-ring and a recess to hold the window in place when it was not under pressure. The through hole was also bored out to 1” to allow for optical access to the entire glass cell.

The new windows were installed and the cell was re-assembled. The cell was then pressurized and checked for leaks. As a precautionary measurement, the cell was...
pressurized to 150 psi and left for 4 days. After the 4-day period, the cell pressure was at 120 psi, which was deemed an acceptable leakage rate.

Next, the heater was turned on and the cell was allowed to heat up to 1000 K. A multimode 62.5 mm core fiber with an NA of 0.2 was attached to a ThorLabs collimation package and was used to collect light from the emission cell. The fiber directed the emitted light into a commercial ANDO AQ-6315A optical spectrum analyzer. The OSA was set to its most sensitive range and a resolution of 1 nm, which was determined to be the optimum value for the large core fiber. It was then scanned over three, 100 nm wide sections of the water emission spectrum: 1320-1420 nm, 1420-1520 nm, and 1520-1620 nm. Each scan took approximately 20 minutes to complete. A plot of the raw emission spectrum obtained is located in Figure 5.1.
The raw emission plot shows that the emission level is steadily increasing on the red side, without any prominent line features. This looked to be caused by background radiation, possibly from the hot metal surrounding the glass cell. To check this assumption, the raw trace was plotted along with the Plank curve at 1000 K. The Planck curve was arbitrarily scaled to show that the measured data follows the trend. This plot is located in Figure 5.2.
In order to compare the measured data with the simulation, the data was smoothed to a resolution of 1 nm, along with the simulation. The derivatives of both the measured data and simulated data were then taken to get rid of the Planck trend in the measured data. The two traces are plotted together in figure 5.3.
The measured data in Figure 5.3 shows that the line positions match up fairly well between the measured and simulated data. Differences in the line heights were attributed to absorption by humidity inside of the OSA. However, the measured trace intensity was only approximately 3% of the simulated intensity, so it was scaled for comparison purposes. The cause of the reduced signal level was not found.

After these measurements were taken, the heater was turned off and the cell was left to cool overnight. Upon checking the cell the next morning, it was noticed that the pressure in the outer pressure vessel had dropped to 0 psi. It is believed that the heating of the cell caused the flange gaskets to leak excessively as they cooled. The glass cell was inspected
through the pressure vessel windows, and was discovered to have broken. The cell was still hot when the pressure escaped from the outer vessel, causing it to burst from internal pressure.

The breakage of the glass cell provided a good opportunity to disassemble the cell and to check for anything that might be attenuating the light excessively. The windows of both the glass cell and pressure vessel were found to be relatively clean. Nothing was found that could explain the 3% transmission measured.

Next, the accuracy of the OSA power scale was checked with a broadband light source called a super-luminescent light emitting diode (SLED.) The SLED was first measured with a calibrated IR power meter. Next the fiber was switched to the OSA. The power measured with the power meter was 4.25 mW, and the power measured by integrating all of the OSA scanned lines was 3.11 mW. This shows that the OSA reads about 27% low, probably again from the absorption of light by humidity inside the OSA.

Figure 5.3 also shows that the measured lines from approximately 1375 to 1425 nm are weaker than what is predicted in the simulation. This was believed to be from room water absorption both between the pressure vessel window and collimation lens, and from inside the sealed OSA. This was tested again with the SLED broadband light source. The spectrum of the SLED was obtained with the OSA, and baseline curve was fitted to the data approximating the actual SLED emission. The OSA measured data was divided by this baseline, showing the water absorption inside of the OSA housing.
A plot of the OSA water absorption lines is given in Figure 5.4. These absorption lines show up more strongly than they actually are due to the resolution used on the OSA being relatively broad. Still, they matched well to the weak lines in the measured emission from the HTHP test cell, which could partially explain the differences between the simulated and measured line strengths.

Figure 5.4: OSA water absorption
CHAPTER 6 - DISCUSSION AND FUTURE WORK

Emission based sensors seem like ideal candidates for the measurement of combustion gas temperatures. They can be made relatively simply, and since they don’t require a laser source, they are generally cheaper than a laser based absorption sensor. The main obstacle to overcome is the low light levels emitted by the hot gas when compared to laser sources.

A variety of sensors based on emission spectroscopy were tested for usefulness in measuring combustion gas temperatures. None of the techniques emerged as a clear winner, but a variety of the techniques showed promise of being useful with some revisions. This chapter will outline the future work required to turn some of the tested concepts into useful temperature sensors.

6.1 AOTF Water Emission Sensor

The AOTF based sensor was tested and was able to look at the emission spectrum of water from a gas turbine combustor over a broad range. It proved useful for determining band structure, however, the spectral resolution of the AOTF was too low to be able to resolve individual rovibrational transitions. Also the scan speed is relatively slow and transmission efficiency was shown to drop with increasing scan speed. Due to these discovered limitations, AOTF based sensors seem to be only applicable to very steady, continuous combustion systems. Other techniques seem to be much more useful for temperature measurements.
6.2 High Resolution Etalon Water Emission Sensor

The etalon based water emission sensor was not tested in an engine due to its poor efficiency. Most of the components had dramatically lower efficiencies than they were specified to have. Testing was going to be performed using the HTHP test cell, but it broke before testing could be performed.

The sensor should be verified with a source of continuous emission at known temperatures, such as the next version of the HTHP test cell, before future work is performed. In testing the CO$_2$ Blackbody sensor, it was noticed that cold boundary layers could affect the ratio of the emission channels. This could also occur in this sensor, which would severely affect the accuracy of such a sensor based on the ratio of individual emission lines.

If the cold boundary layer absorption proves to not be a problem, then a new search for line pairs should be performed in a region of the water spectrum that emits light more strongly. The original line pair is located in a region with relatively weak emission, with other water bands exhibiting emission around 100 times greater. Once the new line pair is found, etalons and an AOTF that work at the required wavelength should be used.

Another method involving etalons that might be pursued is the rapid tuning of an etalon to resolve multiple emission lines. This could be accomplished by rapidly decreasing the pressure in a pressure-tuned etalon, or by controlling the interference cavity length with piezoelectric actuators, similarly to the method outlined in [6]. This method would
require a way to tune a fringe rejection filter along with the etalon so that the etalon filtered light is not blocked by the fringe rejection filter. The resulting spectrum could be resolved to 0.5 nm or better by choosing the correct etalon characteristics.

6.3 CO$_2$ Blackbody Emission Sensor

Initial testing of the CO$_2$ blackbody sensor in the Triptane engine showed that it has promise of being useful in the determining combustion temperatures in an IC engine. Two techniques were tested, the first being a two-color pyrometric technique utilizing optically dense CO$_2$ as the emitter and the second being a single channel technique correlating the intensity of emission from optically dense CO$_2$ directly to temperature.

The two-channel, ratiometric technique had problems with gas temperature non-uniformity. It was determined that a thin layer of cold gas preferentially absorbed light from one channel more than light from another channel. This makes temperature measurements using this technique nearly impossible due to the need to know the temperature profile along the collected light path.

The single channel technique had the same problems with cold boundary layer absorption, but to a lesser degree. A region of the spectrum was used that emits strongly, yet does not absorb at cold temperatures. The optics used in the sensor were not spectrally narrow enough to collect only this emission feature, so some of the collected light was from a region suffering from cold layer absorption. Temperature was still able
to be determined, but the accuracy suffered due to the aforementioned boundary layer absorption.

The next generation of the CO$_2$ blackbody sensor should be built using a single detector. A narrow spectral width filter, most likely an etalon, should be used to select a 5 nm wide slice of the emitted light centered on 4178 nm. If an etalon is used, an interference filter needs to be used to reject the additional fringes passing through the etalon. The sensor should be able to be built in a fairly small envelope, allowing it to be placed more easily when testing an engine. Additionally, fiber coupling can be used to determine gas temperature in non-optically accessible engines. The fiber would need to be able to transmit light in the mid-IR, and would have to be aimed across the top of the combustion chamber to avoid path length changes caused by the piston moving up and down.

The single channel temperature measurement technique would be most useful in a combustion process that is well controlled, such as an HCCI engine or a shock tube, due to the need to correlate intensity at one time during the measurement to a temperature.

### 6.4 OSA Based Spectroscopy

The optical spectrum analyzer was used as a diagnostics tool in the research conducted in this thesis, but it may be useful as a temperature sensor in itself. An OSA can be used to obtain very accurately resolved spectra. It is also a commercial instrument, so it is very simple to operate and can be obtained fairly cheaply. Its main drawback was found to be the slow spectral scanning speed when used with low light emission levels.
One method to increase the spectral scanning speed would be to look at strongly emitting species and regions of the spectra. The problem with this is that most commercial OSAs are designed for testing light at communications wavelengths, in the near IR region of the spectrum. If an OSA could be obtained or built for use at different wavelengths, more light could be collected and used to speed up the wavelength scans.

Another method to decrease the scanning speed would be to build an OSA using multiple detectors. The grating would be scanned at the same speed, but different wavelength regions could be handled by different detectors, reducing the required scan range of the grating. The effective scan speed would thus increase proportionally to the number of detector elements. This technique would require a multi-channel, high-speed data acquisition system for fast measurements, increasing costs when compared to a simple temperature sensor.

6.5 HTHP Test Cell

The high temperature, high pressure test cell is a very useful tool in the testing of sensor systems. By having a source of gas at a known temperature, pressure, concentration, and path length, many simulated parameters can be experimentally verified. The cell constructed in this thesis was able to provide emission from water at 1000K and a pressure of 7 atm for a long enough period to be useful in testing a sensor. However, poor pressure vessel flange sealing caused the quartz cell to explode after the first test.
The derivative of the measured spectrum was used to filter out greybody emission from the stainless steel tube surrounding the quartz cell. This has the effect of correcting for any slowly varying changes in signal intensity. This method proves useful in filtering out any slowly varying interference, such as would be found with greybody emission or preferential attenuation from window fouling.

The next generation of HTHP test cell should be made longer to decrease the effects of thermal cycling on the pressure vessel sealing gaskets. This will also reduce the beamsteering effects seen when trying absorption spectroscopy measurements.

In addition, a method to more easily vary the species, concentration, and pressure would be desirable. The current design requires the quartz cell to be swapped for every change of the above. If a suitable method is not discovered, quartz cells should be sourced from ThorLabs, as they make pre-assembled sealed quartz cells with different species contained within. This will make it possible to assemble a library of cells for easy measurement of different species and conditions.

6.6 Conclusions

In conclusion, emission spectroscopy seems to be a viable method for combustion gas temperature measurements. There are numerous challenges to overcome, but the simplicity and low cost of such a system makes them competitive when compared to laser-based systems. High resolution, multiple line measurements seem to be the best option since they can be easily correct for fouling and background interference problems.
BIBLIOGRAPHY


Body hole must be coaxial to the main body of the adaptor. Swage lock hole and main.

Note: Cut off swage lock piece below lower hex flats and weld.

Material: Stainless steel.

All dimensions in inches except where noted.

Adapter

Tripod Probe

3.937

1.25

0.750

14 mm hex flats

M14 x 1.25 threads

3.937

7.35
Cold boundary layer effects were found to be a problem when studying the results of the CO₂ blackbody emission sensor. The cold boundary layer would preferentially attenuate one channel over the other channel, making ratiometric measurement techniques very difficult. For this reason, it was decided to study the effects of cold boundary layers on the emission features used in the high resolution water emission sensor. As can be seen in figure B1, the cold boundary layer has less of an effect at cold temperatures. Also, the effects of cold boundary layers were much less of a problem than in the CO₂ blackbody emission sensor measurements. This is because the region used in the high resolution water emission sensor has weak emission, therefore the re-absorption is also weak.

Figure B1: Cold Boundary Layer Effects