BLACKBODY TEMPERATURE CALCULATIONS FROM VISIBLE AND NEAR-IR SPECTRA FOR GAS-FIRED FURNACES

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by
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The undersigned, appointed by the Dean of the Graduate School, have examined the dissertation entitled

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and hereby certify that in their opinion it is worthy of acceptance

[Signatures]
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NOMENCLATURE

Terminology - Description

Laminar – elements of the gas flow more or less along parallel lines following the contours of adjacent solid surfaces.

Turbulent – elements of the gas become more irregular and no longer follow streamlined flow.

Fuel – the element of the chemical reactions, usually containing carbon, which is needed along with an oxidizer in order for combustion to occur.

Oxidizer – the element of the chemical reactions, usually oxygen from air or pure oxygen from a tank, which is needed along with the fuel in order for combustion to occur.

Combustion Products – the elements in the chemical reactions formed after the fuel and oxidizer combust.

Premixed – fuel and oxidizer are mixed prior to combustion

Nonpremixed – fuel and oxidizer are mixed during combustion; nonpremixed flame are also referred to as a diffusion flame

Stoichiometric condition – the condition where the total amounts of oxidizer and fuel are consumed by the chemical reactions during combustion leaving no excess oxygen in the products

Fuel-lean condition – the condition where the total amount of fuel is consumed but excess oxygen is present after all of the chemical reactions have taken place during combustion

Fuel-rich condition – the condition where there is excess fuel but the total amount of oxygen has been consumed after all of the chemical reactions have taken place during combustion

Spectrum (pl. spectra) – the distribution of energy emitted by a radiant source, as by an incandescent body, arranged in order of wavelengths

Crown – the roof portion of a furnace

Melt – the melted raw material of glass inside a furnace
Batch – the non-melted raw material of glass

Symbols Used

$\alpha$    attenuation factor
$\alpha_k$  non-dimensional heat release
$\alpha_\lambda$ absorptive quantity
$B_k$    Boltzmann number
c    speed of light (in vacuum)
$C$    constant
$C$    capacitance
$C_1$  $2\pi hc^2$
$C_2$  $hc/k$
$d$    distance
$\varepsilon_\lambda$    emissivity
$E$    energy
$E_k$    activation energy
$h$    Planck’s constant
$I_{\lambda,T}$    intensity
$k$    Boltzmann constant
$k_k$    specific reaction rate constant
$K_\lambda$    extinction factor
$\lambda$    wavelength
$L$    path length
$\nu$    frequency
$N^*$    number of excited atoms
$N^0$    number of atoms in ground state
$\bar{n}$    average number of photons measured
$P_E$    probability of an excited atom emitting energy
$P_A$    probability of an atom in the ground state absorbing energy
$Q$    charge on the capacitor
$R_0$    molar gas constant
$\sigma$    variance
$\sigma$    Stefan-Boltzmann constant
$S$    mole fraction of soot
$T$    temperature
The goal of this research work is to develop a sensor capable of measuring multiple factors of interest in the operation of gas-fired furnaces. The primary focus is on the development of a practical solution based on empirical modeling for calculating wall or flame temperatures from gas-fired furnaces using a blackbody radiation approach in the visible spectral range. A simple and two advanced methodologies necessary to provide the needed corrections to use the two-color method using the visible spectrum have been developed. The visible spectral range can provide data for multitask applications such as emission line analysis and temperature calculation simultaneously.

Three spectrometers are employed that measure near-IR, visible, and ultraviolet spectra. This allows the results for temperature calculations in the visible range to be compared with those taken in the near-IR range under the same conditions, primarily at a commercial multi-burner glass furnace and a steel reheat furnace. This comparison indicates that temperatures calculated from visible region are as accurate as the ones obtained from near-IR region at high temperature furnaces. The ultraviolet spectrometer allows the monitoring of hydroxyl emission lines, which can be correlated to changes in NO$_X$ and oxidizer/fuel ratios.

After setting up the probe, containing a lens connected to the fiber-optic cables, at a port looking into the furnace, it is then aimed toward the flame or wall. Spectral intensity data is fed back to a spectrometer and then to laptop computer. The approach is first applied to various research source types including a halogen lamp, an electric furnace, a pilot-scale glass furnace and a research boiler using the visible range to establish a baseline for the technique and to develop an empirical dynamic correction
model for temperature calculations. The advanced methodologies are then used at industrial settings including a multi-burner commercial glass furnace, a steel reheat furnace and a coal-fired boiler. The results of the empirical model developed show that the accuracy and practicality of such a dynamic model is quite good. Challenges associated with this technique, as well as future work that may be derived from this work are also discussed.
1 INTRODUCTION

Non-intrusive methods for temperature measurement have been developed employing varied techniques by many researchers. These techniques range from new methods using lasers to modifications of methods developed many years ago. Many researchers have developed laser-based methods over the past several years. For example, in recent years Elliot et al. and Cessou have developed laser-based methods for flame temperature measurements. Elliot’s technique requires molecular seeds to be added into the flame while Cessou’s deals with laser excited OH radicals.

Fiber-optic sensor probes have also been used to measure combustion temperatures, however, many of these probes need to be inserted in the combustion region to take accurate flame temperature measurements. Similar to the method proposed by Fisenko et al., the fiber-optic sensor introduced here will have no impact on the combustion region since it only needs a straight line-of-sight to the flame and can collect data away from the flame itself. Fiber optic sensors have several advantages including portability, small dimensions, and geometric versatility.

1.1 MOTIVATION

The glass industry relies on temperature measurements inside glass furnaces to create a temperature profile that helps to control the furnace system. Many use thermocouples in place throughout the furnace, as well as the use of hand-held optical IR guns in order to measure these temperatures. Other optical methods are in use today to measure temperatures inside high temperature environments as with a furnace. Most of these common optical methods use the IR or near-IR region to calculate temperature.
and this region of the spectrum is often the focus of researchers\textsuperscript{11}. However, most methods only provide a measurement of the temperature. A sensor that would provide multiple inputs to a furnace operator such as the one designed by Lu \textit{et al}\textsuperscript{12} for a coal furnace that provides concurrent measurements of temperature and soot concentration would be very beneficial for furnace control purposes. The development of a sensor that can provide on-line monitoring of temperature, oxidizer to fuel ratios, and NO\textsubscript{X} emissions is the focus of this work.

Using the visible region, if successful for temperature calculations, can also provide other useful information. For example, the visible region will allow the user to look at chemiluminescent emission lines not present in the IR region, such as sodium. The use of emission lines allow the spectrometer to perform multiple applications simultaneously, such as monitoring UV emission lines that correlate to oxidizer to fuel ratios, to improve fuel efficiency, as well as NO\textsubscript{X} gases to improve pollution control as explained more fully in section 5.3.3. Thus, while monitoring the temperature, the combustion process may be monitored as well, providing both temperature and combustion data to the furnace operator.

\subsection*{1.2 OVERVIEW OF SPECTROMETER AND PROBE SYSTEM}

In order to allow the insertion of the lens/fiber-optic cable assembly into the high temperature environment inside a conventional gas-fired furnace, a water-cooled probe casing [see Figure 1.1a] was specifically designed and built. This probe is similar to the probe built by Bak \textit{et al}\textsuperscript{13}. The innermost compartment is a thin rod designed to hold the fiber-optic cable with a chamber on the end for the collimating lens (Figure 1.2a)
containing a flint glass window to further protect the lens. The larger cylindrical water-cooled jacket houses this small rod inside to provide protection from the heat.

A hose provides compressed air to the interior of the probe casing. A built-in valve allows the adjustment of the air allowing a minimum amount of air to be injected into the furnace. This small amount of purge air sent along the inside of the probe minimizes build-up of residue on the flint glass window that protects the lens. Standard hoses provide the inflow and outflow for the water-cooling system. The impact of the water-cooled probe housing acting as a heat sink on the local furnace temperature near the probe entry point is relatively small. The small amount of purge air introduced will have a minimal impact of the local temperature and on the oxygen content inside the combustion region since the probe does not need to be near the flame. A schematic diagram of the probe is provided in Figure 1.1b.

The fiber-optic cable is trifurcated outside the probe to allow the same input to be sent to each of three spectrometers and processed with each separate grating. The spectrometers used in this work are off the shelf Ocean Optics S2000 spectrometers. The main housing contains three of these 2048-element linear Si CCD Array spectrometers (see Figure 1.2b) to process the incoming light data with each grating. The primary grating, labeled as the master grating and designated VIS in this work, views the visible and near-infrared light (190 nm – 865 nm), though the intensity is very minimal for wavelengths below 400 nm. The next grating installed, labeled as slave 1 and designated UV, is designed primarily to look in the ultraviolet range (195 nm – 410 nm) and the last grating installed, labeled as slave 2 and designated NIR, looks at near-infrared light (640 nm – 1290 nm). Each individual grating has a transmission efficiency that varies
depending on wavelength. Figure 1.3 shows a sample efficiency curve for a VIS grating below.

An important factor in data collection is the integration time. The integration time is the equivalent to the shutter speed of a camera with larger values equaling longer times. The output of the spectrometer is often referred to as “counts”, with these counts being an arbitrary unit for intensity. If the spectral intensity is too low, the integration time should be increased, and if too high, it should be decreased until a signal of approximately 3500 counts is achieved. A filter to attenuate the intensity is often placed in line with the fiber optic cables to the VIS and NIR gratings. This allows longer integration times, giving better results in the UV range without saturating the VIS/NIR spectrometers. The UV data is primarily to observe emission lines of combustion species and is not used to calculate temperatures in this work. Internal to the housing is a converter that allows the data to be sent to the monitoring computer. Connection of the spectrometer to a computer is accomplished with an Ocean Optics SAD500S interface through a USB cable. This combination allows integration times from 5 ms to 60 s.
Figure 1.1: (a) Disassembled Housing for Fiber-Optic Cable and Lens and (b) Diagram of Probe

Figure 1.2: (a) Fiber-Optic Cable with Collimating Lens and (b) S200 Spectrometer
1.3 OVERVIEW OF DISSERTATION

This work will investigate the similarities and differences between using the visible (VIS) and near-IR (NIR) regions of electromagnetic radiation for calculating temperatures. Initial experiments were conducted to derive and test the correction factors needed to use the visible region accurately, and then experiments were conducted to collect simultaneous data in both regions for comparison. This work will also look at the difficulties associated with taking this method from the laboratory into the commercial environment. Correction factors and environmental effects on the system will be discussed.

Initial laboratory tests were conducted with an electric furnace, a pilot scale oxy-fuel fired glass furnace as well as an air-fuel research boiler. These initial experiments were used to fine-tune the model used to calculate temperatures using the visible portion
of the spectrum. Experiments were also conducted at a commercial gas-fired glass furnace, a gas-fired steel plant furnace, and a coal-fired boiler. The air/fuel commercial glass furnace is used for experiments comparing temperatures calculated using the visible portion of the spectrum with those temperatures calculated using the near infrared portion and those measured using a hand-held IR thermometer, commonly referred to as an “IR gun”.

With each natural gas furnace, the reaction zone of the flame was chosen for flame temperature measurement. The probe was aimed such that the OH emission lines in the UV region were maximized; indicating that the spectrometer probe is focused on the reaction zone. A collimating lens is used with the fiber optic probe to minimize the angle of divergence. This means that the intensities measured by the spectrometer are for the light entering the lens from the conical volume viewed by the lens. The “flame temperature” reported in this work is the blackbody temperature derived from these intensities.

Furthermore, wall temperatures are used in this work for the development of correction factors. These are the only measurements available for the electric furnace, which is often used in the creation of various corrections factors reported later. The main benefit from using wall temperatures is the more exact distances available for use in computations.
2 BACKGROUND

To describe how the visible region of the spectrum can be used to calculate temperature, some background material should first be presented. This material will help the reader to understand some of the concepts and terminology that is used throughout this work. Since the primary focus is calculation of furnace temperatures, some important aspects of combustion are explained. In addition, an explanation of the basic concept of electromagnetic radiation spectra is presented. Finally, sources of noise associated with a photon detector are discussed.

2.1 COMBUSTION

Combustion is numbered among the first of technologies mastered by humanity. With the many myths surrounding the discovery of combustion throughout antiquity, it is important to examine the phenomenon of combustion as a fundamental component of physical science. Understanding combustion and the flames produced by combustion is necessary in order to understand the processes internal to a furnace, whether the design is to melt glass in a glass furnace or to heat water in order to make steam in a power plant. The process of combustion is an exothermic chemical reaction in which fuel, primarily natural gas composed mostly of methane (CH4); a mixture of chemical compounds comprised of carbon and hydrogen atoms, is combined with an oxidizer (usually air or pure oxygen) to form carbon dioxide (CO2) and water (H2O). However, due to the complexity of observations of flame propagation, explosions, slow ignition, and critical fuel/oxidizer ratios that depend on combustion conditions\textsuperscript{15}, only the basics of the chemical reactions converting fuel to combustion products will be covered here.
2.1.1 Basic Flames Types

There are four basic types of flames depending on the way the fuel and oxidizer are mixed, and the fluid motion of the flame. If the fuel and oxidizer are mixed prior to being burned, the flame is termed as being premixed. If the fuel and oxidizer are mixed as combustion occurs then it is termed as a non-premixed flame or a diffusion flame. The two fluid flow conditions of the flame are identified as laminar or turbulent. Laminar flames have elements of the gas flow more or less along parallel lines following the contours of adjacent solid surfaces, while in turbulent flames, the elements of the gas become more irregular and no longer follow a streamlined flow. Together these yield the four different types of flame; premixed laminar flames, premixed turbulent flames, laminar diffusion flames, and turbulent diffusion flames. The natural gas furnaces used in the glass industry are predominantly turbulent diffusion flames.

Another aspect in describing flames is the ratio of oxidizer to fuel. Labeled as A/F if the oxidizer is air or O/F if the oxidizer is oxygen, these fuel ratios are often the main value that furnace operators control. If the ratio is such that the fuel and oxidizer consume each other completely in the chemical reactions that will be described later, the flame is considered stoichiometric. The stoichiometric A/F ratio using kg of air to kg of CH₄ is 17.19, though many operators use the volumetric or molar ratio of air or oxygen to fuel where the volumetric O/F ratio for stoichiometry is 2.0 (see EQ 2.1 below).

The fuel equivalence ratio, \( \Phi \), is another value used in flame analysis and is defined as the ratio \( \frac{A/F}{A/F_{\text{stoch}}} \) such that a stoichiometric flame has a \( \Phi \) of one. If there is excess fuel after the combustion processes, it is called fuel-rich and \( \Phi > 1 \). On the other hand, if excess oxygen is present after the combustion process, \( \Phi < 1 \) and the
flame is considered fuel-lean. Each case that is at variance from the given stoichiometry presents a problem. If the flame is fuel-rich, pockets of gas can be created inside a furnace causing a danger of unwanted explosions, as well as carbon monoxide being produced. If the flame is fuel-lean, greater amounts of NOx will form.

2.1.2 Reaction Zone

An important area of a diffusion flame related to combustion is the reaction zone. The chemical reactions taking place in the reaction zone create the highest temperature of any zone in the flame. This is the area of the flame where the fuel and oxidizer meet by diffusion, and the reaction rate of the fuel and oxidizer are approximately equal to the diffusive rates of these same elements. As the chemical reactions deplete the amounts of fuel and oxidizer in the reaction zone, the diffusion of fuel and oxidizer toward the zone keep the process in equilibrium\textsuperscript{17}. This is the reason that a non-premixed flame is more often referred to as a diffusion flame.

2.1.3 Chemical Reactions during the Combustion Process

With the exception of the electric and the coal-fired furnaces, all the furnaces reported in this work use methane, CH\textsubscript{4} or often referred to as natural gas, with either air or oxygen as the oxidizer. The overall reaction for complete methane oxidation (creating a stoichiometric condition) is\textsuperscript{18}:\[ CH_4 + 2 O_2 \rightarrow CO_2 + H_2O \] EQ (2.1)

However, over 200 reactions are routinely used when performing numerical integration in order to calculate hydrocarbon flame structures.

Table 2.1 below shows a sample of some of the more important elementary reaction mechanisms that are associated with methane-air combustion. The first nine
equations are important mechanisms related to the hydrogen-oxygen reactions, the tenth is the equation showing the mechanism that converts CO to CO$_2$, and the others are related to hydrocarbon chemistry. The values given for B, $\alpha$, and E are reaction-rate constants for the Boltzmann number, non-dimensional heat release, and activation energy respectively. The specific reaction-rate constant for the $k^\text{th}$ step is approximated as$^{19}$:

\[
k_k = B_k T^\alpha e^{-E_i/(R_i T)}
\]

EQ (2.2)

The compounds created through the combustion process will absorb and emit radiation at various wavelengths as described below. Therefore, the chemical processes and some of these compounds will be important step in observing changes in the furnace stoichiometry.
<table>
<thead>
<tr>
<th>Step</th>
<th>Reaction</th>
<th>B*</th>
<th>α*</th>
<th>E*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>O₂ + H → OH + O</td>
<td>2.00 10^{14}</td>
<td>0.00</td>
<td>70.30</td>
</tr>
<tr>
<td>1b</td>
<td>OH + O → O₂ + H</td>
<td>1.40 10^{13}</td>
<td>0.00</td>
<td>3.20</td>
</tr>
<tr>
<td>2</td>
<td>O + H₂ → H + OH</td>
<td>1.50 10^{7}</td>
<td>2.00</td>
<td>31.60</td>
</tr>
<tr>
<td>2b</td>
<td>H + OH → O + H₂</td>
<td>6.73 10^{6}</td>
<td>2.00</td>
<td>22.35</td>
</tr>
<tr>
<td>3</td>
<td>OH + H₂ → H + H₂O</td>
<td>1.00 10^{8}</td>
<td>1.60</td>
<td>13.80</td>
</tr>
<tr>
<td>3b</td>
<td>H + H₂O → OH + H₂</td>
<td>4.62 10^{8}</td>
<td>1.60</td>
<td>77.50</td>
</tr>
<tr>
<td>4</td>
<td>OH + OH → H₂O + O</td>
<td>1.50 10^{9}</td>
<td>1.14</td>
<td>0.42</td>
</tr>
<tr>
<td>4b</td>
<td>H₂O + O → OH + OH</td>
<td>1.49 10^{10}</td>
<td>1.14</td>
<td>71.14</td>
</tr>
<tr>
<td>5**</td>
<td>H + OH + M → H₂O + M</td>
<td>2.30 10^{18}</td>
<td>-0.80</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>HO₂ + H → OH + OH</td>
<td>1.50 10^{14}</td>
<td>0.00</td>
<td>4.20</td>
</tr>
<tr>
<td>7</td>
<td>HO₂ + H → H₂ + O₂</td>
<td>2.50 10^{13}</td>
<td>0.00</td>
<td>2.90</td>
</tr>
<tr>
<td>8</td>
<td>HO₂ + H → H₂O + O</td>
<td>3.00 10^{13}</td>
<td>0.00</td>
<td>7.20</td>
</tr>
<tr>
<td>9</td>
<td>HO₂ + OH → H₂O + O₂</td>
<td>2.00 10^{13}</td>
<td>0.00</td>
<td>7.20</td>
</tr>
<tr>
<td>10</td>
<td>CO + OH → CO₂ + H</td>
<td>4.40 10^{6}</td>
<td>1.50</td>
<td>-3.10</td>
</tr>
<tr>
<td>10b</td>
<td>CO₂ + H → CO + OH</td>
<td>4.96 10^{8}</td>
<td>1.50</td>
<td>89.71</td>
</tr>
<tr>
<td>11</td>
<td>CH₄ + H → H₂ + CH₃</td>
<td>2.20 10^{4}</td>
<td>3.00</td>
<td>36.60</td>
</tr>
<tr>
<td>11b</td>
<td>H₂ + CH₃ → CH₄ + H</td>
<td>8.83 10^{2}</td>
<td>3.00</td>
<td>33.53</td>
</tr>
<tr>
<td>12</td>
<td>CH₄ + OH → H₂O + CH₄</td>
<td>1.60 10^{6}</td>
<td>2.10</td>
<td>10.30</td>
</tr>
<tr>
<td>13</td>
<td>CH₃ + O → CH₂O + H</td>
<td>7.00 10^{13}</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>14</td>
<td>CH₃ + OH → CH₂O + H + H</td>
<td>9.00 10^{14}</td>
<td>0.00</td>
<td>64.80</td>
</tr>
<tr>
<td>15</td>
<td>CH₃ + OH → CH₂O + H₂</td>
<td>8.00 10^{12}</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>16</td>
<td>CH₃ + H → CH₄</td>
<td>6.00 10^{16}</td>
<td>-1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>17</td>
<td>CH₂O + H → CHO + H₂</td>
<td>2.50 10^{13}</td>
<td>0.00</td>
<td>16.70</td>
</tr>
<tr>
<td>18</td>
<td>CH₂O + OH → CHO + H₂O</td>
<td>3.00 10^{13}</td>
<td>0.00</td>
<td>5.00</td>
</tr>
<tr>
<td>19</td>
<td>CHO + H → CO + H₂</td>
<td>2.00 10^{14}</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>20</td>
<td>CHO + OH → CO + H₂O</td>
<td>1.00 10^{14}</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>21</td>
<td>CHO + O₂ → CO + HO₂</td>
<td>3.00 10^{12}</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>22**</td>
<td>CHO + M → CO + H + M</td>
<td>7.10 10^{14}</td>
<td>0.00</td>
<td>70.30</td>
</tr>
<tr>
<td>23</td>
<td>CH₃ + H → CH₂ + H₂</td>
<td>1.80 10^{14}</td>
<td>0.00</td>
<td>63.00</td>
</tr>
<tr>
<td>24</td>
<td>CH₂ + O₂ → CO₂ + H + H</td>
<td>6.50 10^{12}</td>
<td>0.00</td>
<td>6.30</td>
</tr>
<tr>
<td>25</td>
<td>CH₂ + O₂ → CO + OH + H</td>
<td>6.50 10^{12}</td>
<td>0.00</td>
<td>6.30</td>
</tr>
</tbody>
</table>

* Here cm, mol, K and kJ are the units.
** Catalytic efficiencies differ for different M; values here are for M = H₂
2.2 ELECTROMAGNETIC RADIATION SPECTRA

Since all materials above absolute zero (0° K) emit radiation based on the temperature of the material, this radiation may be used to find the temperature of the material. This energy is in the form of electromagnetic radiation and consists of a wide range of wavelengths. Three regions of wavelengths are important to this work. The first region is the wavelengths of light that are visible to the human eye, roughly 400 nm to 700 nm. This region is called the visible region and is abbreviated VIS. Wavelengths smaller than this region (10 nm to 400 nm) are in the region known as the ultra-violet region and will be abbreviated UV. The final region is composed of larger wavelengths than the visible region (700 nm to 25 µm) and is the near infrared, abbreviated as the near-IR region.

2.2.1 Background Radiation

Soot created during the combustion process radiates energy according to its temperature and can double or triple the heat radiated by the gaseous products alone. Soot comes to thermal equilibrium with the surrounding gas in approximately $10^{-7}$ s. Determination of the flame temperature will depend on this background radiation. Therefore, understanding of the nature of the background radiation is essential.

2.2.1.1 Blackbody Radiation

A blackbody can be described as an enclosed body that absorbs all incident radiation upon it. When this body is at equilibrium, it will emit radiation at the same rate as it absorbs radiation from the surrounding medium. Sometimes a blackbody is referred to as a “complete absorber”. Therefore, a blackbody “is a radiator which, at any specified temperature, emits in each part of the spectrum the maximum energy obtainable per unit
time from any radiator of equal area solely as a result of temperature\textsuperscript{24}. Figure 2.1 is a graph with sample blackbody intensities based on different temperatures.

Flames should create soot that emits the continuous radiation predicted by Planck’s Law\textsuperscript{25} for a blackbody, which states that the intensity at a given wavelength and temperature can be determined for a blackbody from:

\[ I_{\lambda,T} = \frac{2\pi\hbar c^2}{\lambda^5(\exp(hc/\lambda kT)-1)} \quad \text{EQ (2.3)} \]

Here \( I_{\lambda,T} \) is the intensity at a given wavelength \( \lambda \) and a given temperature \( T \), and the constants \( \hbar \), \( k \), and \( c \) are Planck’s constant, the Stefan-Boltzmann constant, and the speed of light respectively. Therefore the black body intensity for a given wavelength can be calculated if the temperature is known.

![Blackbody Radiation Graph](image)

\textbf{Figure 2.1: Blackbody Intensities Based on Temperature}
2.2.1.2 Non-Blackbody Radiation

Many substances reflect or transmit a portion of the incident radiation. Therefore, the amount of radiation absorbed is less than for a blackbody, and the energy that is emitted will be less than that for a blackbody emitter. A non-blackbody emitter will emit a fraction of radiation compared to a blackbody emitter at the same temperature. This fraction is termed the emittance or emissivity of the non-blackbody and is dependent on the wavelength of the emitted radiation\textsuperscript{26}. Thus, the emissivity is a measure of how close to the maximum amount of radiation a body is capable of emitting. However, for flames, the emissivity in the ultraviolet and visible regions is closer to zero. Once solid particles, such as soot, appear in flames, the emissivity becomes closer to a black or “grey” body. A grey body is such that the emissivity is not one, but varies only slightly with wavelength\textsuperscript{27}. The emissivity of soot does depend on temperature as well, and can be given by:

$$
\varepsilon_\lambda = 1 - \exp\left( -\frac{0.526SL}{\lambda T} \right)
$$

where ‘S’ is the mole fraction of soot, L is the path length, \(\lambda\) is the wavelength and T is the temperature. There is some disagreement as to the actual constant listed above, and the power of the wavelength (\(\lambda\)) is only one at the longer wavelengths and is closer to 1.39 for the wavelength range of 0.556 – 0.665 µm\textsuperscript{29}.

2.2.2 Emission/Absorption Lines

In the presence of enough energy, an atom may be excited to a higher level. If this excited atom then falls back to its ground state, this energy is then released at a characteristic frequency related to these two energy levels as seen in Figure 2.2. \(E_1\) is the energy of the first excited level and \(E_0\) is the energy of the ground state. An atom in the
first excited state releases energy $E$ when dropping from the first excited state to the ground state equal to the difference in the energy levels. This energy is emitted at a frequency related to the energy in EQ (2.5) below:

$$E = h \nu = \frac{hc}{\lambda} = E_i - E_0$$  \hspace{1cm} \text{EQ (2.5)}$$

where $h$ is Planck’s constant, $\nu$ is the frequency, $c$ is the speed of light and $\lambda$ is the wavelength.

---

**Figure 2.2: Basic Energy Level Diagram Showing Emission Energy**

One frequent emission line found in the glass industry is from the metal sodium (Na). In order for sodium to create an emission line, several factors must be present. First, the temperature must be above the dissociation temperature that will break the bonds holding the combustion gas molecules together allowing free atoms to exist. Next, an isolated hydrogen atom (H) in the ground state and/or a free hydroxyl radical (OH) may interact with the sodium metal such as:
Either of these reactions produces a free sodium atom in the ground state. Then with additional energy this free sodium atom may be excited using:

\[ \text{Na}^+ + E' \rightarrow \text{Na}^* \quad \text{EQ (2.8)} \]

where \( E' \) represents energy in a generic sense. This is then immediately followed by the release of radiation at \( \lambda = 589 \text{ nm} \) or \( \nu = 509 \text{ THz} \) (\( \nu = c/\lambda \)) for sodium given by:

\[ \text{Na}^* \rightarrow \text{Na}^+ + h\nu \quad \text{EQ (2.9)} \]

Only a small fraction of atoms become excited and the ratio of excited atoms to atoms in the ground state are given by a Boltzmann distribution:

\[ \frac{N^*}{N^0} = C \exp \left( -\frac{E}{kT} \right) \quad \text{EQ (2.10)} \]

where \( N^* \) is the number of excited atoms, \( N^0 \) is the number of atoms in the ground state, \( C \) is a constant for a particular system, \( E \) is the activation energy, \( k \) is the universal Boltzmann constant, and \( T \) is temperature. The constant \( C \) for sodium is approximately 1.99 (calculated from a table in Ewing), and \( E \) is \( 3.38 \times 10^{-19} \text{ J} \) for \( \lambda = 589.0 \text{ nm} \). Using these constants and rewriting EQ (2.10) to yield the number of excited atoms in terms of atoms in the ground state at temperature \( T \):

\[ N^* = 1.99 N^0 \exp \left( -\frac{2.6395 \times 10^{-3}}{T} \right) \quad \text{EQ (2.11)} \]

\[ \hat{\text{Note the distinction between the dot and asterisk: } H^+ \text{ represents an isolated hydrogen atom (not ion) in its ground state; HO}^+ \text{ represents a hydroxyl free radical. } H^+ \ast \text{ represents an atom of hydrogen in an excited state. The symbol } E' \text{ is used in a generic sense to indicate energy.}} \]
There is also the reverse of EQ (2.9) where an atom in the ground state can absorb energy and move into a higher energy state. Using Figure 2.2 again, the energy necessary to move an atom in the ground state to the first energy level is exactly the same amount as the energy emitted when an atom in the first energy level drops to the ground state. One major difference between absorption and emission is the probability of the occurrence. The probability is effectively one (1) for emission and is less than one (<1) for absorption. All atoms in an elevated energy state will seek to move to the lowest energy level available, which is that of the ground state.

The blackbody background will be changed by the addition of the number of excited atoms emitting energy $E$ minus the number of atoms in the ground state absorbing energy $E$. The following equation approximates this:

\[ \Delta N = P_E N^* - P_A N^0 \]

EQ (2.12)

where $\Delta N = \text{change from the background counts}$, $P_E = \text{probability of an excited atom emitting energy}$ and $P_A = \text{probability of an atom in the ground state absorbing energy}$. Using the assumption that an excited atom will always seek to return to the ground state leads to the assumption of $P_E$ having an approximately value of one. Combining this assumption with EQ (2.11) and simplifying yields:

\[ \Delta N = \left( 1.99 \exp \left( -\frac{2.6395 \times 10^{-3}}{T} \right) - P_A \right) N^0 \]

EQ (2.13)

At some temperatures, sodium has been measured with an emission line (Figure 2.3) while at lower temperatures sodium has an absorption line (Figure 2.4). The higher temperatures provided with oxy-fuel flames will generally yield an emission line, while in some instances the lower air-fuel flame temperatures will have an absorption line.
Figure 2.3: Spectrum Showing Emission Line at 590 nm

Figure 2.4: Spectrum Showing Absorption Line at 590 nm
Additional emission lines that can prove useful is the hydroxyl (OH) emission lines near 507 nm, 510nm and 512nm. The changes in these emission lines can be linked to two other factors important in furnace operations, the monitoring of NO\textsubscript{X} gases and burner stoichiometry. The actual use of these emission lines will be further detailed in section 6.3.3. Again, the higher temperatures associated with the oxy-fuel flames will provide a better resolution for these emission lines.

2.3 NOISE

Noise is an uncertainty in a measured signal level. In general, noise is divided into three major types for a photon detector. The first type is noise associated with the actual creation of the photons being detected, the second is noise created by the detector itself, and finally, electronic noise created by the processor system being used with the detector\textsuperscript{30}.

2.3.1 Photon Noise

Photons created by any source do not do so with any certainty. There is a statistical nature to the generation of photons from the source. The average number of photons created will remain fairly constant if conditions are kept the same, however, in any given time period, the numbers generated will vary from one another. This variance is called photon noise. For a blackbody, the signal radiation noise is related to a root mean square (rms) noise and a Boson factor as shown below:

\[
\sigma^2 = n \left[ \frac{e^{\frac{hv}{kT}}}{e^{\frac{hv}{kT}} - 1} \right] = n \left[ \frac{e^{\frac{hc}{kT}}}{e^{\frac{hc}{kT}} - 1} \right]
\]

EQ (2.14)
where $\sigma$ is the variance and $\bar{n}$ is the average number of photons measured. In most cases used in this work, $hc/\lambda kT$ is large and the Boson factor will be approximately one since $\exp(hc/\lambda kT) - 1 \approx \exp(hc/\lambda kT)$.

The second portion of photon noise is caused by background radiation. When measuring flame temperatures, hot surfaces behind the flames will be radiating photons as well. The opacity of the flame will determine how many photons will penetrate the flame and emerge from the opposite side to make it to the detector for measurement. It has been assumed that the majority of the flames used for this work are opaque and that the noise from this source is minimal.

2.3.2 Detector and Processor Generated Noises

There are six types of noise associated with a photon detector: Johnson noise, shot noise, generation-recombination noise, $1/f$ noise, temperature fluctuations, and microphonics. Johnson noise, also known as Nyquist noise, is caused by the thermal motion of charged particles in a resistive element and can be approximated by one-half of the thermal energy ($\frac{1}{2}kT$). Shot noise is generated in the detector by the random nature of the photon arrival at the detector. Generation-recombination (G-R) noise is caused by the fluctuations in the current carrier generation and recombination. The $1/f$ noise is related to frequency and is so called because of the rapid decrease in this type of noise as frequency increases, however this noise is still not well understood. Temperature fluctuations of the detector system will generate noise in the electrical output. This noise is often called temperature or phonon noise to distinguish it from thermal (Johnson) noise. The last source of noise is called microphonics and results from the mechanical
displacement of components to a system due to a shock or vibration to the system. These same noises are also associated with the processor.

Of these six, only Johnson, shot, and G-R noises will be considered as factors. The spectrometer is kept isolated in a cooler with ice to minimize temperature fluctuations and care is taken to minimize any shock to the system while measurements are being taken. The 1/f noise is taken to be a minimal factor compared to the other sources of noise.

2.3.3 CCD Array Noises

Some additional types of noise are associated with a CCD array, such as that used in this work. In addition to the shot and Johnson noises, there is an input noise associated with transferring a charge onto a capacitor plate\(^ {33} \). There is a transfer inefficiency noise, as not all charges are transferred to the capacitor and a certain number are left behind with each transfer. Again, this is a square root of the average electrons in the transfer times two. This multiple of two arises from the number that is left both arriving on and leaving from the capacitor plate. Another noise that is important in a CCD system is called trapping noise, and is caused by the trapping or emission of fast interface states associated with the transfer of charge from one site to another. The particular model of spectrometer used in this work has a built-in noise reduction feature for a type of noise called dark-current noise, which is where carriers that are thermally generated to bring the potential well into thermal equilibrium create this noise. This is also referred to as thermal generation noise. The coupling of the array gates to the output diode creates a capacitance coupling noise called clock-feed through noise and is important at high frequencies.
Two additional noises are associated with the preamplifier output of the CCD array. These are floating diffusion reset noise and Metal Oxide Semiconductor Field-Effect Transistor (MOSFET) noise. The first noise is associated with the transfer of the charge packet to a floating diffusion, which in turn is connected to a gate of an output MOSFET. This noise is also called kTC noise from equating the energy in a capacitor to the minimum energy for a single degree of freedom in equilibrium:

\[
\frac{Q^2}{2C} = \frac{1}{2} kT \Rightarrow Q^2 = kTC
\]

EQ (2.15)

where Q is the charge on the capacitor, C is the capacitance, k is Boltzmann’s constant, and T is the temperature. The last noise is the MOSFET noise and it is proportional to, 1/2T where T is the period associated with the sampling time.
3 TEMPERATURE MEASUREMENT METHODS

One or more of three possible processes transfer heat from one object to another. They are conduction, convection and radiation. Conduction is the process where the transfer of heat from one object to another is through contact between the objects. Convection is the process where heated substances rise due to differences in density from different temperatures. Radiation is the process where an object emits heat as electromagnetic radiation, where thermal radiation is defined as the radiant energy emitted between the wavelengths of 0.4 µm and 1000 µm$^{34}$.

The temperature profile inside a glass furnace is an important part of the glass-making process. Furnace operators depend on different methods to determine the temperature at different places inside the furnace, however, one of the more difficult to measure locations is the flame from the burners. There are two different methods for temperature measurements for flames, contact and non-contact methods. Most methods involve either conduction or radiation to measure temperature. Methods based on conduction, referred to as contact methods, rely on the Zeroth Law of Thermodynamics that states, “If two bodies are in (thermal) equilibrium with a third body, they are in equilibrium with each other$^{35}$.” The methods that rely on radiation provide the basis for the non-contact methods.

3.1 TEMPERATURE SCALES

Historically, there have been many different scales used to measure temperature. Daniel Fahrenheit created the first reliable scale in the early 1700’s where he used two fixed points to determine temperatures. The first point was the coldest point that he could
get with water, ice and salt, which he set as zero, and the temperature of the armpit of a healthy man, which he set as 96. Using this scale, the freezing point of water at normal atmospheric pressure was 32 and the boiling point was 212. This became known as the Fahrenheit scale and is still in use today. In 1742, Anders Celsius proposed a scale that used the freezing point and the boiling point of water as the set points of the scale, with the freezing point set at zero and the boiling point set at 100. Eventually, Lord William Thompson Kelvin realized that based on the Carnot engine, an absolute temperature scale could be created. Lord Kelvin created a temperature scale that is related to the Celsius scale by the relation:

\[ T_K = T_C + 273 \]  

EQ (3.1)

where \( T_K \) is the absolute temperature in Kelvin and \( T_C \) is the temperature in degrees Celsius. The number 273 is derived from observations made by Renault on the expansions of various gases and the interval between degrees was set to match those of Celsius. Thus, a change of 1 °C is equal to a change of 1 K. Temperatures will be calculated using the Kelvin scale throughout this work.

3.2 CONTACT METHODS

Contact methods are those methods that require some part of the temperature sensor to be in contact with the flame, which measure heat through conduction. This does require the sensor probe to be very robust in order to survive intact in the high-temperature, corrosive flame environment. There are some sensors that can be used within certain temperature ranges, but this requires knowledge of an approximate flame temperature prior to use. Listed below are a few samples of temperature measurement devices that rely on thermal contact to work.
3.2.1 Thermocouples

Thermocouples are perhaps one of the more common forms of temperature measurement in use in furnaces today. Operators often use temperature from thermocouples in the crown of the furnace as one of the control variables that they monitor. However, most thermocouples are not robust enough to withstand the high temperatures and corrosive environment inside a flame. Thermocouples rely on the thermoelectric properties from two dissimilar metals in contact. If these two metals are connected together at each end and there is a temperature difference between these junctions, an electrical potential is developed that is proportional to the temperature. There are many high-temperature thermocouples available commercially, some with upper limits in excess of 1500 K. However at high temperatures (>1000 K) radiation and conduction losses must be accounted for in order to obtain reliable temperature measurements\textsuperscript{37}. This method will yield a “spot” temperature, that is, the temperature at the location of the thermocouple junction. In addition to radiation loss, another disadvantage is that instead of measuring flame temperature(s), what is actually being measured is the temperature of the thermocouple junction and the surrounding gas. Therefore, the putative ‘flame temperature’ is actually being inferred from the thermocouple measurement\textsuperscript{38}. Gas corrections to the thermocouple measurements are used in Section 5.4.2.

3.2.2 Resistance Thermometry

This technique relies on the behavior of the resistance of a metal wire as temperature varies. A noble metal wire is often used for the element of resistance. A constant current source is required and a method to measure the resistance of the wire.
This method generally requires some method of protecting the wire from the direct effects of the flame such as a coating of silica or a rare earth oxide. Again, this method requires correction for radiation losses in order to measure the flame temperature accurately\(^{39}\). In addition, this method gives an averaged “line” temperature as opposed to the spot temperature reported by a thermocouple.

### 3.2.3 Fiber-Optic Probes

There is a contact method using fiber-optic sensors where laser light is passed through a light guide that is in turn placed in the area where the temperature is to be measured. The thermal expansion of the light guide changes the parameters of the index of refraction allowing interferometry of laser signals to provide a temperature. While this method yields measurements with excellent resolution, the temperature ranges are limited due to material considerations. This method has been used successfully up to temperature ranges of 1600 K\(^{40}\).

### 3.3 NON-CONTACT METHODS

Non-contact methods require no direct sensor contact with the flame in order to determine the flame temperature. These methods measure heat through radiation. This is the preferred method of many since these methods usually have little impact on the flame. However, some of these methods require additional non-reactive materials to be added to the fuel mixture and as such must be used where these additional materials will not affect the final desired purpose of the furnace. Some sample methods that require no contact with the source being measured are listed below.
3.3.1 Radiation Absorption Methods

Temperature can be derived from an equation of state relating temperature and gas density. The average molecular weight must be estimated with sufficient accuracy in order for this method to work, and this can be done reasonably well for systems at low pressures (P < 3 atm) and high temperatures (T > 300 K). Since most flame systems are well within these parameters, a method has been developed using soft X-rays. The absorption of X-rays is proportional to the density of the gas, however common flames have a low absorption cross-section for X-rays and it is usually necessary to add a tracer gas with a high absorption cross-section to the mixture\textsuperscript{41}.

3.3.2 IR Guns

These thermometers are generally a “point and shoot” type of instrument using blackbody temperature calculations. They are generally quick, requiring approximately a few seconds to measure a single temperature. These guns are able to focus on an object and measure the temperature of that object and regardless of the environment. Using optical methods like a hand-held IR gun (Figure 3.1), two-surfaces at the same temperature may read differently depending on their emissivity. Many of these IR guns have the ability to adjust the emissivity\textsuperscript{42}, though often a single value is used for all measurements and most often this value is set at one or near one since the actual value for the emissivity is generally unknown. However, to obtain an accurate temperature reading with an infrared thermometer requires consideration of the following factors: aiming, focusing, optical obstruction, interface with other instruments, and maintenance\textsuperscript{43}.
3.3.3 Laser Scattering Methods

A commonly used method for measuring flame temperatures using a laser is Coherent Anti-Stokes Raman Spectroscopy (CARS). Using multi-photon scattering, molecules interact with multiple photons where the mixing provides sum and/or difference frequencies at the resonant energies. The resulting Raman spectrum has the sum or difference frequencies coinciding with one of the molecular levels that are then emitted as a third laser beam. This coherent scattering is stronger than incoherent scattering and is useful where there is another emitting background such as in a furnace. However, the technique is experimentally complex with proper alignment and tuning required making it impractical for use in a commercial furnace.\textsuperscript{44}
3.3.4 Pyrometers

A pyrometer is a temperature-measuring device that projects the images of a blackbody radiator on a photoelectric detector that translates the spectral radiation flux into a photocurrent. This current is then calibrated using a reference standard such as high-stability tungsten strip lamps at different temperatures. Recent advances in pyrometry have allowed the development of pyrometers that have a short-term repeatability of 0.1 K using the copper freezing point, with a combined uncertainty in the calibration and measuring of 0.22 K to 0.8 K in the range of 1073 K to 2473 K\textsuperscript{45}.

3.4 COMPARISON OF CONTACT VS. NON-CONTACT METHODS

Each type of method has its own advantages and disadvantages. Those methods that require contact with a surface are plagued with such errors as contact errors, friction heating errors, heat-sinking errors, and time-based errors. The optical methods have such errors as pre-set emissivity errors, emissivity shift errors, user adjustment errors, and background reflection errors.

3.5 CALIBRATION TECHNIQUES

Any instrument designed to measure a quantity will require some method to ensure that the results are appropriate. Usually this requires the calibration of the instrument in some fashion. Eisenhart describes accuracy as “…the degree of conformity to the truth\textsuperscript{46}.” Therefore, a measurement system is only as good as the system’s ability to produce results that are close to the accepted values. A few common techniques are described in the following sections.
3.5.1 Classifications of Standardization

There are four classifications of temperature standardization methods, primary, secondary, tertiary, and quaternary\textsuperscript{47}. Primary standardization requires the calibration of a temperature using the fundamental interpolation equation with sufficient temperature measurements at different well-known temperatures to determine all variables needed. The temperature points used must be precisely known and thermodynamic invariant in order to qualify for primary standardization.

Secondary standardization is calibration of a temperature using another instrument that has previously been calibrated using primary standardization. This does allow calibrations using any temperature range, however any errors in the primary standardized instrument will be carried over to the next instrument as well. The other standardizations are similar to the secondary standardization in that they compare the instrument to the next higher standardization. Thus, tertiary standardizations are compared to secondary standardizations, and quaternary standardizations are compared to tertiary standardizations. The National Bureau of Standards will calibrate any suitable instrument against their secondary standards and is often done for instrumentation companies. However, the cost of tertiary standardization makes the quaternary standardization the most common level in use by science and industry. Listed below are a few of the common methods used to calibrate temperature-measuring devices relevant to this work.

3.5.2 Thermocouples

Known melting points and boiling points of certain substances, generally with temperatures of 1337 K and less, are used in the calibration of thermocouples\textsuperscript{48}. Even with calibrations, temperature measurement with thermocouples is subject to erroneous
readings due to electromagnetic interference and environmental degradation, as well as equipment drift that require periodic recalibration\textsuperscript{49}. Common melting points in use are water (273.15 K), gallium (302.924 K), tin (505.1181 K), zinc (692.73 K), antimony (903.905 K), aluminum (933.61 K), silver (1235.08 K) and gold (1337.58 K).

3.5.3 Light Pipes

While light pipe radiation thermometers are being used in semiconductor manufacturing and are calibrated by using a heat pipe blackbody, however, the effects of stray light, temperature variations and uncertainties in the optical properties of the surface are still a problem even with the blackbody calibration\textsuperscript{50}. Heat pipes are sealed containers with porous surfaces that allow capillary action to distribute a small amount of liquid to cover the walls. This provides an isothermal chamber useful for calibration. The temperature range is determined by the fluid and wall material combination. The liquid vapor pressure, often controlled by an external pressure created using an inert gas, determines the exact temperature point.

3.5.4 Halogen Lamp

Using a halogen lamp set for a known color temperature allows the calibration of the sensor and reduces the errors from the fiber optic cable and the diffraction grating\textsuperscript{51}. Calibrations using an Ocean Optics LS-1 Tungsten Halogen Lamp with a spectral range of 360 nm – 2 μm and a reference color temperature of 3100 K were used in this work.

3.6 Precision of Measurements

While calibration leads to a better accuracy, the values reported still need a measure of their precision. Precision as described in most books is really a measure of “statistical resolution” and is often reported in terms of the standard deviation of the data.
Values reported with a measure of precision often use either the standard deviation or with multiples of two or three, using the format of $X_{\text{AVG}} \pm n^*\sigma$, where $X_{\text{AVG}}$ is the average value, $n$ is the index for the standard deviation and $\sigma$ is the standard deviation. With $3\sigma$ for the precision, this represents that 99% of the time, the actual value will be within the precision range of the measured value, while $2\sigma$ drop this to approximately 95% and $1\sigma$ drops the chance to 66%. Since $\sigma$ is used as a measure of the precision, values of $\sigma$ are reported when possible throughout this work.
4 DEVELOPMENT OF AN ADVANCED TWO-COLOR METHOD

For over forty years, scientists have used the two-color method to measure temperatures. This method is so named due to the temperature calculation using two different wavelengths, thus the two colors. Initially using colored filters to limit the wavelengths to small ranges, however, the use of a spectrometer allows this method to be used without employing filters. Since the spectrometer measures many wavelengths, the temperatures actually calculated will use multiple wavelengths for temperature determinations; however, these temperature calculations are still firmly rooted in the two-color method.

4.1 THE TWO-COLOR METHOD

The radiation spectrum given off by the combustion process contains two different elements, emission/absorption lines and an underlying blackbody curve. While the emission lines will yield information on the combustion process, as well as temperature, the blackbody curve will provide the information needed for the temperature calculations used in this process. This curve will result from the heat emitted from the soot created during the combustion process, as only a sooty flame yields a grey-body curve that will allow the two-color method to be employed. The temperature of the soot has been estimated to be within ±1 K of the flame-gas temperature.

Starting with Planck’s Law again:

\[
I_{\lambda,T} = \frac{2\pi hc^2}{\lambda^5 \left( \exp\left(\frac{hc}{\lambda kT}\right) - 1 \right)} \quad \text{EQ (4.1)}
\]
for a temperature range from 800 K to 2200 K and using wavelengths in the range from 400 nm – 1000 nm, the exponential term in EQ (4.1) \(\exp(\frac{hc}{\lambda kT}) \gg 1\), thus \(\exp(\frac{hc}{\lambda kT}) - 1 \approx \exp(\frac{hc}{\lambda kT})\). This changes Planck’s Law into Wien’s Law of Radiation:

\[
I_{\lambda,T} = \left(\frac{C_1}{\lambda^5}\right) \exp\left(-\frac{C_2}{\lambda T}\right)
\]

EQ (4.2)

where \(C_1 = 2\pi hc^2\) and \(C_2 = hc/k\). Here \(I_{\lambda,T}\) is the intensity at a given wavelength \(\lambda\) and a given temperature \(T\), and the constants \(h, k,\) and \(c\) are Plank’s constant, Boltzmann’s constant and the speed of light respectively. EQ (4.2) is for a perfect blackbody. However, the furnace environment is not perfect and an additional term for emissivity, \(\varepsilon_\lambda\) at the given wavelength, must be added to the equation.

\[
I_{\lambda,T} = \varepsilon_\lambda \left(\frac{C_1}{\lambda^5}\right) \exp\left(-\frac{C_2}{\lambda T}\right)
\]

EQ (4.3)

Using two wavelengths, \(\lambda_i\) and \(\lambda_j\), and dividing one intensity equation by another the following two-color equation is obtained:

\[
\left(\frac{I_i}{I_j}\right) = \left(\frac{\varepsilon_i}{\varepsilon_j}\right) \frac{\lambda_j^5 \left(\exp\left(C_2/\lambda_j T\right)\right)}{\lambda_i^5 \left(\exp\left(C_2/\lambda_i T\right)\right)}
\]

EQ (4.4)

In this formula, for wavelength \(\lambda_i\) the intensity is given by \(I_i\) and the emissivity is given by \(\varepsilon_i\), and for wavelength \(\lambda_j\), \(I_j\) gives the intensity and \(\varepsilon_j\) gives the emissivity. Rearranging EQ (4.4) to calculate temperature yields:

\[
T_{i,j} = \frac{C_2 \{1/\lambda_j - 1/\lambda_i\}}{\ln\left(I_i/I_j\right) + \ln\left(\varepsilon_j/\varepsilon_i\right) + 5\ln\left(\lambda_i/\lambda_j\right)}
\]

EQ (4.5)

4.2 SIMPLE CORRECTIONS FOR THE TWO-COLOR METHOD

In the development of two-color temperature calculations using a spectrometer, corrections are necessary to derive a useable blackbody background. This section will describe quick and simple corrections for the two-color method. The correction method
recommended by Ocean Optics, the manufacturer of the spectrometer, is the use of a halogen lamp. Further refinements to add a simple correction for distance is also introduced.

4.2.1 Corrections Using a Halogen Lamp

In application to a gas-fired furnace, the collected intensity data is subject to many errors, such as attenuation losses in the gases between the probe and the flame, losses in the lens that receives the incoming light, attenuation losses in the fiber-optic cable and losses due to the grating efficiency of the spectrometer. The last two losses can be corrected for using a known color temperature lamp with the fiber-optic cable and the grating. A halogen lamp set for a known color temperature allows the creation of a correction factor for each wavelength in order to reduce the errors from the fiber optic cable and the diffraction grating. These intensity correction factors are determined by modifying $I_i$ in order to produce the given color temperature using measured intensities from the halogen lamp. The actual measured intensity for the halogen lamp, $I_{iH}$, is the average of several measured spectra. The averaging to produce a single spectrum used to represent the actual measured intensity reduces errors that would arise from the noise associated with a single spectrum. The Planck’s law intensity, $I_{iP}$, is calculated using EQ (4.1) with the color temperature of a halogen lamp, in this case 3100 K. In order to find the correction factor $A_i$, the measured intensity is divided by the Planck’s law intensity for the halogen lamp. Therefore, $A_i$ is found by using:

$$A_i = \frac{I_{iH}}{I_{iP}} = \frac{I_{iH} \lambda_i^5 \left(\exp\left(C_2/\lambda_i \ast 3100\right) - 1\right)}{C_1}$$

EQ (4.6)
The intensity to be corrected will then be divided by the correction factor of the corresponding wavelength. This will lead to a corrected intensity, $I_i'$:

$$I_i' = \frac{I_i}{A_i} \quad \text{EQ (4.7)}$$

### 4.2.1.1 Derivation Of The Temperature Equation

Adding the correction factors $A_i$ and $A_j$ for grating efficiency and losses in the fiber-optic cable derived from the spectrum of a halogen lamp into EQ (4.4) yields:

$$\left(\frac{I_i'}{I_j'}\right) = \left(\frac{\varepsilon_i}{\varepsilon_j}\right) \frac{\lambda_j^5}{\lambda_i^5} \left(\exp\left(\frac{C_2}{\lambda_j T}\right)\right) \left(\exp\left(\frac{C_2}{\lambda_i T}\right)\right) \quad \text{EQ (4.8)}$$

Each separate wavelength will need an individual correction factor. Thus, $A_i$ is the correction factor for the wavelength $\lambda_i$ and $A_j$ is the correction factor for the wavelength $\lambda_j$. If $\lambda_i$ and $\lambda_j$ are sufficiently close together, the assumption that $\varepsilon_i/\varepsilon_j \approx 1$ allows this term to be removed from EQ (4.8). This is a common practice used to remove these terms. The removal of the emissivity terms simplifies the equation further. The maximum difference between $\lambda_i$ and $\lambda_j$ has been 128 nm in all calculations presented in this work, as described in section 4.2.1.2.1.

By using the ratio technique the impact of errors produced by the attenuation losses due to the lens are minimized. Including the correction factors $I_i'$ and $I_j'$ as well as removing the emissivity term based on the above assumption, EQ (4.8) is modified to solve for the halogen corrected temperature as given in EQ (4.9) below:

$$T_{i,j} = \frac{C_2 \left(1/\lambda_j - 1/\lambda_i\right)}{\left(\ln \left(\frac{I_i'}{I_j'}\right) + 5 \ln \left(\frac{\lambda_i}{\lambda_j}\right)\right)} \quad \text{EQ (4.9)}$$
4.2.1.2 **Wavelength Selection**

The wavelengths considered for this work are those received by the VIS spectrometer grating. In choosing which set of wavelengths to use, the first challenge is to avoid any chemiluminescent emission/absorption lines emitted in the furnace. If a wavelength chosen is on an emission/absorption line the blackbody temperature calculation will be invalid\(^{55}\). Figure 4.1 is a sample intensity profile for an electric furnace, described in detail in section 5.2, as measured by the VIS grating spectrometer. For example, one major emission line (sodium) exists near 590 nm in Figure 4.1, which normally arises from the melting of the glass and is not related to the combustion process. In this case, the sodium was injected by an atomizer into the furnace to determine if changes in the sodium emission line corresponded to changes in the sodium concentration inside the furnace. These intensities measured at the electric furnace (Figure 4.1) will be used for all calculation in Section 4.2.

Using EQ (4.7) the profile of the corrected intensities from the same spectrum used to produce Figure 4.1 is seen in Figure 4.2 below. As can be seen, wavelengths below 500 nm have very low intensities. As such, this region is considered too unreliable for temperature calculations as explained in next section and through Figure 4.3. A starting wavelength of 524 nm has been chosen, since it is above 500 nm and well below the upper limit of 700 nm, the upper limit of the visible spectra, though other values are equally acceptable, if within the acceptable bounds mentioned above. The second wavelength will then be chosen at a higher wavelength for the temperature calculations, though still less than the upper limit of 700 nm.
Figure 4.1: Raw Spectral Intensity from Electric Furnace

Figure 4.2: Corrected Spectral Intensity from Electric Furnace
4.2.1.2.1 **Difference in Wavelengths Used**

The temperatures reported in this work are calculated using an equal interval between $\lambda_i$ and $\lambda_j$. Using the starting wavelength of 524 nm, a temperature plot was created (Figure 4.3) that shows the halogen corrected temperatures of the electric furnace calculated using the starting wavelength and every other wavelength between 400 nm and 800 nm. The region within 50 nm of the starting wavelength shows intense fluctuations in the calculated temperatures indicating that the signal-to-noise ratio is very poor in this region. Since the intensities in this region are small in relation to other regions and relatively close to each other, the signal-to-noise ratio is worse in this region than those with increasingly larger wavelengths\(^{56}\). Temperatures calculated with wavelengths less than 500 nm are also unusable due to the low intensities in that region.

The dip in the temperature profile near 590 nm is due to the sodium emission peak in that region. Therefore, the ideal difference in wavelengths should place the upper wavelength region above the 600 nm mark. At wavelengths above 700 nm, the temperature starts to vary, making this the upper limit for this starting wavelength. This leads to a minimum difference in wavelengths of approximately 75 nm for the 524 nm starting wavelength, with an upper limit of around a 175 nm difference. A difference of 128 nm between wavelengths was chosen for the temperature calculations in this work, placing the difference near the middle of the 75 nm to 175 nm range and starting the upper wavelength region at 652 nm.
Figure 4.3: Temperatures with Varying Wavelength Differences

4.2.1.2.2 Best Region

Figure 4.4 shows the temperatures produced by this method using an interval of approximately 128 nm between wavelengths with the flat range of temperatures indicating the best region for temperature calculations. The wavelengths in the x-axis corresponding to the box in Figure 4.4 indicate the values of the first wavelength used in each pair. The intensities used in the temperature calculations are corrected only for grating efficiency by using EQ (4.7).
4.2.1.3 Noise Correction Methods

This section shows two ways to improve the impact of noise even with simple models that only correct for grating efficiency. The spectral intensities recorded also include a certain amount of “noise” created by the spectrometer. Furthermore, turbulence from the flame causes some variations in the temporal intensities emitted from the flame. This would indicate that a single temperature calculation might not represent the true temperature of the region. In order to help account for this noise, temperatures from twenty-five paired channels covering roughly 8 nm are averaged to get the flame temperature. The region with the lowest wavelengths, referred to later as the lower region, starts at 524 nm and extends over 25 channels to 532 nm. The other region, referred to later as the upper region, starts at 652 nm extending over 25 channels to 660 nm. Figure 4.5 shows an example of temperatures corrected only for the grating
efficiency for the twenty-five channel pairs used to calculate a final temperature for the first temperature reported for the electric furnace.

![Temperatures Averaged for Final Temperature](image)

**Figure 4.5: Sample Set of Temperatures Averaged for Final Temperature**

To help minimize the impacts from the noise and flame turbulence, in addition to using multiple pairs of wavelengths as described above to calculate one temperature for each spectrum, the intensity from five spectra are averaged to produce the final intensities used in calculating the actual temperatures reported. Figure 4.6 shows temperatures for seventy-five individual spectrums from a commercial glass furnace described in section 6.1. The equation for the best-fit line, shown in the upper right corner, indicates a slope value of -0.1974, indicating a slight cooling trend in the furnace, and a y-intercept of 1977.7 K.

In cases where the experiments record many sequential spectra, the average of the first five produce the first temperature reported. Then the very first spectrum is dropped
and the second through sixth spectra are averaged to produce the second temperature reported. Each successive temperature is formulated by dropping the lowest spectrum and adding the next higher spectrum not previously used. Figure 4.7 uses this moving average method using the same temperatures as reported in Figure 4.6. Here the values for the best-fit line indicate a slope of -0.2062 with the y-intercept of 1978.8 K, differences of 4.4% and 1.0% respectively from the individual values.

Figure 4.8 uses the same method however, the spectral intensities were averaged first and then the temperatures were found using the two-color method. It is apparent that both of these averaging methods produce similar results. The average temperature for each similar grouping is 1965.4 K with a standard deviation of ±4.9 K for the averaged temperatures group as compared to 1965.6 K with a standard deviation of ±4.9 K for the averaged intensities group. The values for the best-fit line indicate a slope of -0.2066 with the y-intercept of 1979.0 K, differences of 0.19% and 0.01% respectively from the averaged temperature values.
Figure 4.6: Individual Temperatures from Commercial Glass Furnace

Figure 4.7: Averaged Temperatures for Sets of Five Spectra
Figure 4.8: Temperatures for Averaged Intensities of Five Spectra Groups

4.2.2 The Simple Attenuation Correction Factor

From early on in the development of the two-color method using visible wavelengths for temperature calculations, it has been evident that an additional correction is needed along with the correction from the halogen lamp. A correction for scattering and other losses in the medium along the line of sight of the detector is also needed. The distance between the probe and the reaction zone of the flame varies with each furnace used, and this path length is the first factor that will be looked at in creating a correction factor for the attenuation losses through the furnace.

4.2.2.1 Path Length

The path length used in the attenuation correction factor is generally calculated as the distance from the lens in the probe to the estimated point of the reaction zone in the flame, or a known distance for wall temperature readings. The reaction zone is
considered to be roughly at one-third of the flame length as measured from the base of the flame for this work, although the actual reaction zone location changes depending on A/F (or O/F) and gas flow. Using photographs of the flame and known measurements for the furnace, this distance is then estimated for the flame. Though the spectrometer views the area within the cone that enters the collimating lens, the distances beyond the flame are considered inconsequential due to the optical non-transparency of the soot particles57.

4.2.2.2 Development of the Linear Model

The initial correction factor $\phi_d$ is a function of the path length only. $\phi_d$ may also depend on wavelength, however this dependence is assumed to be negligible compared to the path length correction, especially since $\lambda_i$ and $\lambda_j$ are relatively close to each other in this application. This correction factor may also depend on the composition of the furnace environment, as well as the temperature and pressure inside the furnace.

It was assumed that the form of the distance correction would be of the form

$$\phi_d = 1 - \exp(-\alpha d)$$

EQ (4.10)

where $\alpha$ is the attenuation factor and $d$ is the distance between the probe and the reaction zone of the flame for flame temperatures, or the distance to the wall in the case of wall temperature measurements. This leads to values of $\phi_d$ that are less than or equal to 1, with the value of 1 being the equivalent of an uncorrected spectrum. This form was then simplified to a linear form by using an approximation of the exponential function.

The first $\phi_d$ correction factor in this work is then obtained experimentally from Figure 4.9 using an electric and a pilot scale furnace walls, with known temperatures and distances to the point of measurement. The $\phi_d$ correction factor for the research boiler and the commercial glass furnace are also shown in Figure 4.9, though these values are
derived using the $\phi_d$ correction factor from EQ (4.11). Using the pilot-scale wall without a flame, the temperature of the wall is considered to be the same as a thermocouple near the point of measurement. The parameter $\phi_d$ is calculated by modifying the initial intensity, $I_i$, in calculating the wall temperature using EQ (4.9), such that the result equals the known wall temperature.

![Figure 4.9: Linear Plot of Derived Correction Factors for Attenuation](image)

Using the correction factors derived for the electric and the pilot-scale furnaces, a linear formula to determine $\phi_d$ based on distance alone was developed:

$$
\phi_d = -0.0454d + 0.9186 \quad \text{EQ (4.11)}
$$

This formula based on the path length, $d$ (in meters), is then used to calculate $\phi_d$ with known external (out of furnace) distances to the point of measurement for other furnaces.
Adding the $\phi_d$ correction factor into the halogen correction equation yields the equation used to calculate the $\phi_d$ corrected temperatures:

$$T_{i,j} = \frac{C_i \left( \frac{1}{\lambda_j} - \frac{1}{\lambda_i} \right)}{\left( \ln \left( \frac{\phi_i I_i'}{I_j'} \right) + 5 \ln \left( \frac{\lambda_i}{\lambda_j} \right) \right)}$$

EQ (4.12)

The values of $\phi_d$ will be less than one, with smaller values indicating longer distances as shown in Table 4.1.

<table>
<thead>
<tr>
<th>Location</th>
<th>Path Length (m)</th>
<th>$\phi_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric</td>
<td>0.7620</td>
<td>0.8840</td>
</tr>
<tr>
<td>Pilot-Scale</td>
<td>1.1938</td>
<td>0.8644</td>
</tr>
<tr>
<td>Research Boiler</td>
<td>2.3876</td>
<td>0.8102</td>
</tr>
<tr>
<td>Commercial Glass – Flame</td>
<td>9.6822</td>
<td>0.4791</td>
</tr>
<tr>
<td>Commercial Glass – Wall</td>
<td>16.0830</td>
<td>0.1884</td>
</tr>
</tbody>
</table>

While the simple linear approach works out to a few meters, the temperatures calculated using this method for the commercial glass furnace are over-corrected. As can be seen in Table 4.1, the correction for the wall distance drastically reduces the intensities as well as the temperatures calculated. It is clear that the simple method is only useful over short distances and a better correction method is needed for longer distances.

4.3 ADVANCED CORRECTIONS FOR THE TWO-COLOR METHOD

The simple corrections do not produce accurate calculated temperatures in all cases, so more advanced techniques are needed and developed. In this section, a referenced correction is developed that uses a reference temperature in the creation of the correction factor. In addition, an advanced technique is developed for the correction factor and furthermore a dynamic empirical model is created for future users to apply according to their applications.
4.3.1 Referenced Correction with a Known Temperature

The possible factors that can influence the temperatures calculated using the spectrometer include grating and fiber optic cable effects, emissivity, distance between probe and target, and the temperature of the environment between the probe and the target. The distance factor with flame is also variable due to the flame moving back and forth due to turbulence. The method using the halogen lamp for calibration takes into account the grating and fiber optic cable effects, and assumes the effect of emissivity is negligible and using the simple $\phi_d$ correction factor introduces a correction to take into account the distance between the probe and the target. However, the condition of the furnace environment is not addressed, and the difference between the halogen lamp’s temperature of 3100K and the furnace temperatures of around 1000K to 2000K is a factor that should be included. Furthermore, for flame calculations, no good method exists to accurately measure the distance between the probe and the reaction zone of the flame which is needed for $\phi_d$ calculations. Using an estimation for that distance results in a small error in the $\phi_d$ correction factor then obtained.

4.3.1.1 Halogen Correction Curve

Similar to work done by Saeger$^{58}$, a halogen correction curve can be created using the halogen lamp. This correction curve is the ratio of the measured intensity of the halogen lamp to the intensity found using Planck’s law for each given wavelength and then normalizing the result to one. Essentially, this is the normalized $A_i$ correction factor found in EQ (4.6) and repeated below as EQ (4.13).

$$A_i = \frac{I_{iH}}{I_{iP}} = \frac{A_i^5 \exp\left(C_2 / \lambda_i \cdot 3100\right) - 1}{C_1}$$  

EQ (4.13)
This curve for the halogen lamp reported earlier is shown below in Figure 4.10. The halogen correction curve above 450 nm is similar to the relative transmission efficiencies provided by the Ocean Optics website\textsuperscript{59} as seen in Figure 4.11. This curve will correct for the grating efficiency as used earlier, however it only works for short distances, as the probe-to-source distance for the halogen lamp is less than 5cm. It also works well for temperatures near 3100 K, and the only emissivity corrected for is that of the lamp itself, which is assumed to be near one (1) due to the approximate blackbody nature of the lamp.

![Halogen Correction Curve at 3100 K](image)

**Figure 4.10: Halogen Correction Curve at 3100 K**
4.3.1.2 Blackbody Referenced Correction Curves

Therefore, a blackbody-based referenced correction was developed that uses the spectrometer and a known source reference temperature to eliminate the inappropriately high temperature of the halogen lamp at 3100 K. The referenced correction created using this method corrects for grating and fiber optic cable effects, emissivity, distance between probe and target, and the environment between the probe and the target. Each furnace will then generate its own referenced correction curve in place of using the halogen correction. To create this referenced correction curve, initial spectral data for the source and an approximation of the source temperature is needed. The actual measured intensity for the source, \( I_{IS} \), is again the average of several measured spectra used to create a single spectrum. The Planck’s law intensity, \( I_{IP} \), is calculated using EQ (4.1) with the
approximate reference temperature of the source, $T_S$. Using a process similar to that used to create $A_i$, the blackbody-based referenced correction is created using:

$$B_i = \frac{I_{is}}{I_{ip}} = \frac{I_{is} \lambda_i^5 \left( \exp \left( \frac{C_2}{\lambda_i T_S} \right) - 1 \right)}{C_i} \quad \text{EQ (4.14)}$$

$B_i$ is then normalized to create the referenced correction curve and is used in a similar method to $A_i$ to create the corrected intensity $I_i'$ using:

$$I_i' = \frac{I_i}{B_i} \quad \text{EQ (4.15)}$$

This corrected intensity is then used in EQ (4.9) as before:

$$T_{i,j} = \frac{C_2 \left( \frac{1}{\lambda_j} - \frac{1}{\lambda_i} \right)}{\left( \ln \left( \frac{I_i'}{I_j'} \right) + 5 \ln \left( \frac{\lambda_i}{\lambda_j} \right) \right)} \quad \text{EQ (4.16)}$$

Figure 4.12 shows the referenced correction curve for the electric furnace. The low intensities measured at 450 nm and below result in a change from the curve created using the halogen lamp. There are also noise effects in this region that are seen as the values fluctuate away from a smooth curve, primarily a signal-to-noise ratio effect. These noise effects are due to the nature of the blackbody curve. At lower temperatures, expected intensities are reduced at these wavelengths, and correspondingly, lower intensities are measured making any noise effect much larger than at higher wavelengths. As temperatures are reduced, these noise effects will be seen at higher wavelengths, which make blackbody-based temperature calculations at low temperatures in the visible range more complicated.

One benefit of using this method is that there is some correction for emission lines as seen for the sodium line at 589 nm below. However, if the emission line intensity
fluctuates, then the temperatures measured using those wavelengths are still not accurate, thus, the emission lines still need to be avoided.

![Electric Furnace Referenced Correction Curve at 1773 K](image)

**Figure 4.12: Electric Furnace Referenced Correction Curve at 1773 K**

Figure 4.13 shows the comparison of the halogen correction and the electric referenced correction curves. The effects of distance are minimized at the electric furnace compared to the other furnaces since it is the shortest distance at 0.76 m of any of the furnaces used. Both environments are relatively clean. Therefore, the main difference between these two curves is the difference in emissivity, temperature and distance. The two curves do not match indicating that the halogen lamp does not represent the electric furnace well and these differences between the electric furnace and the halogen lamp must be taken into account later for development of the empirical model for temperature calculation.
Comparison Between Halogen Correction at 3100 K and Electric Furnace Referenced Correction at 1773 K

![Comparison Between Halogen Correction at 3100 K and Electric Furnace Referenced Correction at 1773 K](image)

**Figure 4.13: Comparison between Electric and Halogen Correction Curve**

Additional referenced correction curves were create for the pilot-scale furnace using a wall temperature, the research boiler using flame temperature, the commercial multi-burner glass furnace using a wall temperature and the coal furnace using a wall temperature. Figure 4.14 shows the comparison of these correction curves with the halogen and electric correction curves shown in Figure 4.13.
Comparison between Referenced Corrections for Halogen at 3100 K, Electric Furnace at 1773K, Pilot-Scale Glass Furnace at 1406K, Research Boiler at 1850K, Commercial Multi-Burner at 1846K, and Coal Furnace at 1178K

Figure 4.14: Comparison between Multiple Correction Curves

The initial maximum intensity of the spectrum used to create the internal correction curve is another important factor during the creation process. If the maximum intensity is too low, the internal correction curve will contain numerous fluctuations at the lower wavelengths that could affect the normalization process. Ocean Optics recommends maximum intensities of 3000 or greater for best results. Using a spectrum from the commercial furnace with a maximum intensity of around 1200 counts produces a calibration curve with these fluctuations. Figure 4.15 compares this calibration curve with the one generated at the electric furnace created with a maximum count around 3900. The comparison has been limited to viewing the wavelengths from 400 nm to 600 nm where these fluctuations exist.
Another possible effect that could cause correction curves to be inaccurate is an incorrect reference temperature. Using the same data from the electric furnace with different reference temperatures shows a shift in correction curves as seen in Figure 4.16 below. It is clear that the accuracy of the reference temperature is directly reflected in the correction curve. For every degree that the reference temperature is above or below the actual temperature, the calculated temperature will have roughly the same difference. Thus, accurate reference temperatures and a sufficiently high intensity are two important factors that will affect the accuracy of the final temperature calculation if they are overlooked.
4.3.1.3 **Dynamic Empirical Correction Model**

Looking back at EQ (4.8) and using EQ (4.7) to expand the corrected intensities into the components used to create them yields:

\[
\frac{I_i/A_i}{I_j/A_j} = \frac{\varepsilon_i}{\varepsilon_j} \lambda_j^5 \left( \exp \left( \frac{C_2}{ \lambda_j T} \right) \right)
\]

EQ (4.17)

This equation contains all of the corrections necessary to create the dynamic empirical correction model. Rearranging the equation and placing all of the correction terms together yields:

\[
\left( \frac{I_i}{I_j} \right) = \left( \frac{A_i \varepsilon_i}{A_j \varepsilon_j} \right) \lambda_j^5 \left( \exp \left( \frac{C_2}{ \lambda_j T} \right) \right)
\]

EQ (4.18)
Rearranging this equation to yield temperature gives:

\[
T_{i,j} = \frac{C_2 \left(1/\lambda_j - 1/\lambda_i\right)}{\left(Ln\left(I_i/I_j\right) + Ln\left(A_j e_j / A_i e_i\right) + 5Ln\left(\lambda_i/\lambda_j\right)\right)} \]  

EQ (4.19)

Replacing all of the correction terms with \(\xi_\lambda\), the new dynamic empirical correction model term, yields the final dynamic empirical correction model temperature equation:

\[
T_{i,j} = \frac{C_2 \left(1/\lambda_j - 1/\lambda_i\right)}{\left(Ln\left(I_i/I_j\right) + Ln\left(\xi_\lambda\right) + 5Ln\left(\lambda_i/\lambda_j\right)\right)} \]  

EQ (4.20)

Once the correction factor \(\xi_\lambda\) is obtained, then EQ (4.20) can be used to calculate temperatures, since the intensities \(I_i\) and \(I_j\) are measurable and the wavelengths \(\lambda_i\) and \(\lambda_j\) are known. The remainder of this chapter will provide the procedure to generate an equation used to calculate \(\xi_\lambda\).

4.3.1.4 Ratio Determination and Smoothing

Looking closely at the grating efficiency curves and the halogen correction curve, there seems to be two separate regions that are nearly linear. These two areas are highlighted on the halogen correction curve in Figure 4.17. The first wavelength for the ratio series is chosen to be 550 nm, which places it around the middle of the first area. However, using the 128 nm separation between the first and second wavelength in the ratio places the second wavelength toward the end of the preferred wavelength range. Keeping the second wavelength roughly where it is considered optimal in the earlier trials changes the wavelength difference to around 100 nm. This difference is still in the acceptable range as determined earlier.
Figure 4.17: Two Linear Regions in the Correction/Calibration Curves

In order to reduce noise effects inherent in the correction curves, correction ratios set at approximately 100 nm apart for each calibration curve are determined. Starting at 540 nm in order to use values both above and below the set starting wavelength of 550 nm, the correction for that wavelength is set as the average of the intensity at 540 nm and the 2 channels below and the 2 channels above. Correction values are determined for wavelengths at intervals of five nm, starting at 540 nm and ending with 575 nm. A second set of values was calculated using the same method starting at 640 nm and ending with 675 nm, again at five nm intervals. Correction ratios are then calculated using these values by dividing the longer wavelength calibration value by the shorter wavelength calibration value, thus yielding values that are less than one.

Figure 4.18 shows the plot of these ratios for the halogen lamp, electric furnace, pilot scale glass furnace, research boiler and commercial glass furnace. Each of these
furnaces is considered to be relatively clean and thus comparable. A linear best-fit line is determined for each furnace and the values produced by these equations will be used in all future uses of the ratios for the corresponding furnace.

Figure 4.18: Correction Ratio Trends for Various Sources

4.3.1.5 Distance and Wavelength Effects

In order to determine the effects of distance on the correction, each correction ratio starting at 540 nm wavelength for each furnace listed above is plotted to evaluate the trend. Figure 4.19 shows the results of plotting these ratios against the probe to source distance with a best-fit line fitting the trend. This best-fit line resembles the form of emissivity or absorptive effects on intensity shown below:

\[ \varepsilon_\lambda = \alpha_\lambda = 1 - \exp(-K_\lambda L) \]  

EQ (4.21)
where $\varepsilon_\lambda$ is the emissivity at wavelength $\lambda$, $\alpha_\lambda$ is the absorptive quantity at wavelength $\lambda$, $K_\lambda$ is the extinction factor at wavelength $\lambda$, and $L$ is the distance. If a generalized form of $\alpha_\lambda$ can be determined for these furnaces, then an empirical model for temperature calculation may be created that works for furnaces of this general type.

![Correction Ratio vs Distance](image)

**Figure 4.19: Distance Trends for a Single Ratio**

A series of best-fit lines for correction ratios at multiple starting wavelengths is generated using the method mentioned above. The wavelengths for 540 nm to 575 nm in 5 nm intervals are plotted (see Figures 4.20 and 4.21) and the best-fit lines determined. These best-fit lines follow a logarithmic pattern:

$$\xi_\lambda = M \cdot \ln(x) + C$$

EQ (4.22)

where $\xi_\lambda$ is the dynamic empirical correction model term, $M$ is the logarithmic term multiplier, $x$ is the distance (in m) and $C$ is the constant term. In order to determine the
wavelength effect on this form, the multiplier M and the constant C are plotted against the wavelength (in µm) of the best-fit line derived from these terms (Figure 4.22). A linear best-fit line is the optimal form for wavelength effects on both the multiplier and the constant term. The wavelength unit is set to µm in order to produce a more precise multiplier term in the linear equation and then returned to nm with the appropriate translation.

Figure 4.20: Distance Trends for Even Series of Calibration Ratios
Correction Ratios vs Distance

\[ y = -0.0169 \ln(x) + 0.6111 \]
\[ y = -0.0154 \ln(x) + 0.5849 \]
\[ y = -0.0139 \ln(x) + 0.5586 \]
\[ y = -0.0125 \ln(x) + 0.5323 \]

Figure 4.21: Distance Trends for Odd Series of Calibration Ratios

Constant and Multiplier Change with Wavelength

\[ y = -2.6271x + 2.0429 \]
\[ y = 0.1471x - 0.0971 \]

Figure 4.22: Wavelength Trends for Multiplier and Constant Terms
Using the linear best-fit information from Figure 4.29 yields the final form for the new dynamic empirical correction for “clean” furnaces as:

\[ \xi_{\lambda} = (0.1471\lambda - 0.0971)\ln(x) + (-2.6271\lambda + 2.0429) \]  \hspace{1cm} \text{EQ (4.23)}

Since this value is obtained by using the ratio of the referenced correction terms at 100 nm intervals, this term can be used as long as the difference between the wavelengths used to determine the temperature is approximately 100 nm, though another correction can be created using a different wavelength difference if needed. It will also work best with the initial wavelength between 540 and 575 nm as used in the creation of the best-fit data.

If other intervals or different starting wavelengths are needed, the process used to create this correction can be repeated and a new dynamic empirical correction can be created to replace this one. Likewise, a new correction can be created that includes correction rations from a new furnace in order to improve the results for that furnace. If the environment inside the furnace is different enough from the current method, it yields inaccurate results, such as in the coal furnace mentioned later in section 6.3. However, the process described in this chapter can be repeated with sufficient similar furnaces of differing distances to create the appropriate \( \xi_{\lambda} \) for that furnace, therefore this empirical modeling is called dynamic.
5 LABORATORY DATA ACQUISITION AND RESULTS

In addition to the halogen lamp mentioned earlier, three other laboratory sources are used for the initial experimentations. This allows the testing of the initial models under controlled conditions. The three sources cover a wide variety of applications. The first is a small electric furnace; the second is a natural gas pilot-scale glass furnace and the final is a research boiler that can utilize a number of different types of fuel.

5.1 HALOGEN LAMP

An Ocean Optics LS-1 Tungsten Halogen Lamp (Figure 5.1) with a spectral range of 360 nm – 2 µm and a reference color temperature of 3100 K was the first source to be measured using the spectrometer. The halogen lamp is connected to the end of the fiber-optic cable without using the probe casing. This method also bypasses the collimating lens used in all the other measurements. Temperature calculations using the halogen lamp data involve the highest temperatures and the shortest distances as compared to the other sources used in this work.

Figure 5.1: Tungsten Halogen Lamp
5.1.1 Intensity Profile

The intensity profile primarily indicates the effects of the fiber-optic cable and spectrometer grating on incoming light. A sampling time of three milliseconds is used to obtain each color spectrum, as the spectral intensity associated with a temperature of 3100 K is quite high. With the halogen lamp, no emission or absorption lines occur indicating what a blackbody background will look like when the effects of the grating and cable are not corrected. The intensity values in Figure 5.2 are arbitrary count values controlled by the integration time of the spectrometer. The integration time is set such that the maximum background intensity is approximately 3000 to 3500 counts.

![Figure 5.2: Measured Spectral Intensity Profile for Halogen Lamp](image)

5.1.2 Calculated Temperatures

Since the halogen lamp is necessary to create a correction for the fiber-optic cable and spectrometer grating, as well as to create an approximation for a blackbody curve,
any temperature calculations using halogen data corrections will be near the target
temperature of 3100 K as this value is used in the creation of the correction factor.
However, viewing temperature calculations using the halogen lamp with this correction
will show the variation in temperature due to electronic noise; temperature using the
dynamic empirical correction model, and will demonstrate the accuracy of this model
when a source similar to the halogen lamp is used.

As shown in Figure 5.3, each calculated temperature using the halogen correction
is relatively close to the expected temperature. Each temperature is within ±6° K of the
expected temperature with an average calculated temperature of 3099.0° K and a standard
deviation of ±2.5° K. The twenty-five temperatures averaged to get the reported
temperatures have a maximum standard deviation of ±16.9° K (0.54%) for the set.

Using the dynamic empirical correction model, EQ (4.23), with a delta of 100 nm
and the starting wavelength of 550 nm yields temperatures similar to the halogen
corrected temperatures above (see Figure 5.4). Each reported temperature is within ±5°
K of the expected temperature and has an average calculated temperature of 3099.4° K
with a standard deviation of ±3.2° K. The twenty-five temperatures averaged to get the
reported temperatures have a maximum standard deviation of ±17.2° K (0.55%) for the
set using the dynamic empirical correction model. This indicates that the dynamic
empirical correction model is as accurate as the halogen correction for the halogen lamp.
Figure 5.3: Halogen Corrected Temperatures for Halogen Lamp

Figure 5.4: Dynamic empirical correction Model Temperatures for Halogen Lamp
5.2 ELECTRIC FURNACE

To establish the validity of the technique, experiments were conducted at an electric furnace [Figure 5.5] where a reference thermocouple temperature was available. Here the only radiation emission is from the wall, and the calculated temperatures are from only one main source, the furnace wall. This electric furnace has a cavity of around 50 liters. The temperature control for the furnace is accomplished through a thermocouple attached to the side of the furnace wall. The furnace temperature is kept at a constant 1773° K for the entire duration of these experimental runs.

Figure 5.5: Electric Furnace

5.2.1 Intensity Profile

Figure 5.6 shows the measured spectral intensity profile for the electric furnace. (Note the sodium line near 590 nm.) The sodium was added to the furnace chamber
using an atomizer to inject a mist of sodium solution into the furnace cavity so that the sodium emission line could be studied as sodium concentrations within the chamber changed. This is the only emission line present as no combustion is taking place. A sampling time of 25 milliseconds is used to obtain each spectrum, with continuous sampling indicating that there is more than one spectrum per second.

![Electric Furnace Graph](image)

**Figure 5.6: Measured Spectral Intensity Profile for Electric Furnace**

### 5.2.2 Calculated Temperatures

Sample temperatures calculated from the spectra from this experimental run are given in Figure 5.7 below. The Spectrum number is an index used to identify a particular set of spectra as opposed to a time since multiple samples were collected with the same time stamp. The calculated temperatures shown in Figure 5.7 are halogen corrected only. These results show the inaccuracy of the visible range ratio technique for a blackbody emission source without any correction other than the grating efficiency using a halogen
lamp. The average temperature calculated for this run was $1849^\circ \text{K}$, a difference of $76^\circ \text{K}$ from the thermocouple, with a standard deviation of $\pm 1.9^\circ \text{K}$ in the reported temperatures. The cause of this temperature difference is mainly from the intensity loss for each wavelength resulting in higher calculated temperature (see EQ 4.6). The twenty-five temperatures averaged to get the reported temperatures have a maximum standard deviation of $\pm 9.4^\circ \text{K}$ (0.51%) for the set.

![Electric Furnace Halogen Corrected Temperatures](image)

**Figure 5.7: Halogen Corrected Temperatures for Electric Furnace**

Using the thermocouple readings provided to monitor the electric furnace, a referenced correction is created. Using this calibration, another set of temperature data (Figure 5.8) for the electric furnace is calculated. The average temperature calculated for this set is $1771.9^\circ \text{K}$ with a standard deviation of $\pm 1.7^\circ \text{K}$. As predicted in the derivation of the referenced correction, the calculated temperatures are fairly close to the expected
temperature of 1773° K. The twenty-five temperatures averaged to get the reported
temperatures have a maximum standard deviation of ±9.0° K (0.51%) for the set.

Figure 5.8: Referenced Correction Temperatures for Electric Furnace

While the distance between the lens and the furnace wall is not exactly known,
and is only estimated at 30 inches (0.762 m), the errors created by using this estimation
should be small. This source, along with the halogen lamp and the pilot-scale glass
furnace, is used in the creation of the dynamic empirical correction model equation
described in Chapter 4. Calculated temperatures using this method are shown in Figure
5.9. While the temperatures calculated using this method are not as accurate as those
created using the referenced correction (Figure 5.8), the average difference from the
reference corrected temperature is only 16.5° K (0.93%) with a maximum difference of
18.3° K (1.03%). The standard deviation of these temperatures is only ±1.6° K, which is
slightly less than the standard deviations for the other methods. The twenty-five temperatures averaged to get the reported temperatures have a maximum standard deviation of ±7.1° K (0.40%) for the set, again slightly less than the other methods.

<table>
<thead>
<tr>
<th>Spectrum #</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1760</td>
</tr>
<tr>
<td>2</td>
<td>1765</td>
</tr>
<tr>
<td>3</td>
<td>1770</td>
</tr>
<tr>
<td>4</td>
<td>1775</td>
</tr>
<tr>
<td>5</td>
<td>1780</td>
</tr>
<tr>
<td>6</td>
<td>1785</td>
</tr>
<tr>
<td>7</td>
<td>1790</td>
</tr>
<tr>
<td>8</td>
<td>1795</td>
</tr>
<tr>
<td>9</td>
<td>1800</td>
</tr>
<tr>
<td>10</td>
<td>1805</td>
</tr>
<tr>
<td>11</td>
<td>1810</td>
</tr>
</tbody>
</table>

Comparing the halogen corrected, the referenced calibrated, and the dynamic empirical correction model temperatures, it is clear that using the halogen correction alone is not suitable for the electric furnace. If a suitable reference temperature is available, the referenced correction calculations yield highly accurate temperatures. However, the dynamic empirical correction model equation provides temperature calculations for the electric furnace that are within an acceptable range of ±10% of the expected temperature.

**Figure 5.9: Dynamic empirical correction Model Temperatures for Electric Furnace**

![Electric Furnace Dynamic Correction Temperatures](image)

- **Calculated Temperatures**
- **Expected Temperature**
5.3 PILOT SCALE GLASS FURNACE

Initial tests were conducted at a 23 – 146 kW pilot-scale glass furnace located at the Rolla campus of the University of Missouri campus [Figure 5.10] that can melt from about 45 – 900 kg of glass/day. It utilizes a single burner system with a turbulent diffusion flame. Furnace design allows both air-gas and oxy-fuel combustion with different burner types and burner arrangements, though only oxy-fuel was used for these experiments. The control of the furnace is through a Labview hardware and software control system.

![Figure 5.10: Probe Set-Up at Pilot Scale Glass Furnace](image)

5.3.1 Intensity Profile

A sample plot of spectral intensity similar to what is seen by viewing the spectrometer during data collection is shown in Figure 5.11. At the time of these experiments, the IR grating is not present. The red line is the master grating that provides
a view of the visible region, and the cyan line is the slave grating that views the UV region. The highest peaks visible for the UV grating are from emissions from excited OH molecules. These three peaks are located at 306.72 nm, 309.39 nm and 312.38 nm. The sodium emission line near 590 nm goes off the chart, as this is necessary to place the maximum background intensity near 3000 counts.

![Spectrometer Interface](image)

**Figure 5.11: Sample of Spectrometer Screen Showing Raw VIS and UV Spectra**

### 5.3.2 Temperature Measurements

Several experimentations are performed with various oxygen and fuel (O/F) ratios. The O/F ratio is determined by dividing the volumetric flows of O\(_2\) by those of natural gas (NG). An O/F ratio of 2.1 is the nominal control value used at this furnace. Run #1 is a baseline run set at an O/F ratio of 2.1 with O\(_2\) and NG flow rates set at the nominal control values for this particular furnace. Runs #2 through #10 are conducted at steady values of O/F ratios 1.8, 2.1, and 2.4 while varying NG flow rates. Runs #11
through #13 keep the flow rate of O₂ the same while varying the NG flow rates to achieve O/F ratios of 1.8, 2.1, and 2.4. The temperatures calculated for these experiments conform to the halogen correction method given in section 4.2.1. In general, the temperature trends follow the expected trends created by the changing O/F ratio. This indicates that the method can follow temperature changes due to changes in O/F ratio thus providing another input into furnace monitoring. A table listing the various O/F ratios at different flow rates is provided in Table 5.1 below:

### Table 5.1: Sample Calculated Temperatures from the Pilot-Scale Glass Furnace

<table>
<thead>
<tr>
<th>Run #</th>
<th>NG (m³/h)</th>
<th>O₂ (m³/h)</th>
<th>O/F Ratio</th>
<th>Temp (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.11</td>
<td>6.54</td>
<td>2.1</td>
<td>1581.4</td>
</tr>
<tr>
<td>2</td>
<td>2.27</td>
<td>4.08</td>
<td>1.8</td>
<td>1572.4</td>
</tr>
<tr>
<td>3</td>
<td>3.11</td>
<td>5.61</td>
<td>1.8</td>
<td>1587.6</td>
</tr>
<tr>
<td>4</td>
<td>3.96</td>
<td>7.14</td>
<td>1.8</td>
<td>1621.9</td>
</tr>
<tr>
<td>5</td>
<td>2.27</td>
<td>4.76</td>
<td>2.1</td>
<td>1573.8</td>
</tr>
<tr>
<td>6</td>
<td>3.11</td>
<td>6.54</td>
<td>2.1</td>
<td>1625.2</td>
</tr>
<tr>
<td>7</td>
<td>3.96</td>
<td>8.33</td>
<td>2.1</td>
<td>1562.5</td>
</tr>
<tr>
<td>8</td>
<td>2.27</td>
<td>5.44</td>
<td>2.4</td>
<td>1557.3</td>
</tr>
<tr>
<td>9</td>
<td>3.11</td>
<td>7.48</td>
<td>2.4</td>
<td>1590.4</td>
</tr>
<tr>
<td>10</td>
<td>3.96</td>
<td>9.49</td>
<td>2.4</td>
<td>1668.1</td>
</tr>
<tr>
<td>11</td>
<td>2.72</td>
<td>6.54</td>
<td>2.4</td>
<td>1589.9</td>
</tr>
<tr>
<td>12</td>
<td>3.11</td>
<td>6.54</td>
<td>2.1</td>
<td>1566.2</td>
</tr>
<tr>
<td>13</td>
<td>3.62</td>
<td>6.54</td>
<td>1.8</td>
<td>1636.5</td>
</tr>
</tbody>
</table>

Using spectral data measured at a wall of this furnace, the various temperature calculation methods are compared. First, temperatures from a sample set of spectra using the halogen correction method are generated (Figure 5.12). These temperatures are similar to those listed in the table above. The average temperature calculated for this set is 1562.5° K with a general decreasing trend. This is as expected since the wall is cooling down during this period without any heat input. The twenty-five temperatures averaged to get the reported temperatures have a maximum standard deviation of ±13.8° K (0.89%) for the set. This deviation is a slightly higher percentage of the averaged
temperature as compared to the halogen lamp or the electric furnace, though still less than one percent of the temperature.

**Figure 5.12: Halogen Corrected Temperatures for Pilot Scale Glass Furnace**

Using the wall temperature of 1498° K taken with an IR gun for a reference, a set of referenced correction temperatures is created and shown in Figure 5.13. Again, the cooling trend is visible, however the temperatures are at or below the wall temperature measured with the IR gun. Using the halogen correction method, the temperatures were approximately 65° K higher than the measured wall temperature. The average temperature calculated for this set is 1493.6° K with the twenty-five temperatures averaged to get the reported temperatures have a maximum standard deviation of ±13.1° K (0.88%) for the set. The percentage of the maximum standard deviation is again close to that calculated when using the halogen correction method. Using the halogen
correction method results in an increase in the calculated temperatures due to the high halogen lamp temperature of 3100 K as compared to the actual furnace temperature as well as the unaccounted intensity losses in the furnace.

![Pilot Scale Glass Furnace Referenced Calibration](image)

**Figure 5.13: Referenced Correction Temperatures for Pilot Scale Glass Furnace**

Using the well-known distance for the pilot scale furnace and the dynamic empirical correction model method for temperature calculations generates the temperatures shown in Figure 5.14. The average temperature of this set is 1499.5° K while the twenty-five temperatures averaged to get the reported temperatures have a maximum standard deviation of ±10.6° K (0.71%). While the temperatures are slightly higher than those created with the referenced correction method, the maximum difference between the two is 10.2° K--a percentage difference of 0.68%, again within the acceptable temperature range.
In comparing these different methods, one noticeable difference is the rate at which the furnace cools. Using the halogen correction, the trend shows the furnace cools 6.6° K, where the referenced correction shows a cooling of 6.1°K and the dynamic empirical correction model calculations show a cooling of only 3.8° K over the same time.

![Graph showing temperature variations](image)

**Figure 5.14: Dynamic Empirical Correction Model Temperatures for Pilot Scale Furnace**

### 5.3.3 Correlations to the OH Radical

In addition to temperature calculations, the spectrometer can provide other information that will be useful to furnace operators. These multiple uses are one of the added benefits of this probe system and is mentioned in Chapter 7. Emission lines, which are to be avoided in temperature calculations, can provide other types of information. Two different uses have been tied to the OH radical, best seen in the UV region, though it
can sometimes be monitored on the VIS scale since the wavelengths in question are measured on both spectrums. However, the UV data is better due to the resolution obtained. These two uses are the monitoring of NOX gases, a pollutant that is often required to be monitored, and burner stoichiometry.

As the O/F ratio is changed, the emission spectrum in the UV range is also changed, as can be seen in Figure 5.15. Both the background intensity and the values of the OH emission data changed as the O/F ratio increased. The OH radical data is measured as a relative intensity by taking the peak intensity and subtracting the background intensity from it. The background intensity is found by taking the average of the two wavelengths on either side of each peak. The background intensity increased as the O/F ratio increased (see Figure 5.15). Figure 5.16 shows the changes of the OH radical peaks as the O/F ratio changes at the pilot scale glass furnace. Monitoring of all three OH peaks show the same trend as seen in Figure 5.15.
Figure 5.15: Emission Spectrum from 200 nm – 400 nm for Various O/F Ratios

Figure 5.16: Variation in OH Peak Intensities as O/F Ratios Change
5.3.3.1 OH Correlation to NOx

Two oxides of nitrogen, NO and NO\textsubscript{2}, are considered to be acid rain and smog pollutants and are produced primarily from combustion processes\textsuperscript{61}. These oxides are referred to as NO\textsubscript{X} gases in most combustion related operations. When there is excess oxygen in a furnace, greater amounts of NO\textsubscript{X} gases are produced. Likewise, when there is a greater amount of excess oxygen, there is a greater amount of OH. Figure 5.17 shows the variation in OH radical peak intensities as the O/F ratio changes from 1.8 to 2.1 for the 310 nm OH radical peak. As the O/F ratios increase, the OH peak increases. This indicates that as the O/F ratio increases, the fuel and oxidizer mix for a less complete burn, increasing the amount of excess oxygen and likewise OH. Figure 5.18 indicates that as the O/F ratio increases, and thus the amount of oxygen increases, the amount of NO\textsubscript{X} measured increases.

![Figure 5.17: Variation in OH Peak Intensities as O/F Ratios Change](image-url)
Figure 5.18: Measured NOx Values vs. O/F Ratios

Figure 5.19: Measured NOx Values vs. OH Radical Peak Intensity
5.3.3.2 **OH Correlation to Changes in Stoichiometry**

Changes in the O/F ratio in a step manner demonstrate that the OH radical can follow these changes. During the step test, the O/F ratio changes sharply from 1.8 to 2.4, stays at this level for one minute and then sharply drops back to 1.8, with data taken every ten seconds. The raw data for the spectrum is shown in Figure 5.20. Since flame data has fluctuations, three data points were averaged to provide the value shown in Figure 5.21. This value was plotted against time with a one step time delay, i.e. the 10 second, 20 second and 30 second data points are averaged and plotted against the 20 second time. The first data point was then dropped and the next was averaged with the remaining two in order to get the next point. The step test results show that the OH radical at 310 nm follows the measured O/F ratio changes with a slight time delay due to the moving average being used.

![Figure 5.20: OH Radical Changes during the Step Test Raw Data](image-url)
Figure 5.21: OH Radical Changes during the Step Test with Moving Average

5.4 RESEARCH BOILER

Experimental flame measurements were made at a single-burner, multi-fuel package boiler [Figure 5.22] at Pennsylvania State University campus. This research boiler is of the A-Frame water-tube type designed and built by Cleaver Brooks. The boiler is capable of using natural gas, oil, pulverized coal and coal-water-slurry as fuel. All the experiments use natural gas for this work. A single swirl burner with a 3x3x7 ft rectangular box combustion chamber fires the boiler. This burner allows adjustment of air to fuel ratio and secondary to tertiary air ratio, which affects burner stoichiometry, mixing rate, and secondary air swirl. To promote and enhance combustion, a ceramic burner throat (“quarl”) extends the combustion chamber by two feet. This section supports difficult to ignite fuels by storing radiant heat energy. The major difference between this furnace and the others is the relatively cool environment between the
spectrometer lens and the burner due to the water in the tubes acting as heat sinks, which in this case is the majority of the 2.38 m furnace length.

![Research Boiler with Spectrometer and Probe](image)

**Figure 5.22: Research Boiler with Spectrometer and Probe**

### 5.4.1 Intensity Profile

The intensity profile for the research boiler as shown in Figure 5.23 is very similar to that of the pilot-scale glass furnace. While the integration time was set to 10 milliseconds, this interval was relatively short for an optimal background that would yield a maximum background intensity of 2750 counts. Emission lines are at approximately 590nm for sodium, and 767 nm and 770 nm for potassium. These emission lines are normal products of methane combustion and should appear to some extent in all flames.
5.4.2 Temperature Measurements

A type ‘S’ thermocouple is used to take temperature measurements inside the quarl. The thermocouple uses a platinum, platinum-10 percent rhodium junction coated with a thin ceramic layer to eliminate catalytic effects. Thermocouple time-averaged readings are corrected for radiation effects using EQ (5.1) where $\sigma$ is the Stefan-Boltzmann constant, $\varepsilon$ is the emissivity and $h$ is a convection coefficient with units of W m$^{-2}$ K$^{-1}$, and $T$ representing the temperature of the gas, quarl measurement by thermocouple, and wall thermocouple depending on the subscript.

$$T_{\text{gas}} = T_{\text{meas}} + \left[ \frac{\sigma \varepsilon}{h} \cdot (T_{\text{meas}}^4 - T_{\text{wall}}^4) \right]$$

EQ (5.1)

Figure 5.24 shows thermocouple temperatures for ten experimental runs performed at the research boiler as well as the corresponding temperatures calculated.
using the dynamic empirical correction method. Each run reported represents a different firing condition of the boiler. Run 1 was considered a baseline measurement with a molar air/fuel ratio (A/F) of 17.10. Runs 2 through 5 changed the A/F ratio to 14.75, 15.25, 19.25, and then 18.00 respectively. Runs 6 and 7 changed the swirl ratio (primary air/secondary air) from the baseline value of 2.5 to 0.75 and 1.4. Runs 8 through 10 changed the firing rate from the natural gas baseline values of 0.496 m$^3$/h to 0.637 m$^3$/h, 0.595 m$^3$/h, and 0.340 m$^3$/h respectively.

![Spectrometer Temperature vs Measured Temperature](image)

**Figure 5.24: Comparison between Dynamic Corrected Spectrometer and Corrected Thermocouple Temperatures for Research Boiler**

In Figure 5.24, the temperatures calculated with the spectrometer follow the same trend as measured using the thermocouple. These calculated temperatures are corrected for the all losses between the flame and spectrometer lens locations using the dynamic empirical correction model. The actual location of the thermocouple measurements are located in the quarl, which is a slightly different location than where the spectrometer is
aimed, thus creating some discrepancies between the thermocouple temperatures and the calculated temperatures using the spectrometer.

A sample set of research boiler temperatures, using the baseline data Run #1 from Figure 5.24, allows the comparison of the three methods using flame data with a reference temperature of 1850 K measured by thermocouple. The halogen corrected temperatures (Figure 5.25) again are higher than the reference temperature by over 150° K, showing that the halogen correction by itself is not suitable for calculating either wall or flame temperatures. The average temperature calculated for this set is 2003.1° K with the twenty-five temperatures averaged to get the reported temperatures have a maximum standard deviation of ±8.7° K (0.43%) for the set.

Referenced correction temperatures using the temperature calculated with the thermocouple inserted into the quarl as a reference temperature for this set of data are shown in Figure 5.26. Since this data set is for flame, a larger variation in temperatures is expected even during the small time duration used to collect each spectrum. These temperatures do not exactly follow the temperature trends as seen in the halogen corrected temperatures in Figure 5.24, and the difference between the lowest and highest temperatures is 135.6° K as compared to 53.4° K for the halogen corrected temperatures. The average temperature calculated for this set is 1862.7° K with the twenty-five temperatures averaged to get the reported temperatures have a maximum standard deviation of ±10.1° K (0.54%) for the set.
Figure 5.25: Halogen Corrected Temperatures for Research Boiler

Figure 5.26: Referenced Correction Temperatures for Research Boiler
Using the dynamic empirical correction model method, calculated temperatures are shown in Figure 5.27. While the temperature trends for the referenced correction method do not follow the halogen corrected temperatures, the trends for the dynamic empirical correction model method and the referenced correction method follow one another as expected. The difference between the lowest and highest temperatures for the dynamic empirical correction model method is 143.0° K as compared to 53.4° K for the halogen corrected temperatures. The average temperature calculated for this set is 1882.1° K with the twenty-five temperatures averaged to get the reported temperatures have a maximum standard deviation of ±7.9° K (0.42%) for the set. The maximum difference between the referenced correction and the dynamic empirical correction model method is 22.0° K, which is a percent difference of 1.2%. While this is one of the larger differences in the research group, this is flame data as compared to wall data earlier.

![Figure 5.27: Dynamic Empirical Correction Temperatures for Research Boiler](image-url)
5.5 COMPARISON OF LABORATORY RESULTS

In all other cases, using only the halogen correction in temperature calculations leads to temperatures higher than the reference temperature for that source. This may be explained by the high temperature of 3100 K, much higher than any other source used. Furthermore, while the halogen corrects for the grating and fiber optic cable effects, corrections for the other factors, emissivity, distance between probe and source, and the temperature of the environment between the probe and the source are clearly needed.

The referenced correction yields temperatures that are close to the reference temperature for the source since that is used in the creation of the calibration. This method can therefore produce very accurate temperatures in cases where another accurate source of temperature is available.

The dynamic empirical correction model can produce temperatures that are within approximately one percent of the target temperature (see Table 5.2). Further refinement could improve these values for the electric furnace. The research boiler, which also produced one of the higher differences, is actually flame temperature and may be improved by creating a correction from a set of flame data, though this does indicate that the model also works fairly well for flames. However, the creation of such a flame correction would require an accurate probe to flame distance.

Table 5.2: Comparison of Calculated Temperatures for Laboratory Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Reference: Temp (K)</th>
<th>Dynamic Model (K)</th>
<th>Difference (K)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halogen Electric</td>
<td>3101.5</td>
<td>3099.7</td>
<td>1.8</td>
<td>0.1%</td>
</tr>
<tr>
<td>Pilot Boiler</td>
<td>1769.6</td>
<td>1789.3</td>
<td>19.6</td>
<td>1.1%</td>
</tr>
<tr>
<td>Pilot</td>
<td>1492.2</td>
<td>1499.5</td>
<td>7.3</td>
<td>0.5%</td>
</tr>
<tr>
<td>Boiler</td>
<td>1858.4</td>
<td>1878.0</td>
<td>19.6</td>
<td>1.1%</td>
</tr>
</tbody>
</table>
6 COMMERCIAL DATA ACQUISITION AND RESULTS

After initial trials at laboratory facilities, the different methods were used to calculate temperatures in an industrial environment. The first facility was a commercial multi-burner glass furnace. This is also the first facility to use the near-IR grating. The second commercial facility where the methods were used is a commercial steel plant. The final commercial facility was a coal-fired plant that produces both electricity and steam. This final facility was used to see how well the method could be transferred to a different fuel type.

6.1 MULTI-BURNER GLASS FURNACE

The commercial furnace is a 179.4x10⁶ kJ/hr gas/air-fired multi-burner used to produce float-glass. This regenerative furnace runs in twenty-minute cycles on each side with a period of a few seconds between firings as the furnace changes firing sides. Air is sent through a regenerator on one side and hot exhaust gases are removed from the other side. The exhaust gases heat bricks in the regenerator and when the cycle changes, these bricks then give up this heat to the air used to fire the furnace. Heating the air this way increases flame temperatures, and as the air cools, the flame temperature cools also. This trend can be seen in the flame temperatures calculated for this furnace.

The furnace has six ports on each side with five ports containing paired burner jets and one port with a single burner jet. A viewing port looking through an air regenerator directly behind the burner was used to collect the data as seen in Figure 6.1. With the sensor focused on a single burner flame, the results are limited to one individual burner allowing for a single burner in a multi-burner system to be monitored and controlled. A hand-held optical IR gun was used to obtain temperatures in the same area
of the furnace, either flame or wall, that is designated to monitor intensities and to calculate temperatures.

Figure 6.1: Probe Set-Up at Commercial Multi-Burner Glass Furnace

6.1.1 Visible Temperature Calculations

The methods developed in the laboratory facilities using the visible region are tested at the first commercial glass plant. The experiments at this furnace are an important step in testing the attenuation correction factor due to the large distance between the probe and reaction zone in the flame, as well as testing the dynamic empirical correction model on various dates for reproducibility of the results. The design of the furnace provides two regions, the air regenerator and the interior furnace, with different temperatures, as may be common in other commercial facilities. These separate
regions, which may affect the $\phi_d$, do not seem to have adverse effects on the dynamic empirical correction model.

6.1.1.1 Intensity Profile

Intensity measurements were taken using port 5 of the multi-burner furnace. This port looked at the burner pair referred to as burner #5, and the right burner of the set was used each time for data collection. The flame data was generally taken while the nearside burners were firing, as the flame opacity made aiming at the reaction zone on the far side difficult. The intensity profile of the multi-burner furnace was again similar to the pilot-scale glass furnace as seen in Figure 6.2. However, the sodium line in this particular case is an absorption line, due to the lower air/fuel flame temperature and the cool outside air used. The wavelength selection and best region determined at the laboratory facilities are used to determine how well the methods can be transferred to an industrial setting.
6.1.1.2 Temperature Calculations with $\phi_d$

Figure 6.3 shows a comparison of the calculated flame temperatures with halogen correction and with $\phi_d$ correction to the measured temperatures by a hand-held IR gun and crown thermocouple. The uncorrected temperatures are roughly $500^\circ$ K higher than the temperatures that are corrected with the $\phi_d$ attenuation factor. Since in this furnace the flame data has a longer path length of any of the previous furnaces, it is quite evident that an attenuation correction factor must be used for the method using wavelengths in the visible spectrum.

The IR gun temperatures are plotted showing a plus/minus one (1) standard deviation bar determined by this set of data. Furthermore, the reported adiabatic air/fuel (methane) flame temperature is $2236^\circ$ K\textsuperscript{63}. The valley located near the 13:13 mark indicates a time when the furnace is shut down in order to change over to firing on the opposite side. Therefore, the IR gun and the corresponding spectrometer temperatures taken inside this valley include wall temperatures from the opposite wall since no flame is being produced. After this point, the temperatures are of the flame produced by the burners on the opposite side.
Figure 6.3: $\phi_d$ Corrected Visible and IR Gun Temperatures Comparison

The initial $\phi_d$ correction factor is included in the temperatures calculated for the multi-burner furnace to account for the external distance from the regenerator wall section and the estimated distance from this point to the reaction zone of the flame. The furnace control system indicates that the temperatures reported by the crown temperature (measured by a thermocouple) at the furnace ceiling in the region of port 5 had an average of 1860° K during this experimental run. Whereas the calculated flame temperatures are higher than the average crown temperature, the IR gun temperatures are approximately 100° K lower than the calculated temperatures. This is an indication that at greater distances the simple $\phi_d$ attenuation factor is insufficient to yield accurate temperatures.
6.1.1.3 Temperature Calculations with Advanced Corrections

Figure 6.4 shows temperatures calculated with the dynamic empirical correction model and compares these temperatures to the IR gun temperatures used earlier in comparison to the $\phi_d$ corrected temperatures. The majority of the IR gun temperatures fall within one standard deviation of their measurements from the dynamic empirical correction temperatures. This indicates that the correction created by the dynamic model is more accurate than the simple attenuation factor as expected. The data used for these comparisons was collected in April of 2003.

![Temperature Comparisons 4/29/03](image)

**Figure 6.4: Dynamic Corrected Visible and IR Gun Temperatures Comparison**

Additional data from different dates is used to test the repeatability of the accuracy of the dynamic empirical correction model. The temperatures calculated using the dynamic model are measured against temperatures calculated with the same data
using the reference correction. For these comparisons, each spectrum is used individually to create a temperature rather than averaging in order to provide more points in the data set. Figure 6.5 also shows the three IR gun temperatures used to create the referenced correction for this date. The initial point and the final two points are flame data, while the other points are for the opposite wall of the furnace. The error bars plotted are for the dynamic empirical correction model indicating one standard deviation. The temperatures measured using the referenced calibration all fall within this error range, with the greatest temperature difference being ±5.4 K (0.29%) and an average difference of ±0.3 K (0.02%).

![Temperature Comparison Graph](image.png)

**Figure 6.5: Dynamic and Referenced Corrected Temperatures Comparison 3/24/04**

Figure 6.6 is from a data set taken roughly seven months later. For this particular set, no flame data is included and individual spectra are again used for the temperature calculations. The expected cooling trend to the wall temperatures in the absence of the
flame is highly visible with this data. For this particular run, all of the dynamic corrected temperatures are greater than the similar reference corrected temperature; with a maximum difference of ±6.9 K (0.36%) and an average difference of ±3.9 K (0.20%). Again, the reference corrected temperatures are within one standard deviation of the dynamic corrected temperatures.

![Temperature Comparison Graph](image)

**Figure 6.6: Dynamic and Referenced Corrected Temperatures Comparison 10/12/04**

Finally, using data taken roughly two years earlier (Figure 6.7), the dynamic corrected temperature is again similar to the reference corrected temperatures for the same date. The initial three points are flame data again, with the remaining points indicating wall temperatures. It should be mentioned that the flame temperatures are not accurate measurements for the flames, since there is a difference in distance between the flame and wall data, though no difference is used in these calculations. Using an estimation for the reaction zone would produce flame temperatures more in line with the
actual values. For this particular run, all of the dynamic corrected temperatures are again greater than the similar reference corrected temperature; with a maximum difference of ±10.6 K (0.57%) and an average difference of ±4.2 K (0.22%). The reference corrected temperatures are within one standard deviation of the dynamic corrected temperatures.

![Temperature Comparison Graph](Temperature_Comparison_11/19/02.png)

**Figure 6.7: Dynamic and Referenced Corrected Temperatures Comparison 11/19/04**

For multiple dates, the dynamic empirical correction model has followed the reference corrected data closely, with a maximum difference of 0.57%. Dynamic corrected temperatures also compare well with multiple IR gun readings throughout an extended run. This indicates the dynamic correction can be used long term without frequent recalculation.

### 6.1.2 Near IR Temperature Comparisons

On two separate data acquisition and experimentations, data for both visible and the near-IR were collected. Temperatures calculated using both regions are compared to
temperatures from the thermocouple located in the crown of the glass furnace as well as temperatures measured with a portable IR gun.

### 6.1.2.1 Intensity Profiles

The same commercial multi-burner glass furnace is used to compare the temperature calculations using the visible region with those calculated using the near-IR region. Figure 6.8 shows the (a) visible and (b) near-IR spectra obtained at the furnace. The master grating produces the visible spectrum and the second slave grating produces the near-IR spectrum. Again, the visible spectrum is similar to the pilot scale furnace (Figure 5.6). While shaped slightly different, the NIR spectrum is also similar to the spectra used earlier for VIS temperature calculation in that few emission lines exist.

When calculating temperatures for the near-IR wavelengths, the halogen correction method is used as for the VIS wavelengths. However, the wavelength selection, wavelength difference and best region need to be re-examined. The process used to select the initial wavelength and best region for the VIS calculations will be repeated using the NIR data. In order to make each version as similar as possible, the 128 nm difference between wavelengths used in the halogen correction, section 4.2.1.2.1, is retained for the NIR halogen correction.
6.1.2.2 Wavelength Selection

The near-IR region has only one emission/absorption line near 1185 nm to be avoided in the selection of wavelengths. To minimize the effects from noise, the region chosen is in the near-IR between 650 nm and 1000 nm where the counts are relatively large. A halogen correction curve using EQ (4.13) for the NIR spectrum is created similar to the VIS data. Figure 6.9 shows the corrected intensities for the NIR spectrum using this curve. The corrected intensities for wavelengths less than 650 nm are unstable and yield low raw intensities. Wavelengths higher than 900 nm have very noticeable fluctuations, even after the halogen correction, with fluctuation size increasing as wavelengths increase. Intensities drop off rapidly after 1050 nm, which may be caused by a cut-off due to the fiber-optic cable design.
Figure 6.9: Halogen Corrected Intensities of Near-IR Spectrum

6.1.2.3 Difference in Wavelengths Used and Best Region

Again, an approximately 128 nm difference between wavelengths is used for temperature calculations. Figure 6.10 is a plot of the temperatures using this difference plotted against the starting wavelength of the pair. As it can be seen, the temperatures plotted from the initial wavelengths less that 650 nm are unsuitable for use. Temperatures plotted from the wavelengths higher than 950 nm are also unsuitable for use. There is some fluctuation in the temperatures within the selected region, however the region from around 690 nm to 820 nm is fairly flat. The initial wavelength chosen for using the two-color method in the NIR range is 800 nm. This value is chosen so that both wavelengths used in the temperature calculations would lay within the accepted range for near-IR of 700 nm to 25 µm.
6.1.2.4 Temperature Comparisons

Figure 6.11 shows the comparison of the results using both regions where the data is after one firing cycle on the right side of the furnace. No attenuation correction was employed in the determination of the near-IR temperatures. The grating correction factors $A_i$ and $A_j$ needed for the near-IR grating were again created from the halogen lamp. Both the visible and near-IR data is taken of the far wall at the same time.

The calculated visible temperatures with no correction are above the calculated near-IR temperatures by a maximum of 135 K. At this furnace, the distance between the probe and the flame is composed of two regions with gases at different temperatures and compositions. This indicates that an improved attenuation correction factor is needed to incorporate additional variables as mentioned in the background section of this work.
Figure 6.11: Temperature Comparisons between Uncorrected Visible and Near-IR Halogen Corrected Temperatures with Corresponding Linear Fits

6.2 STEEL PLANT FURNACE

Data from a steel reheat furnace is used to test the use of the probe system in other high temperature natural gas-fired furnaces. The data taken is from a typical steel reheat furnace comprised of three zones designed to pass steel billets through in order to heat them for further processing. Each zone has two sets of burners, above and below the rollers where the steel passes. The first zone in a steel reheat furnace is the preheat zone with the highest heat input. The next zone is labeled the heating zone, with less heat input than in the preheat zone. The probe was installed along with a camera at a port at this zone (Figure 6.12). This portion of the reheat furnace has temperatures of approximately 1500 to 1550 K. The last zone is called the soak zone and has the least heat input of all zones. A diagram of these three zones is included in Figure 6.12.
6.2.1 Intensity Profiles

In Figure 6.13, sample intensities from both the VIS and NIR data are shown. The maximum intensity for the VIS data is not sufficient for reliable temperature calculations; therefore only halogen corrected temperatures have been created using this data. NIR temperature data is shown to compare to the control thermocouples. Additional experiments at steel facilities are required to further prove the accuracy of the dynamic empirical correction model. However, all indications show that the model should provide accurate temperatures for this type of facility.
6.2.2 Temperature Measurements

Both visible and near-IR spectral data is available for analysis from the steel reheat furnace. Data taken in the control room at the start of the run show the A/F ratio along with an average of six thermocouple readings representing the furnace operation temperature. Initially, the A/F ratio is 11.35 with a reading of 1533.6° K for temperature. Approximately two minutes into the run, the A/F ratio is 14.38 with a reading of 1535.8° K for temperature. Around four and a half minutes into the run the A/F ratio is 9.12 with a reading of 1529.1° K for temperature.

The VIS halogen corrected temperatures (Figure 6.14) are in the 1644 K to 1652 K range, and the near-IR halogen corrected temperatures (Figure 6.15) are in the 1548 K to 1558 K range. The temperature rose then dropped and then rose again. This major
trend is a cyclic variation in temperature that corresponds to the oscillations of the control system. The fluctuations are more apparent with the VIS data, being of greater magnitude. The NIR data appears to follow the changes in the A/F ratio only, while the VIS data seems to also show the control oscillations.

![Steel Plant Baseline VIS](image)

**Figure 6.14: Halogen Corrected Temperatures for Steel Plant VIS spectra**

Comparing thermocouple data with the temperature graphs, we see that the temperature trends follow the changes in A/F ratio fairly well, starting out with a temperature that is moderate, drops to a lower temperature and then climbs back to a moderate temperature again. Average VIS temperature for the entire run was 1648° K, average NIR temperature is 1533 correction and average thermocouple temperature is 1533° F for the plant data, again showing that more than just the halogen correction is needed for this type of furnace.
Figure 6.15: Calculated Temperatures for Steel Plant near-IR spectra

6.3 COAL-FIRED POWER PLANT BOILER

This boiler is an over-feed chain grate stoker designed to burn bituminous coal and is rated at 34,000 kg/hr. The probe and camera are installed at a door looking over the coal bed as seen in Figure 6.16. This coal plant is used to provide electricity and steam for the University of Missouri – Columbia’s needs. The coal power plant has a distance of approximately 4.7 m between the probe and the source wall with no intervening flames. This places the distance somewhere between the research boiler and the commercial multi-burner glass furnace. However, the soot concentration is expected to be much higher at a coal facility as compared to a natural gas-fired furnace.
6.3.1 Intensity Profiles

The intensity profile for the research boiler as shown in Figure 6.17 is similar to that of the pilot-scale glass furnace with the exception of the addition of multiple small emission lines scattered along the entire length of the spectrum. The noise from these small emission lines will increase the variation in the temperatures averaged to calculate the final reported temperature. One reason for these small emission lines is that the integration time was set to a high value of 1000 milliseconds. This interval was relatively long in order to get an optimal background that would yield a maximum background intensity of 3500+ counts. Again, the major emission lines are sodium at approximately 590nm, and potassium near 767 nm and 770 nm.
Temperature Measurements

Since prior work has proven that the halogen correction alone is insufficient to create accurate readings, no halogen corrected temperatures were calculated. It is expected that with the higher concentration of soot within the coal furnace that the temperatures calculated will be even higher as compared to the reference temperature than with the other furnaces.

A referenced correction curve (Figure 6.18) was created for the coal boiler using temperatures measured with an IR gun just prior to taking the experimental data. The data are of the far wall and does not include flames. One important factor for generating the reference correction curve is the low temperature of the reference, which is only 1178 K and approximately 200 K lower than the next coolest furnace examined, the pilot-scale glass furnace. As predicted earlier, the lower temperature creates larger fluctuations at
the shorter wavelengths. However, as seen in Figure 4.21 (repeated below as Figure 6.19), the most noticeable difference is the rapid decrease in the correction curve, reaching a factor of less than 0.4 by 550 nm, where the next correction curve reaches 0.4 by approximately 650 nm. This increase in correction needed for a smaller distance as compared to the commercial multi-burner glass furnace is evidence that the soot concentration is much higher in the coal furnace.

![Coal Furnace Referenced Correction Curve at 1117 K](image)

**Figure 6.18: Referenced Correction Curve for Coal Boiler**
Figure 6.19: Comparison between Multiple Correction Curves

Temperatures are calculated (Figure 6.20) using data taken just after the creation of the referenced correction. The temperatures calculated for this set average 1181.3 K with a standard deviation of ±1.9 K. As predicted in the derivation of the referenced correction, the calculated temperatures are close to the expected temperature of 1178 K, with only a 0.31% difference. The twenty-five temperatures averaged to get the reported temperatures have a maximum standard deviation of ±1.4 K (0.12%) for the set. This last information is a bit surprising as the small emission lines were expected to increase the standard deviation of the averaged temperatures.
Temperatures using the dynamic empirical correction model are shown for the same data in Figure 6.21. These temperatures are expected to be much higher than the reference temperature due to the increased absorbance in the environment. This increased absorbance will create the same effect on the intensity ratio as not using any correction other than the halogen lamp, and thus will yield the same increased temperature effect. As can be seen, the temperatures are over 500 K higher than the reference temperature, almost a 43% variance. At least two other coal furnaces with varying distances will be needed to create a dynamic empirical correction suitable for use in a coal environment. The temperatures calculated for this set average 1722.0 K with a standard deviation of ±4.6 K. The twenty-five temperatures averaged to get the reported temperatures have a maximum standard deviation of ±9.7 K (0.56%) for the set. This standard deviation is closer to what is expected due to the small emission lines.
Figure 6.21: Dynamic empirical correction Temperatures for Coal Boiler
7 PROPOSED SYSTEM DESIGN AND IMPLEMENTATION

While presently not in service at any commercial plant, a sensor system has been designed that would incorporate a few of the additional features discussed in this work. A spot temperature of the reaction zone along with OH data would provide insight into changes in temperature, NOx and fuel ratios.

7.1 PROPOSED SYSTEM DESIGN

The sensor system design includes thoughts on the probe installation, installation of the spectrometer, connection to the computer and design of the software used for the temperature calculations. There is a single prototype of the probe casing that is used in collecting the experimental data presented here, however, no long term installation has been experimented.

7.1.1 Probe Installation

In order for this sensor system to be installed in a facility, a supply of water and air is needed as well as drainage for the water once it has passed through the probe housing. The sensor must be aimed correctly prior to a permanent installation. Once installed, the probe should be able to be removed easily if necessary and reinstalled without needing to be realigned again. Access to the back of the unit allows the interior rod to be removed easily without requiring the removal of the water-cooled casing. This would allow the more delicate fiber-optic cable and collimating lens to be removed when necessary for cleaning, inspection, or replacement if necessary.

7.1.2 Spectrometer Installation

The spectrometer casing must be placed within a set distance of the probe depending on the length of the fiber-optic cable. This fiber-optic cable must be protected
from damage in some manner, as it is somewhat fragile. If the environment is too hot, then the fiber-optic cable should also be protected. In addition, some method of cooling must also be used for the spectrometer casing. For short-term operation in hot environments, the spectrometer was placed within a cooler on top of a sheet of cardboard with ice underneath. For a permanent installation, the best cooling method would be some type of small water-cooling unit similar to the probe, since a fan moving the already hot air around would be insufficient.

7.1.3 Connecting Computer and Spectrometer

A USB cable must then run from the spectrometer casing to the monitoring computer. Ideally, the controlling computer should be close to the spectrometer casing. The length of the fiber-optic cable has a direct bearing on the system as longer fiber optics introduces greater intensity losses due to the cable. This can be corrected with the calibration system, but will increase the integration time, slowing the system’s response time. An increase in the USB cable length may also introduce signal errors due to the increased resistance that cannot be corrected using the calibration system. This would indicate that if the probe and controlling computer are a great distance apart, the larger portion of the length should be in the fiber-optic cable as opposed to the USB connection. These two factors will place a limit on the distance between the computer and probe.

7.2 FEATURES OF THE PROPOSED SYSTEM

This system is designed in order to fulfill multiple roles in the operation of a furnace. The system allows continuous temperature measurement as well as monitoring of additional features such as pollutants and burner stoichiometry. Each feature is discussed in further detail below.
7.2.1 **In Situ Measurement**

The probe design allows installation of the lens inside a furnace wall for prolonged periods as long as air and water are supplied. The primary cooling is through the water-cooled casing; therefore, the water is the more important of the two coolants. The design of the probe allows the inner rod to be removed while the outer casing remains in place, allowing the lens and fiber-optic cable to be recovered in the event of a water supply failure. This also allows replacement of either fiber-optic cable or lens as needed without realigning the probe.

7.2.2 **Real Time Measurements**

The speed with which the spectrometer can take data will allow for rapid measurements. The processing speed of the computer is the other important factor in speed of calculations. Measurement time for data acquisition is less than 250 milliseconds at the slowest, with calculations estimated on the same order. This would allow the updating of results at least once per second, which can then be used to create a time vs. data plot to follow burner trends. This would allow the sensor to continuously monitor flame temperature using the visible region while providing combustion information from the same visible region.\(^{65}\)

7.2.3 **NOx Correlations**

As demonstrated from the experiments conducted at the pilot-scale glass furnace\(^{64}\), emissions from the OH radical can be monitored in order to observe changes in NOx concentrations. While at present, even with a direct correlation between NOx and OH, no exact calibration has been developed. However, this apparatus still allows the
user to monitor changes in NOx, providing a method for detecting increases in NOx prior to a stack exhaust analysis.

7.2.4 Monitoring Of Fuel Ratios (A/F or O/F)

Changes in fuel ratios away from stoichiometry at the burners presents less than optimum conditions for any furnace. Excess air lowers the flame temperature and requires more fuel to be burned in order to provide the same heat input as the stoichiometric flame, where excess fuel causes incomplete combustion of the fuel, again requiring a greater flow rate to provide the same heat input. Excess air also leads to increased NOx production as mentioned above. Excess fuel causes incomplete combustion of the fuel, again requiring a greater flow rate to provide the needed heat input. Excess fuel also leads to the production of CO as well as explosive pockets of gas. Early detection of changes in a burner’s stoichiometry can provide a reduction in the amount of fuel used in a furnace, thereby lowering cost of fuel supplies for industrial applications, as well as preventing the other problems caused by excess air or fuel.

7.3 PROPOSED SYSTEM IMPLEMENTATION

In order for this system to provide real-time temperature inputs for furnace control, a program to interface with the spectrometer needs to be developed. Software controls exist that would allow this interface to be developed. The program would access the spectrometer and use the wavelength and intensity inputs to calculate the temperature using the method that has already been designed. The averaging of several spectra will produce only a slight delay in temperature calculation time. Currently, the computer saves the data into files that are subsequently analyzed.
8 FUTURE EXPERIMENTS, CHALLENGES AND CONCLUSIONS

The corrections for temperature calculations created in this work still allow for additional experiments to be performed. Additional features, such as correlations using sodium or potassium may be developed. Explorations in totally new directions using this work as a starting point are possible. Challenges involved in this work will be discussed, and the final conclusions will be presented below. One example of a new direction for temperature calculations is first given below.

8.1 Future experiments

Future experimentations can involve further refinements of the dynamic model, and developing a correction for coal-based furnaces. Developing the intensity translation method that will incorporate distance and a dynamic process allowing it to be used in multiple environments is another future project. Writing a program necessary to interface with the spectrometer in order for real-time processing will be another important future step. After the program is developed, the maximum distance between computer and probe can be explored along with the individual effects of lengthened cables of each type. Long-term effects such as drift and environmental effects also need to be studied.

8.1.1 Further Development of the Intensity Temperature Relationship

This observation was discovered while looking to see if fluctuations in intensities affect the temperature calculations using the two-color methods mentioned before, and if so, can the fluctuation in the data be used to smooth the final temperature results. Using the same twenty-four minutes of data, the ratio of the averaged intensities used in the temperature calculation match the temperatures calculated using the two-color method with the simple $\phi_d$ attenuation corrections as listed in section 4.2.2.
8.1.1.1 **Intensity Temperature Relationship**

The spectral regions corresponding to those same regions used to calculate temperatures with the two-color method are used in the development of the intensity translation process. The intensities of these wavelengths will be corrected using EQ (4.12). This correction will correct for the grating efficiency in the spectrometer with the halogen lamp correction as well as the simple $\phi_d$ attenuation correction will be used to correction for attenuation losses in the furnace environment.

The temperatures reported here are from data from a baseline run at the commercial multi-burner glass furnace. The data is taken at roughly six-second intervals over a twenty-four minute firing time that started with the furnace firing on the opposite side, through the change over to firing on the near side, the twenty minutes of firing on the near side, and through the change over to firing on the far side again. Figure 8.1 shows the temperatures using the two-color method with the $\phi_d$ correction over this period. Since this includes flame data, the moving average method is used in the temperature calculations.
Inspecting the ratio of the high and low regions as used in the two-color method led to a near perfect match when comparing the intensity ratio to the temperature. In order to create the intensity ratio used for comparison, the intensities from the twenty-five wavelengths used for the shorter wavelength, $\lambda_1$, and the intensities from the twenty-five wavelengths used for the longer wavelength, $\lambda_2$, are each averaged to get representative intensities for each region. The averaged intensities for $\lambda_1$ is labeled $I_S$ indicating the short wavelength region and the averaged intensities for $\lambda_2$ is labeled $I_L$ indicating the long wavelength region. The intensity ratio of $I_L/I_S$, again using a moving average, is plotted on a second axis with the temperatures from Figure 8.1 in Figure 8.2 The scale has been adjusted on each axis to show the near perfect match of the plotted lines. The main areas where there is a discrepancy between the two is at the points where the flame
shuts off for the cycle change and this is due to the change of distance that is not used in the temperature calculations.

Figure 8.2: Comparison of Temperatures with Intensity Ratios

This leads to a linear form for the intensity temperature relationship in order to match the blackbody two-color method with the $\phi_d$ correction:

$$ T = m \left( \frac{I_L}{I_S} \right) + b $$

EQ (8.1)

This does require a set of temperatures, one low and one high, to fit in order to find $m$ and $b$. Compare this to the two-color temperature calculation with the $\phi_d$ correction as shown again in EQ (8.2) below with the $i$ and $j$ subscripts replaced with the $L$ and $S$ subscripts representing the long and short wavelength regions again:

$$ T_{L,S} = \frac{C_2 \left( \frac{1}{\lambda_S} - \frac{1}{\lambda_L} \right)}{\left( \ln \left( \phi_d A_S I_L / A_I I_S \right) + 5 \ln \left( \frac{\lambda_L}{\lambda_S} \right) \right)} $$

EQ (8.2)
8.1.1.2 Rationale behind the Intensity Temperature

A question arises as to why the ratio of intensities map directly to the temperature generated by the two-color method with the $\phi_d$ correction. Since the same sets of wavelengths are used, each term that includes a wavelength is approximated by the average of the 25 wavelength pairs. Thus, all of the wavelengths that are used as $\lambda_1$ in the temperature calculations are averaged together to get $\lambda_S$, and the same is done with the $\lambda_2$ wavelengths to yield $\lambda_L$. This means that $C_2 (1/\lambda_S - 1/\lambda_L)$ in EQ (8.2) can be approximated by the constant $C_3 = C_2 (1/\lambda_S - 1/\lambda_L) = -5300.4 \, \text{K} \pm 80.0 \, \text{K}$, where the reported deviations are those from the averaging of $(1/\lambda_S - 1/\lambda_L)$ for the set of wavelengths used in the temperature calculation. Likewise the $5 \, \text{Ln} (\lambda_L/\lambda_S)$ can be approximated by the constant $C_4 = -1.0831 \pm 0.0089$. This changes EQ (8.2) to:

$$T = \frac{C_3}{(\text{Ln}(\phi_d A_S I_L/A_L I_S) + C_4)}$$

EQ (8.3)

The halogen correction factors, $A_S$ and $A_L$, are the average of the twenty-five corrections corresponding to the twenty-five wavelengths used in each region for the temperature calculation. Inverting both sides yields a linear relationship with $(I_l/I_S)$:

$$T^{-1} = \frac{(\text{Ln}(\phi_d A_S I_L/A_L I_S) + C_4)}{C_3}$$

EQ (8.4a)

$$T^{-1} = \frac{\text{Ln}(\phi_d A_H I_L/A_L I_H) + C_4}{C_3}$$

EQ (8.4b)
At this point, in order to obtain only the ratio \((I_L/I_S)\), \(\phi_d A_S I_L / A_L I_S\) must be separated and simplified. Thus:

\[
\phi_d (A_S I_L / I_S A_L) = (\phi_d A_S / A_L) (I_L / I_S) = C_5 (I_L / I_S)
\]  

EQ (8.5)

where \((\phi_d A_S / A_L) = C_5 = 0.5121 \pm 0.0106\). These values are within 2.08\% of the actual corrected values.

A linear fit for the natural log of the ratio will result in values that are within 0.05\% of the log values for \(I_L/I_S\) ratios in the range 0.502 to 0.534. This will allow \(\ln(I_L/I_S)\) to be replaced with \(C_6 (I_L/I_S) + C_7\). Therefore, \(\ln(C_5(I_L/I_S))\) can be approximated by:

\[
\ln(C_5(I_L/I_S)) = \ln(C_5) + C_6 (I_L/I_S) + C_7
\]  

EQ (8.6)

where by using graphical method, \(C_6 = 1.9311 \pm 0.0009\) and \(C_7 = -1.6582 \pm 0.0008\).

Substituting EQ (4.17) into EQ (4.15b) yields:

\[
T^{-1} = \frac{C_6 (I_L/I_S) + C_7 + \ln(C_5)}{C_3} + \frac{C_4}{C_3}
\]  

EQ (8.7a)

\[
T^{-1} = \frac{C_6 (I_L/I_S) + C_4 + \ln(C_5) + C_7}{C_3}
\]  

EQ (8.7b)

Using the values of the constants in EQ (8.7b) gives the linear fit for the inverse temperature of:

\[
T^{-1} = m' (I_L/I_S) + b' = -3.6433 \times 10^{-4} (I_L/I_S) + 6.4345 \times 10^{-4}
\]  

EQ (8.8)

where including estimated errors for \(m'\) and \(b'\) yields \(m' = -3.6433 \times 10^{-4} \pm 5.7537 \times 10^{-6}\) and \(b' = 6.4345 \times 10^{-4} \pm 1.5722 \times 10^{-5}\).
8.1.1.3 Results

The linear relationship in EQ (8.1) is used to generate temperatures by changing the slope and y-intercept until the linear best-fit line for each method matches exactly. This yields a match between the graphical temperatures and the $\phi_d$ corrected temperatures as seen in Figure 8.3. The average difference between the two methods is 0.02°C with a standard deviation of 0.11°C and a maximum variation of 0.41°C, which is a 0.02% difference from the average temperatures.

![Temperature Comparison Near Side Burner #5 Firing Right Side](image)

**Figure 8.3: Comparison of Two-Color and Intensity Translation Temperatures**

The intensity translation temperature is inverted to reflect the inverse temperature on the left side of the EQ (8.8) and again a graphical match is made between the inverted temperatures from the two-color method and the intensity translation temperature (see Figure 8.4). The average difference between the two methods is $7.67 \times 10^{-10}$ K$^{-1}$ with a
standard deviation of 2.39x10^{-8} K^{-1} and a maximum variation of 9.01x10^{-8} K^{-1}, which is a 0.02% difference from the average inverse temperature of 4.55x10^{-4} K^{-1}. Using the linear best-fit yielded \( m' = -3.6515 \times 10^{-4} \) and \( b' = 6.4387 \times 10^{-4} \). This will yield an equation that will produce an inverse temperature directly from the intensity ratio as seen in EQ (8.9).

\[
T^{-1} = m' \left( \frac{I_L}{I_H} \right) + b' \quad \text{EQ (8.9)}
\]

---

**Figure 8.4: Inverse Temperature Comparisons between the Two Methods**

Using the linear fit found in Figure 8.4, normal temperatures are calculated using EQ (8.10) below:

\[
T = \frac{1}{\left( m' \left( \frac{I_L}{I_H} \right) + b' \right)} \quad \text{EQ (8.10)}
\]

Both methods match against each other extremely well. Comparing the results of the linear fit for the data using the inverse temperature ratio intensity, \( m' = -3.6515 \times 10^{-4} \)
and \( b' = 6.4387 \times 10^{-4} \), to the calculated \( m' = 3.6433 \times 10^{-4} \) and \( b' = 6.4387 \times 10^{-4} \). This results in a percent difference of 0.22\% for \( m \) and 0.06\% for \( b \). The error range for the calculated values of \( m' \) and \( b' \) are 1.58\% and 2.44\% respectively. This places the best-fit value of \( m' \) and \( b' \) within the expected calculated error range.

### 8.1.1.4 Dynamic Intensity Translation Method

In order to make this process more robust, a generalized method needs to be developed similar to the dynamic correction model mentioned in later in section 4.3.2. The next step in the development of the method would be to incorporate the integration time into the method, looking at counts per unit time rather than counts only. It is expected that further modifications incorporating distance will be necessary as well since this process is from only a single furnace and the losses observed while developing the dynamic empirical correction model vary exponentially with distance.

### 8.2 Challenges

Several challenges were encountered when using a spectrometer for data acquisition to calculate flame and wall temperatures. The first challenge was selecting appropriate wavelength regions to calculate temperature. The avoidance of emission/absorption lines was necessary, as well as the requirement of sufficient maximum background intensities needed in order to produce acceptable results. While the difference between the first and second wavelength was set to either 128 nm for the simple corrections or 100 nm for the more advanced corrections, the actual difference range was to be partially based on the initial wavelength used. The available range of wavelength differences for the 525 nm starting wavelength appeared to be approximately 75 nm to 150 nm. Again, the actual best region depends on the difference used to create
the ratio, with the 128 nm difference leading to a best region from approximately 475 nm to 575 nm for the first wavelength in the pair.

The high temperature environment near a furnace required cooling the spectrometer to prevent the electronics from overheating and locking up. The short term solution to this problem was to place the spectrometer in a cooler, with ice under the spectrometer. A longer-term solution is needed if this system is to be installed and used on a continuous basis. One method would be the development of a water-cooled housing similar in design to the probe housing for the fiber-optic cable. Heat may be removed from this system using a purge air system also.

In general, a section of twenty-five wavelength ratios was used to calculate temperatures in order to reduce the temperature variation due to electronic noise. When calculating flame temperatures, while turbulence is needed for mixing fuel and oxidizer in a diffusion flame, the effects from this turbulence of the flames in the combustion region on intensity had to be minimized in order to produce more stable temperatures. Therefore, the intensities from five successive spectra were averaged to reduce the amount of noise due to this turbulence. A method was developed to use this in a continuous manner by dropping the first spectrum of the group and adding the next spectrum measured. This form of moving averages allows temperature trends to be monitored without turbulence interfering.

The final challenge was in creating a method for correcting the temperature calculations to take into account the attenuation losses in the gases from the point of measurement to the source. The first simple method involved creating a linear model based solely on distance. This model was created using the electric furnace, the pilot-
scale furnace and the research boiler. After using the halogen correction, the lower wavelength intensity was corrected using the $\phi_d$ correction. At longer distances, this method proved to be insufficient to calculate accurate temperatures, and more advanced corrections that included the distance effects were created.

### 8.3 Conclusions

A recap of the major accomplishments of this work:

- A sensing system was designed and built in order to perform multiple functions, including temperature calculations, and correlating OH emission lines to A/F or O/F and NOX.
- This system has been tested in research settings, including a halogen lamp, an electric furnace, a pilot-scale glass furnace and a research boiler. Additional testing was performed in industrial settings, including a commercial multi-burner glass furnace, a steel reheat furnace and a coal-fired boiler.
- Corrections to take into account grating and fiber optic losses, emissivity, distance between probe and source, as well as environmental temperature effects were generated. The problems of using a high source temperature for the development of a correction method were also discovered.
- Temperature calculations using the visible spectrum are just as accurate as temperature calculations using the near-IR spectrum.
- A simple correction for temperature calculations to compensate for intensity attenuation due to distance between probe and source was determined.
• An advanced correction for temperature calculations based on a reference temperature and a sample intensity from the source was designed in order to take all possible corrections for that source into account.

• A dynamic empirical correction model was developed that used the halogen lamp, electric furnace and a pilot-scale glass furnace to generate a correction for relatively “clean” gas-burning furnaces.

• This empirical model is dynamic implying that it can be modified by adding an additional furnace in order to improve the accuracy for that “clean” furnace not included in the initial correction process, or by using a complete new set of sources for furnaces of a different type.

• A direct relationship between temperature and the intensity ratio used to calculate it using a modified two-color method was observed.

The system developed here is composed of a set of three spectrometers, fiber optic cable with a collimating lens, and a probe that allows the fiber optic cable and lens withstand the high temperature environment associated with being near a gas-fired furnace. With the use of the multiple spectrometers, this system is capable of performing multiple functions associated with furnace control, such as temperature calculations and the monitoring of OH emission lines, which correlate to O/F or A/F fuel ratio and NOX values, which is required to be monitored in many states.

Result of temperature calculations using the blackbody model in the visible range with the two-color ratio technique were reported here for various sources including a halogen lamp, an electric furnace, a pilot scale oxy-fuel fired glass furnace, an air-fuel
research boiler and a commercial air-fuel glass furnaces. Additional data taken from a steel reheat furnace and a coal-fired boiler were also examined.

The initial correction generated by using a halogen lamp, as recommended by spectrometer manufacturer Ocean Optics, was sufficient to correct for grating effects and losses in the fiber optic cables. However, additional corrections were needed in order to use the visible range of the spectrum for temperature calculations. The effects of emissivity, which was assumed to be negligible in the halogen correction, must be corrected in the visible range. This then made the distance between probe and target another important factor, as the intensity losses associated with emissivity effects increase exponentially as distance increases. The temperature of the environment between the probe and the target also influenced the intensity, as lower temperatures produce greater losses. The last effect was the source temperature. When using the halogen lamp, the source temperature of 3100 K was much higher than any of the other sources used in this work. The higher furnace temperatures calculated as a result of using the halogen lamp indicated that a correction with a source temperature closer to the furnace temperatures would be desirable.

When using data corrected using the halogen corrections only, the final results were less accurate than the more advanced versions developed in this research work. The halogen only corrected temperatures calculated were higher than the expected temperatures in all cases other than the halogen lamp, sometimes in excess of 10% of the known temperature. This was expected primarily due to uncorrected intensity losses and the large difference in the halogen lamp temperature of 3100 K and the source temperatures (1178 K – 1850 K) under examination. Using the simple $\phi_d$ attenuation
correction worked reasonably well at shorter distances, however, its shortcomings became evident at longer distances. At the commercial multi-burner glass furnace, attenuation corrected temperatures were approximately 100 K (5.3%) above the reference temperatures. When used to calculate temperatures at the coal furnace, it became clear that the derivation of the $\phi_d$ attenuation correction factor using relatively clean furnaces is insufficient to correct for the sootier coal environment.

The most accurate method to calculate temperatures was the referenced correction method, developed using a model similar to the halogen correction. This correction not only included the correction for attenuation losses in the gasses but also grating and fiber optic cable effects, emissivity, and the distance and temperature of the environment between the probe and the target. In general, the variations in temperatures using this method were within 0.10% of the expected temperature as found in the halogen lamp reported earlier and the electric furnace, where the data reflected a nearly uniform temperature environment.

An advanced dynamic empirical correction model was designed to create a correction suitable for all furnaces with similar furnace conditions in Chapter 4. Using the research sources of the halogen lamp, the electric furnace and the pilot-scale glass furnace, a sample dynamic empirical correction was shown that corrected for the environment of the mostly clean furnaces. The sample correction created for the clean furnaces is reasonably accurate, including when used with flame data. This method produced temperature results within $\pm$ 1.2% of the source temperature.

The dynamic empirical correction was developed to allow additional furnaces to be added to the correction model, or an entirely new correction to be derived based on a
different type of furnace environment, such as for the coal furnace, and thus the name
dynamic was associated with this model. This adaptability made this method suitable to
be used in nearly any high temperature environment.

The measured intensity’s direct proportionally to the calculated temperature was
also detected. Using a single furnace, a linear translation from the intensity ratio used in
the two-color method directly to temperature was possible. Mathematically, this was
possible by using a linear fit of the exponential function as explained in section 8.1. To
further improve this intensity translation process and develop a more robust method, the
translation form will most likely be an exponential or logarithmic form that requires the
inclusion of distance as well. Including the use of intensity per unit time is another
possible way to improve this intensity translation process.
APPENDIX A: SAMPLE IR GUN SPECIFICATION SHEET

CYCLOPS 53

Cyclops 53 produces a fast, reliable reading independent of operator judgement in a wide range of high temperature industrial applications.

- Temperature range: 600 to 3000°C/1100 to 5500°F
- Target size: 5mm at 1m/0.19in at 39.3in
- Spectral response: 0.8 to 1.1µm

- Narrow angle field of view (one third of a degree).
- Variable focusing from 1 metre/39 inches to infinity.
- Optional close up lenses allow measurement as small as 0.4mm/0.016in diameter.

APPLICATIONS FOR CYCLOPS 153/153A and 53

- Semi-conductor doping
- Coke ovens
- Furnace refractories
- Ceramic kilns
- Heat treatment
- Rolling mills
- Glass fibre
- Glass stream
- Glass tank and forehearth
APPENDIX B: SAMPLE SPECTRAL DATA

B.1 SAMPLE FILE HEADING

OOIBase32 Version 2.0.0.5 Data File
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Date: 11-19-2002, 13:42:10
User: Valued Ocean Optics Customer
Spectrometer Serial Number: MC2J314
Spectrometer Channel: Slave1
Integration Time (msec): 250
Spectra Averaged: 1
Boxcar Smoothing: 0
Correct for Electrical Dark: Enabled
Time Normalized: Disabled
Dual-beam Reference: Disabled
Reference Channel: Master
Temperature: Not acquired
Spectrometer Type: S2000
ADC Type: ADC1000USB
Number of Pixels in File: 2048
Graph Title:
>>>>>Begin Spectral Data<<<<<<

B.2 PORTIONS OF A SAMPLE DATA SET

The important portions of this data set are shown below. These include the regions used in the visible range for temperature calculations, 520 nm – 540 nm for the shorter wavelengths and 640 nm – 660 nm for the longer wavelengths. The section of the ultraviolet of importance includes the wavelength section 305 nm – 320 nm, though the OH radical is minimal for this data set due to the use of air as the oxidizer. The near-IR section is similar to the visible in that the sections used for temperature calculations are shown, 790 nm – 810 nm for the shorter wavelengths and 920 nm – 940 nm for the longer.
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<th>Near Infrared</th>
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VITA

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He has published in Hyperfine Interactions (C) for his work with Mössbauer Spectroscopy presented at the 1997 International Conference on the Applications of the Mössbauer Effect in Rio de Janeiro, Brazil. He has also published material presented in this dissertation in IX Ceramic Transactions Volume 155, 2003 and Fuel Volume 83 Number 9 June 2004.