Laser Induced Fluorescence Spectroscopy for measuring hydroxyl concentration in flames.

Author:
D.J. Heusinkveld

Supervisors:
Dr. A.V. Mokhov
Prof. dr. H.B. Levinsky

Department of Combustion Technology

May 18, 2019
Summary

In this research the hydroxyl concentration in methane/air flames was measured by the technique of Laser Induced Fluorescence (LIF). Two approaches can be used to determine the hydroxyl (OH) concentration. First, a fitting program was used to determine the OH concentration from a measured spectrum. The influence of the temperature dependence on the linewidth in this fitting program was tested by generating theoretical spectra at various temperatures and fitting them with a spectrum with linewidth at fixed temperature 2000 K. The difference between the actual temperature or concentration and fitted temperature or concentration was in all cases less than 5%. Second, the OH concentration was determined by a calibration procedure, where the fluorescence intensity was measured at different OH concentrations. At a fixed equivalence ratio the calibration curve is approximated by a line. However, the slope changed with different equivalence ratio’s. This could be caused by the uncertainty in for example the flow rates. Each calibration line can be used separately for future quantitavie LIF measurements.
# Contents

1 Introduction 4

2 Theory 5
   2.1 General properties of combustion .......................... 5
   2.2 Laminar Premixed Flames .................................. 6
   2.3 Laser Induced Fluorescence Spectroscopy .................. 8

3 Line broadening 11
   3.1 Doppler broadening ....................................... 11
   3.2 Collisional broadening .................................... 12
   3.3 Voigt profile ............................................. 13
   3.4 Spectral line broadening .................................. 14
   3.5 Methods .................................................. 15
   3.6 Results .................................................. 16

4 Experimental setup 20

5 Fluorescence intensity 22
   5.1 Methods .................................................. 22
   5.2 Results .................................................. 22

6 Conclusion 25
1. Introduction

Combustion is a process that is integrated in our everyday lives, from cooking to heating systems, energy production in power plants and transport. Combustion describes a chemical reaction between a fuel and oxygen. Various hydrocarbons can be used as fuel, a commonly researched fuel is methane, which is also used in this research. In combustion processes many harmful substances can be formed, such as nitrogen oxides, carbon monoxide and soot. Developing new technologies aiming to increase efficiency and decrease pollutant formation can be significantly accelerated by better understanding processes occurring in flames. The goal of this research is to measure the hydroxyl concentration of a flame, by using Laser Induces Fluorescence (LIF) methods. The hydroxyl (OH) radical is chosen due to its importance as a reactive species in combustion. It initiates the oxidation process by removing hydrogen atoms from the fuel. Determining the OH concentration was done in two ways. First, a fitting program was used to fit a measured excitation spectrum to get the OH concentration. The influence of line broadening effects on the fitting program were tested. Second, the dependence of the LIF signal upon the OH concentration has been determined, to be used as a calibration curve in future studies of flames, [1].
2. Theory

2.1 General properties of combustion

General combustion can be represented schematically as the following process:

\[ \text{fuel} + \text{oxidizer} \rightarrow \text{combustion products} \quad (2.1) \]

One of the important parameters describing a mixture of fuel and oxidizer is the equivalence ratio \( \phi \), which is determined as:

\[ \phi = \frac{\left( \frac{\text{Fuel}}{\text{Oxidizer}} \right)_{\text{actual}}}{\left( \frac{\text{Fuel}}{\text{Oxidizer}} \right)_{\text{stoichiometric}}} \quad (2.2) \]

where \( \left( \frac{\text{Fuel}}{\text{Oxidizer}} \right)_{\text{stoichiometric}} \) is the ratio of concentrations of fuel and oxidizer when complete oxidation of fuel to water and carbon dioxide occurs. This is called the stoichiometric mixture with equivalence ratio 1. At \( \phi \) lower than one there is a surplus of air, which is called lean combustion and at \( \phi \) higher than one the mixture has a surplus of fuel, also called rich combustion, [2, 3]. In the specific case of methane/air 2.1 can be written as:

\[ \text{CH}_4 + 2(\text{O}_2 + 3.76\text{N}_2) \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 2 \cdot 3.76\text{N}_2 \quad (2.3) \]

According to this formula combustion products consists only of \( \text{H}_2\text{O}, \text{CO}_2 \) and \( \text{N}_2 \). In reality combustion occurs in many steps and many intermediate species are formed in the process. One of these intermediate species is the hydroxyl molecule, that is studied in this research.
In figure 2.1 the temperature, OH concentration, CO\textsubscript{2} concentration, H\textsubscript{2}O concentration, N\textsubscript{2} concentration and CO concentration are shown as a function of φ. The temperature is at a maximum at φ is 1. In lean combustion the temperature is lower due to the excess of oxygen and in rich combustion the temperature is higher due to an excess of methane. The OH concentration, H\textsubscript{2}O concentration and CO\textsubscript{2} concentration follow the same trend with a maximum at φ is 1 at complete combustion. N\textsubscript{2} shows a higher concentration in lean combustion and CO shows a higher concentration in rich combustion, where there is a higher concentration of methane and a shortage of O\textsubscript{2}.

2.2 Laminar Premixed Flames

There are generally two types of flames used in combustion research, premixed and non-premixed flames. In premixed flames the fuel and oxidizer are mixed together and then ignited. In non-premixed flames the fuel and oxidizer enter the reaction zone separately.
A one-dimensional laminar flame is typically used in experimental setups. The typical structure of a laminar 1D-premixed flame is shown in figure 2.2. There are four zones: the unburned zone, the preheat zone, the reaction zone and the burned gas zone. The unburned zone is before ignition, when the fuel mixture is ignited the preheat zone starts and the temperature increases. In the reaction zone most of the intermediate species are formed. The thickness of the reaction zone is dependent on the pressure and the equivalence ratio. The preheat zone and reaction zone together is called the flame front. Lastly, the burned gas zone is where the burned gas approaches its equilibrium condition.

![Schematic representation of the combustion zones of a laminar premixed flame](image)

Figure 2.2: Schematic representation of the combustion zones of a laminar premixed flame, [4].

An important characteristic of the flame is its laminar flame speed ($S_L$), which is the speed of the flame front propagation into the unburned zone. This is represented in figure 2.3. The laminar flame speed depends on the type of fuel, temperature, pressure and equivalence ratio. Two situations can be distinguished, [5]. First, when the velocity of the unburned gas/air mixture ($v$) > $S_L$ the flame moves away from the burner. Second, $v$ < $S_L$ heat is transferred to the burner which causes the temperature to decrease and $S_L$ will decrease as well. When $S_L$ becomes equal to $v$ the burner stabilizes. Thus by changing the exit velocity of the unburned gas/air mixture, the flame temperature can be varied at fixed equivalence ratio’s.
2.3 Laser Induced Fluorescence Spectroscopy

Laser Induced Fluorescence (LIF) spectroscopy is used to measure several properties of flames, such as the concentration of a species or temperature. Figure 2.4 shows the possible absorption and emission processes. Each atom or molecule has a large set of electronic, vibrational and rotational energy levels or states in which transitions can occur. Transition between state i and k can occur as fluorescence or non radiative emission. Quenching takes place when no photon is emitted and the excitation energy is transferred to another molecule due to collisions.

In a typical experiment, the fluorescence signal is measured with changing the wavelength of the pumping radiation. When the wavelength is in resonance with a molecule’s transition a fluorescence signal is emitted and an example of a resulting spectrum of species OH is shown in figure 2.5.
The intensity of the fluorescence signal is [6]:

\[ I_{\text{FL}}(\nu) = CN_i \frac{I_L}{Q} F_C(\nu) \]  \hspace{1cm} (2.4)

Where \( C \) is a constant depending upon the experimental setup (collecting angle, detector efficiency, spectral filter, etc.), \( N_i \) is the population of initial state \( i \), \( I_L \) is the spectral intensity of laser radiation, \( Q \) is the quenching rate and \( F_C \) is the convolution integral.

The population in state \( i \) is related to the total population as [6]:

\[ N_i = \frac{N_{\text{TOT}} g_i e^{-E_i/kt}}{q} = \frac{P X g_i e^{-E_i/kt}}{q} \]  \hspace{1cm} (2.5)

Where \( N_{\text{TOT}} \) is the total population, \( g_i \) is the degeneracy of level \( i \), \( E_i \) is the energy of level \( i \), \( k \) is the Boltzmann constant, \( T \) is the temperature, \( X \) is the mole fraction and \( q \) is the partition function. The slope of the resulting plot will give the value of \( T \), as seen by:

\[ \ln(N_i) = -\frac{E_i}{kT} + \text{Constant} \]  \hspace{1cm} (2.6)

The quenching rate \( Q \) is determined by collisions with flame molecules and thus depends upon temperature and composition. It can by approximated by [6]:

\[ Q = \sum_i \sigma_i N_i v_i \]  \hspace{1cm} (2.7)
Where \( N_i \) is the number of molecules, \( v_i \) is the relative speed and \( \sigma_i \) is the cross-section. \( \sigma_i \) can be found elsewhere [7].

Provided that all parameters in 2.4 are known we can derive an expression for determining the concentration of the OH molecules from the measured fluorescence signal at wavenumber \( \nu \):

\[
X = \frac{qI_{FL}(\nu)QkT}{CPg_iI_LF_Ce^{(-E_i/kT)}}
\]  

(2.8)

Alternatively, the concentration and temperature can be derived from the whole spectrum by using the fitting procedure. In this procedure, the spectrum parameters are determined by minimizing the sum of squares of differences between the measured and calculated spectrum. This program was created by dr A.V. Mokhov using the Cantera database, [8]. An input parameter of the fitting program is the linewidth, which depends on several line broadening effects discussed in the next chapter. The linewidth is taken as a constant which does not depend on the temperature. However, the accuracy of the program is not optimal so the temperature influence of the linewidth is tested. Figure 2.6 shows an example of an experimental spectrum fitted with the fitting program.

![Figure 2.6: An experimental OH spectrum with fit, [8].](image-url)
3. Line broadening

As was mentioned in chapter 2, the LIF signal depends upon the convolution integral. The parameter $F_C(\nu)$ is a convolution between the laser spectral line ($F_{\text{las}}(\nu)$) and absorption spectral profile ($F_{\text{abs}}(\nu)$) of absorption transition $i \rightarrow k$ and is given by [7]:

$$F_C(\nu) = \int_{-\infty}^{\infty} F_{\text{las}}(\nu') F_{\text{abs}}(\nu - \nu') d\nu'$$  

(3.1)

In two limiting cases, one of the functions in the integral can be treated as a delta function, and result in:

$$\Delta \nu_{\text{las}} << \Delta \nu_{\text{abs}} \rightarrow F_C(\nu) = F_{\text{abs}}(\nu)$$  

(3.2)

$$\Delta \nu_{\text{las}} >> \Delta \nu_{\text{abs}} \rightarrow F_C(\nu) = F_{\text{las}}(\nu)$$  

(3.3)

The light absorbed or emitted by a molecule is not a single wavelength but instead has a finite bandwidth. This finite bandwidth is due to the effect of line broadening. Line broadening is characterized by the spectral line profile. The linewidth is defined as the full width at half maximum (FWHM).

Two effects have an influence on the line broadening: the laser spectral line profile and the absorption spectral line profile. The laser spectral line is determined by the broadening effects of the laser, which is defined by the experimental setup. The absorption spectral profile is defined by the broadening effects that occur in the flame. These are Doppler broadening, natural broadening and collisional broadening. Natural broadening is neglected due to the small value in comparison to the other broadening effects.

3.1 Doppler broadening

Doppler broadening is caused by the random motion of the molecules or atoms. This random motion causes a red or blue Doppler shift relative to the observer. The cumulative effect of these shifts translates in linewidth broadening. The Doppler profile is given by [7]:

$$F_D(\nu - \nu_{ik}) = \sqrt{\frac{4ln2}{\pi}} \frac{1}{\Delta \nu_D} \exp[-4ln2(\frac{\nu - \nu_{ik}}{\Delta \nu_D})^2]$$  

(3.4)

Where [7]:

11
\[ \Delta \nu_D = \nu_{nm} \sqrt{\frac{8 \ln 2 k_B T}{m c^2}} \]  

(3.5)

With \( \Delta \nu_D \) the Doppler linewidth at FWHM, \( \nu \) the wavenumber, \( c \) the speed of light, \( k_B \) the Boltzmann constant, \( T \) the temperature and \( m \) the molecule mass.

Equation 3.4 indicates that the Doppler profile has a Gaussian profile. Figure 3.1 shows the Doppler linewidth as a function of temperature. The linewidth increases with increasing temperature. There is a 20% increase in the Doppler linewidth from the temperature 1500 K to 2300 K.

Figure 3.1: The Doppler Linewidth as a function of temperature.

### 3.2 Collisional broadening

Collisional broadening is caused by collisions between molecules or atoms. Collisions can interrupt the emission process, which increases the uncertainty of the wavelength of the photon which is emitted. The profile of collisional broadening is given by [7]:

\[ F_{col}(\nu - \nu_{ik}) = \frac{\Delta \nu_{col}}{2 \pi} \frac{1}{(\nu - \nu_{ik})^2 + (\frac{\Delta \nu_{col}}{2})^2} \]  

(3.6)

Where the collisional linewidth is given by [9, 10]:

\[ \Delta \nu_{col}^i = \Delta \nu_{0}^i \frac{P_i}{P_0} \frac{T_0^{n_i}}{T} \]  

(3.7)
With $\Delta\nu_{\text{col}}$ the collisional linewidth at FWHM of species $i$, $\Delta\nu_0$ the reference collisional linewidth at FWHM of species $i$, $P_i$ the partial pressure of species $i$, $P_0$ the reference pressure at 1 atm, $T_0$ the reference temperature, $T$ the temperature and $n$ the temperature exponent for species $i$.

The profile of the collisional broadening is Lorentzian as seen in equation 3.6. The main species that contribute to the collisional linewidth are $H_2O$, $CO_2$, $N_2$, and $CO$. The total collisional linewidth as a function of temperature and for different equivalence ratios is shown in figure 3.2. The variation in $T$ for each $\phi$ is roughly 10%. The difference between the various $\phi$ is at most a 20% difference, [9, 10].

![Figure 3.2: The Collisional linewidth as a function of temperature for different equivalence ratios.](image)

### 3.3 Voigt profile

The absorption spectral profile is the convolution of the Doppler and collisional profile, which is called the Voigt profile. The three lineshapes are shown in figure 3.3, [6].
The Doppler profile is described by a Gaussian profile and the collisional profile by a Lorentzian profile. The Voigt profile is given by the convolution integral of Gaussian profile and Lorentzian profile:

\[ F_V(\nu) = \int_{-\infty}^{\infty} F_G(\nu') F_L(\nu - \nu') d\nu' \] (3.8)

The Voigt linewidth is approximated by [11]:

\[ \Delta \nu_V = 0.5346\Delta \nu_L + \sqrt{0.2166\Delta \nu_L^2 + \Delta \nu_G^2} \] (3.9)

With \( \Delta \nu_V \) the measured linewidth with a Voigt profile, \( \Delta \nu_L \) the Lorentz linewidth, \( \Delta \nu_G \) the Gaussian linewidth.

### 3.4 Spectral line broadening

As mentioned before the spectral line broadening is given by the convolution of the laser spectral line profile and the absorption spectral line profile. The manual of the dye laser gives a laser linewidth of \( \Delta \nu_{las} = 0.19 \text{cm}^{-1} \). The calculated absorption linewidth is in the same order of magnitude as the laser linewidth. The convolution integral can thus not be approximated with a delta function. The shape of the laser line is not specified, but is assumed to be a Voigt profile. To calculate the convolution of the laser spectral line profile and the absorption spectral line profile, the convolution of a Voigt profile with a Voigt profile is calculated. Using the idealized Lorentzian and Gaussian components
of the laser line profile and the absorption line profile, the Lorentzian and Gaussian components of the convolution integral are calculated by [12]:

\[
\Delta \nu_C^L = \Delta \nu_{L,\text{las}} + \Delta \nu_{L,\text{abs}} \quad \Delta \nu_C^G = \sqrt{\Delta \nu_{G,\text{las}}^2 + \Delta \nu_{G,\text{abs}}^2}
\] (3.10)

Where \( \Delta \nu_C^L \) is the Lorentzian linewidth of the convolution integral and \( \Delta \nu_C^G \) is the Gaussian linewidth of the convolution integral.

Two scenarios for the laser linewidth are calculated. One scenario where the laser linewidth is a Lorentz profile and one where it is a Gaussian profile, this is given by:

\[
\Delta \nu_{L,\text{las}} = 0.19 \text{ cm}^{-1} \quad & \quad \Delta \nu_{G,\text{las}} = 0
\]

\[
\Delta \nu_{L,\text{las}} = 0 \quad & \quad \Delta \nu_{G,\text{las}} = 0.19 \text{ cm}^{-1}
\] (3.11)

Figure 3.4 shows the dependence of the linewidth of the total spectral line on the temperature. There is an increase in linewidth of about 10% with increasing temperature. The difference between the Gaussian laser profile and Lorentz laser profile is approximately 20%.

![Figure 3.4: The linewidth of the spectral line as a function of temperature, with two scenario’s. One where the laser line is Lorentzian and one where the laser line is Gaussian.](image)

3.5 Methods

The dependence of the temperature on the linewidths in the spectrum fitting program was tested. Spectra were generated with different conditions, shown in table 3.1. Each spectrum was generated twice. Once with a Gaussian laser linewidth and once with a
Lorentzian laser linewidth. The generated spectra were fitted using fixed linewidths at $T = 2000K$.

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T(K)$</td>
<td>1666.7</td>
<td>1839.5</td>
<td>1997.9</td>
<td>2135.4</td>
<td>2226.4</td>
</tr>
<tr>
<td><a href="ppm">OH</a></td>
<td>0.000244</td>
<td>0.000729</td>
<td>0.001613</td>
<td>0.002675</td>
<td>0.002851</td>
</tr>
</tbody>
</table>

Table 3.1: Equivalence ratio with corresponding temperature and OH concentration of the generated spectra, [8].

The temperature and OH concentrations were obtained using Cantera and GRI mech 3.0, [8, 13]. The code simulates the flame structure shown in figure 2.2. The procedure was repeated for generated spectra at each condition with a 3% noise level. This was done four times to calculate an average and standard deviation. The generated spectra were fitted again with a fixed linewidth at $T = 2000K$.

### 3.6 Results

The difference in temperature given by the fit compared to the temperature of the generated spectrum was plotted in figure 3.5. The small temperature variation in figure 3.4 translated to a small error in the temperature difference. The error is at most 2.5 K, which at the temperature of 1666.7 K corresponds to a 0.15% difference.

![Figure 3.5: The temperature difference as a function of the real temperature of the spectrum, with two scenario’s. One where the laser line is Lorentzian and one where the laser line is Gaussian. The temperature of the fitted spectrum is 2000 K.](image)

The difference in OH concentration as a function of temperature was plotted as well in figure 3.6. The maximum difference in OH concentration is 25 ppm, this corresponds
to 1.1\% at a temperature of 2226.4 K. This small difference is again related to the temperature variation as seen in figure 3.4.

Figure 3.6: The OH concentration difference as a function of the real temperature of the spectrum, with two scenario’s. One where the laser line is Lorentzian and one where the laser line is Gaussian. The temperature of the fitted spectrum is 2000 K.

The following generated spectra had a 3\% noise level. Each spectrum was generated four times to calculate an average and standard deviation for the temperature and concentration difference. The generated spectra were fitted with a fixed linewidth at $T = 2000K$. Figure 3.7 and figure 3.8 show the difference in temperature and OH concentration as a function of the real temperature, respectively. The average temperature difference is at most 30 K at the temp 1666.7 K, which corresponds to a 1.8\% difference. This small difference coincides with the small temperature difference in the linewidth from 3.4. For the OH concentration the highest difference is 50 ppm at 2135.4 K, which corresponds to 2.3\%.
The temperature difference as a function of the real temperature of the spectrum. Two scenario’s are done: A Lorentzian laser line and a Gaussian laser line. The theoretical spectrum has a noise level of 3% and the temperature of the fitted spectrum is 2000 K.

The difference in OH concentration from the generated spectrum compared to the fit is at most 50 ppm. This corresponds to a 2.3% at 2135.4 K. The small difference is relative to the small temperature difference as seen in figure 3.4.
Figure 3.8: The OH concentration difference as a function of the real temperature of the spectrum. Two scenario’s are done: A Lorentzian laser line and a Gaussian laser line. The theoretical spectrum has a noise level of 3% and the temperature of the fitted spectrum is 2000 K.

The temperature and OH concentration differences are all lower than 5%, which coincides with the small increase in linewidth calculated before. For simplification of the fitting procedure and a lower computational time, the influence of the temperature on the linewidth is not taken into account in future experiments.
4. Experimental setup

Figure 4.1 shows a schematic of the experimental setup used in this research. The laser radiation is generated by a Nd:YAG laser, which is followed by a second harmonic generator, with a frequency of 8 pulses per second. The pump laser is followed by a dye laser which can be adjusted to a wavelength in the region around 612 nm. The dye laser is followed again by a second harmonic generator, which halves the wavelength. Two mirrors are used to direct the laser to an attenuator, which is used to adjust the laser power. A lens follows with a focal point of 800 mm and followed by another mirror. A beam splitter is used to direct part of the laser to a photo diode and the other part to the burner. After the burner the laser radiation is detected by a photo diode for the absorption measurements. Fluorescence radiation is collected by a lens with a focal length of 105 mm and measured by a photomultiplier. A filter is placed in front of the photomultiplier to select a spectral region around 350 nm.
Figure 4.1: The experimental setup for measuring Emission and Absorption spectra. The laser is generated with a pump laser and directed via mirrors to the detection instruments, the photo diodes and the photomultiplier.

The burner used in the experiment is a premixed burner. The fuel and air are mixed before combustion happens. Methane is mixed with air. The flame is ignited by locally initiating a spark on the surface of the burner, while the gas flows are open. The burner is moved in the direction perpendicular to the laser beam, the y direction.
5. Fluorescence intensity

The second method to achieve a concentration measurement is to measure the fluorescence intensity as a function of the OH concentration. Using these results a calibration line was made.

5.1 Methods

The fluorescence of the OH concentration was measured with a burner at z is -10 mm and y is -2.5 mm. The signal was averaged 10 times to increase the accuracy. Four different equivalence ratios were measured, 0.7, 0.8, 0.9 and 1.0. The OH concentration and temperature corresponding to each equivalence ratio was obtained using Cantera and GRI mech 3.0, [8, 13]. At each equivalent ratio two different types of flames were measured: a Stabilized flame and Free flame. This was repeated for three wavelengths that were in resonance with peak R2(7), R2(13) and R1(15), as seen in figure 2.5.

The second measurement was done with equivalence ratio 0.8 and 1.0. The exit velocity of the methane/air mixture was varied, which corresponds to a change in OH concentration. The measurement was done in resonance with peak R2(7).

5.2 Results

A calibration line was made by measuring the fluorescence intensity of the OH concentration in the flame. This was done at three different wavelengths that were in resonance with peak R2(7), R1(15) and R2(13). The intensity was measured for different equivalence ratio’s and different types of flames. Figure 5.1 shows the fluorescence intensity as a function of OH concentration. The values were plotted according to equation 2.4. The three peaks show lines, with different slopes. According to the theory the slope is expected to be equal. There are several uncertainties present in the experiment. First, the OH concentration was computed and can be different from the actual concentration. The flow rates vary with time, which increases the uncertainty in the concentration. There is an uncertainty present in the $S_{line}$ variable. As the last uncertainty, the wavelength used may not be at the maximum of a peak. In this measurement two variables were varied, the exit velocity and methane concentration, to change the equivalence ratio. To decrease the uncertainty in the variables a second measurement was done, with one variable.
Figure 5.1: OH intensity times the quenching rate, divided by laser power and the spectral line as a function of OH concentration for a stabilized flame at $\phi = 0.8$ and $\phi = 1.0$. At the burner coordinates of $z = 1.0\,cm$ and $y = -2.5\,cm$.

Figure 5.2 shows the OH intensity as a function of OH concentration according to equation 2.4. The exit velocity was varied and the methane concentration was kept constant at equivalence ratio 0.8 or 1.0. In the graph two lines with different slopes can be seen for the different equivalence ratio’s. Several uncertainties are present in the experiment. There is an uncertainty in the flow rates, which varies with time. The OH concentration is calculated and can vary from the actual concentration of the flame. Another uncertainty is in the $S_{\text{line}}$, were the wavelength may not exactly at maximum of a peak. Each of these calibration lines can be used separately to perform quantitative LIF measurements.
Figure 5.2: OH intensity times the quenching rate, divided by laser power and the spectral line as a function of OH concentration for a stabilized flame at $\phi = 0.8$ and $\phi = 1.0$. At the burner coordinates of $z = 1.0\text{cm}$ and $y = -2.5\text{cm}$. 
6. Conclusion

Two approaches can be made to determine the concentration of a flame. First, a fitting program can be used to calculate the OH concentration from a measured spectrum. The influence of the temperature dependence on the linewidth in the fitting program was tested. This was done by generating spectra at various temperatures and fitting them with a linewidth at a fixed temperature of 2000 K. The difference between the input and fitted parameters were small, less than 5%. This is true for the generated spectra with 3% noise as well. The noise does not have a significant influence. The influence of the temperature on the linewidth can be neglected in future experiments.

In the second method the concentration of a flame was determined by measuring the fluorescence intensity as a function of OH concentration. The OH concentrations were computed for each equivalence ratio. These results were used to make a calibration line for the OH concentration. The experiment was done for wavelengths that are in resonance with the peaks R2(7), R1(15) and R2(13). In the first measurement the lines of the three peaks did not collapse into a line with one slope. According to theory the result was expected to be a single line. In this measurement two variables were changed per measurement, the methane concentration and the exit velocity. The second measurement was done at a constant methane concentration with a variable exit velocity. It was repeated for equivalence ratio 0.8 and 1.0. Similar results were observed where the two equivalence ratio’s result in lines with different slopes. There were several parameters in the experiment with an uncertainty, such as the computed OH concentration, the $S_{line}$ or the flow rates. Reducing the experimental uncertainty will increase the reliability of the measurements. Each calibration line can be used separately for quantitative LIF measurements.
Bibliography


